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Open reWall: Survey-to-Production Workflow for Building Renovation

Filipe Jorge da Silva Brandão

PhD in Architecture of Contemporary Metropolitan Territories,
specialisation of Digital Architecture

Supervisors:
Doctor Alexandra Paio, Assistant Professor, Iscte-IUL

October, 2022

TECNOLOGIAS
E ARQUITETURA

Department of Architecture and Urbanism

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Jury:

Doctor Teresa Madeira, Assistant Professor, Iscte-Instituto Universitário de Lisboa (President)
Doctor José Pinto Duarte, Full Professor, Penn State University (USA)
Doctor José Pedro Sousa, Associate Professor, Faculdade de Arquitetura da Univesidade do Porto
Doctor Vasco Moreira Rato, Associate Professor, Iscte-Instituto Universitário de Lisboa
Doctor Alexandra Paio, Assistant Professor, Iscte-Instituto Universitário de Lisboa (supervisor)

October, 2022

À Lu, Valentina e Valéria

Agradecimentos/Acknowledgements

Em primeiro lugar, quero agradecer à minha orientadora por todo apoio, paciência e pela confiança no longo caminho da construção desta tese.

Agradeço a todos os participantes nas experiências e workshops realizados cujo contributo foi fundamental para atingir os objetivos propostos, Ana Rita Patrício, Bruno Patrício, Pedro Vilaça, João Filipe Sousa, Marco Mendes, Liliana Mendes, Rui Teixeira, Diogo Teixeira, Marta Campos, João Couto, Vanessa Duarte, Carlos Silva, António Sousa, Eduarda Grego, Maria Almeida, Marco Leite, Rui Gonçalves, Andreia Leite, Adriana Lima, Angélica Ponzio, Cristina Matsunaga, Giordana Pacini, Juliana Nery, Tiago Nascimento e Ana Lacerda.

De igual forma agradeço aos entrevistados que disponibilizaram o seu tempo, conhecimento e experiência, nomeadamente o Eng. António Carlos, Eng. José Moreira, Prof. José Amorim Faria, Prof. Joaquim Teixeira, Prof. Vasco Freitas, Prof. Paulo Mendonça, Arq. Brimet Silva, Eng. Tiago Ilharco e Eng. João Miranda Guedes.

Agradeço a disponibilidade da Casais para participar na apresentação do trabalho realizado, em particular ao Eng. António Carlos e Eng. Miguel Pires, e à Amorim e Laminar pelo apoio material prestado fundamental para a realização das experiências que foram efetuadas.

Agradeço aos colegas de doutoramento, Ricardo Correia pelas longas discussões sobre reabilitação e KDE, Rolando Volzone, e Filipa Osório pela amizade e partilha que contribuíram para fazer o caminho, e ao Professor Adriano Lopes que me deu o empurrão que precisava para enfrentar os desafios do desenvolvimento de algoritmos.

Um agradecimento especial aos colegas da cooperativa PARQUR, Nuno Sanches, Sofia Herrera, Tiago Ramos e Gil Ribeiro, pelo apoio, crítica e por aguentar o barco durante a minha ausência. Aos colegas e amigos da AORP, Fred Moura e Sá, Zita Torres, Isa Clara Neves, Jorge Bártolo, João Couto e Marta Campos pela disponibilidade e interesse para ouvir e discutir as minhas inquietações.

Ao Nuno Antunes pela amizade e disponibilidade para me receber em sua casa nas muitas estadias por Lisboa e pela ajuda nas simulações. Ao João Pedro Sousa pela boa vontade e paciência de alinhar e ajudar a concretizar todas as experiências que me propus no Vitruvius FABLAB. À minha irmã pelos logos desta tese e aos meus pais por tudo.

No lugar mais importante, agradeço à Lu pela infinita paciência e por segurar todas as pontas durante este longo caminho.

Este trabalho foi financiado pela Bolsa de Mérito da ISTA - Escola de Tecnologias e Arquitetura do ISCTE - Instituto Universitário de Lisboa, pela bolsa FCT - Fundação para a Ciência e Tecnologia, I.P - com referência 2020.08659.BD, e parcialmente financiado por fundos nacionais através da FCT, no âmbito dos projetos UIDB/04466/2020 e UIDP/04466/2020.

Resumo

A reabilitação de espaços interiores, num contexto de personalização em série, requer uma mudança na forma como os sistemas construtivos são desenhados, construídos e reutilizados. Recorrendo a plataformas digitais para a participação os arquitetos, em colaboração com outros atores na indústria AEC, podem desenvolver e oferecer soluções personalizadas e desmontáveis a utilizadores genéricos.

Esta investigação propõe o uso de sistemas de construção personalizada em série (CPS) para fornecer sistemas de divisórias desmontáveis fabricadas digitalmente usando metodologias do levantamento à produção ligadas a configuradores online, em que os utilizadores co-projetam soluções para a reabilitação de espaços interiores.

A metodologia de investigação socorre-se de pesquisa e análise teórica para definir critérios e objetivos a serem explorados em resolução de problemas de projeto. A partir destas experiências são sintetizados princípios e uma metodologia para a conceção de sistemas CPS de sistemas de divisórias personalizáveis e desmontáveis para a reabilitação. A metodologia clarifica os papeis dos atores, passos, e arquitetura do sistema para implementar um sistema CPS do levantamento à produção.

A investigação demonstra que a metodologia de levantamento proposta é utilizável por utilizadores especialistas e não-especialistas, com os últimos a apresentarem em média melhores resultados, e que estes levantamentos têm precisão suficiente para processos do desenho à produção. Também se demonstra que a metodologia do levantamento à produção, a gramática genérica, e os critérios são úteis para os arquitetos conceberem sistemas de divisórias desmontáveis e personalizáveis para sistemas CPS abertos.

Palavras-chave: Desenho Paramétrico; Fabrico Digital; Reabilitação; Personalização em série, As-is Surveys; Metodologia

Abstract

Building renovation of interior spaces, in the context of mass customization, requires a shift in how construction systems are designed, built, and reused. Leveraging digital frameworks for user participation, architects in collaboration with other stakeholders in the AEC industry may design and deliver customized and disassemble-able solutions to generic end-users.

The research proposes mass customization construction (MCC) systems can deliver cost-effective digitally fabricated and disassemble-able construction systems using survey-to-production workflows deployed in web configurators for end-users to co-design solutions in building renovation.

The research methodology uses theoretical inquiry and analysis to define criteria and objectives to be explored in design problem solving. From these experiments generalizable principles and a low-key workflow for the design of MCC systems of customizable and disassemble-able partition wall construction systems for open building renovation are synthetized. The workflow clarifies stakeholder roles, steps, and system architecture to implement an MCC system from survey to production.

This investigation demonstrates the proposed survey workflow is usable by non-expert and expert instance-designers, with the former having on-average better results, and that these can survey spaces with sufficient precision for design-to-production workflows. It is also shown the survey-to-production workflow, the generic grammar, and criteria are useful for architects to design customizable and disassemble-able partition wall systems for open MCC systems.

Keywords: Parametric Design; Digital Fabrication; Building Renovation; Mass Customization, As-is Surveys, Workflow

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List of Acronyms

2D – Two-Dimensional

3D – Three-Dimensional

AI – Artificial Intelligence

MC – Mass Customization

MCC – Mass Customized Construction

RTMC – Real-Time Mass Customization

OSArc – Open-Source Architecture

PF – Personal Fabrication

AEC – Architecture, Engineering and Construction

DfD – Design for Disassembly

DfMA – Design for Manufacturing and Assembly

SAR - Stichting Architecten Research

OBOM – Open Building Strategic Studies (OBOM) Research Group, Delft, The Netherlands

CIB - International Council for Research and Innovation in Building and Construction

BAMB – Building as Material Banks

CAD – Computer Aided Design

CAM – Computer Aided Manufacturing

CAE – Computer Aided Engineering

JIT – Just-in-Time

TPS – Toyota Production System

e-MC – electronic Mass Customization

e-MPC – electronic Mass Customization and Personalization

CNC – Computer Numerical Control

MIT – Massachusetts Institute of Technology, Cambridge, Massachusetts,

United States of America

CBA – Center for Bits and Atoms

ISCTE-IUL – Instituto Universitário de Lisboa, Lisbon, Portugal

TU Delft –Delft University of Technology, Netherlands

OSB – Oriented Strand Board

OSS – Open-Source Software

ArcMac – Architecture Machine Group

BIM – Building Information Modelling

UI – User Interface

CDS – Concept Design Systems

DDS – Detail Design Systems

CEN – European Committee for Standardization

EOTA – European Organization for Technical Assessment

ETAG – European Technical Assessment Guidelines

ICOMOS – International Council on Monuments and Sites

LCA – Life Cycle Assessment

CE – European Conformity, marking

MDF – Medium Density Fiber boards

ICB – Insulation Cork Board

CEO – Chief Executive Officer

MsC – Master of Science

PhD – Doctor of Philosophy

SAAS – Software-as-a-Service

HTTP – Hypertext Transfer Protocol

CMS – Content Management Systems

VPL – Visual Programming Language

TLS – Terrestrial Laser Scanning

PHG – Photogrammetry

JPEG – Joint Photography Experts Group lossy and compressed image file format

RAW – image files containing minimally processed and uncompressed image data from digital imaging sensors

SD – Standard Deviation

CEAAD - Curso de Estudos Avançados em Arquitectura Digital (Advanced
Studies Course in Digital Architeture)

CRW – Cork reWall

VFabLab – VITRUVIUS FabLab, Iscte-IUL, Lisbon

CCW – counter-clockwise

BRep – Boundary Representation

UNESCO – United Nations Educational, Scientific and Cultural Organization

NURBS – Non Uniform Rational B-splines

Introduction

Contemporary society is tightly connected, people are better informed and more demanding, needs change more rapidly requiring faster, customized, sustainable and higher quality solutions. In many European countries, building renovation has superseded new building construction, due to several factors, and is expected to continue to increase as the building stock ages (Vainio, 2011). Architects should strive to design solutions to this diverse context, enabling rather than determining human activity, integrating time as a dimension of design, and distributing control to the building end-users. Buildings should be capable of being adapted to specific user needs in a timely and cost-effective way without burden to the environment.

This thesis argues that these challenges may be met if architects combine an open building approach to building renovation with currently available digital design and fabrication tools coupled with configurators. It is a departure from the methodology of designing large scale standardized mass housing for generic clients. Replacing it for the design of open mass customized disassemble-able construction systems in building renovation. The shift of focus to building renovation empowers us to forgo the mindset of the new and different with that of common, shared principles and values as a framework for difference to emerge (Habraken, 2017).

This idea of using digital frameworks to support user-participation in the design of the built environment can be traced back to the sixties to the work of Yona Friedman (1971) or Nicolas Negroponte (1976) and it is (re)gaining momentum with developments in mass customization construction (MCC) systems, integrating computational design, digital fabrication, and online configurators. In a sense it is the reframing of the modernist utopia of providing affordable housing at scale, by replacing the traditional paternalistic top-down design method with co-design methods implemented in digital systems to provide context specific solutions to generic clients.

Covid-19 has contributed to accelerate digitalization trends, with consequences such as a transition to homeworking, long foreseen by authors such as Alvin Toffler (1980). This transition will affect all aspects of the built environment from the way cities and houses are organized to very nature of construction. Moving work back to the home will likely increase the frequency of interior renovations which already accounts for a large portion of the carbon emissions over the building's life.

The above trends and the contemporary context of climate emergency require a fundamental shift in how buildings are procured, designed, constructed, (re)used and demolished. The urgency of the matter calls for open innovation to develop building systems for local contexts based on sustainability criteria. Open-source digital frameworks to enable the design, fabrication, delivery and reuse of systems, components and materials must be imagined and implemented (Ratti & Claudel, 2015)

The present investigation seeks to explore the potential of cost-effective digitally fabricated construction systems to enable the design of disassemble-able partition wall systems for building renovation of interior spaces by generic users. The research aims to develop a low-key workflow to assist designers in designing open mass customization construction systems of partition walls for building renovation.

Motivation

This investigation is motivated by the opportunity digital design and fabrication tools provide to develop more adaptable and reusable construction systems, using widely available cost-effective circular materials, such as wood-based products or insulation cork board, and digitally fabricated joinery. For wood-based materials and cork to truly fulfill their potential as carbon storage, increasing their reusability is key as are enabling more favorable end-of-life scenarios. In fact, in the Inventory of Carbon and Energy (ICE) Database 3.0, timber and engineered wood products, sourced from responsibly managed forests, are the only materials with negative embodied carbon. Yet, Silvestre et al (2016) has reported insulation cork board also has a similar profile as timber and similar limitations. These production methods can accommodate local geometrical variability without incurring into significant production overheads, a fundamental enabler of mass customization. Digital fabricated joints can be reversible, components and systems demountable and reusable making them compatible with the principles of design for disassembly (DfD) and open building.

The above opportunities are particularly relevant in the renovation of interior spaces where partition walls are the most frequently changed components. Current solutions are not demountable or reusable, and mostly depend on materials that are not circular. It is a conviction of this thesis that cost-effective digitally fabricated systems proposed by researchers have not adequately considered the intersection of the requirements and criteria of building renovation, DfD, and mass customization. From the negotiation of these multidisciplinary contributions, it can be possible to achieve a clearer framework of criteria for developing partition walls systems that meet the aforementioned challenges.

Another important motivator of this thesis is the recognition that the integration of design-to-fabrication workflows with web configurators presents an opportunity for designers, in collaboration with the industry, to extend their practices to generic clients that could not otherwise afford it. To explore this opportunity configurators must link specific solutions with the physical, sociocultural, technologic, and personal context of each user. In building renovation of interior spaces this implies considering the geometry of the envelope, frequently not orthogonal, to be intervened. Yet, in practice there is a lack of simple methods meta-designers can use to allow the instance-designer to provide information about their physical context, which has limited the use of these methods to isolated objects designed by experts such as pavilions, or to the customization of finishes in prefabricated housing. Thus, it is urgent to fill this gap with research and innovation on semi-automated survey methods of interior spaces based on the empiric methods traditionally used by architects, including triangulation algorithms to assist the automation of the design of the plans and sections.

This thesis is also motivated by the opportunity mass customization as a business and production paradigm provides to the AEC industry as whole. Although architects were pioneers in exploring the consequences of the concept, they have mostly focused on issues of form rather than process. Yet, this has concurred to the dissemination of the use of parametric design tools, such as Grasshopper, and digital fabrication, leading to a new "material praxis" and fostering the emergence of a new field of exploration for building designers to take the role of meta-designer, developing meta-types for instance-designers – architects, builders, clients – to configure. To operate in this context architects must add to their skills the navigational instinct of entrepreneurs but also increasingly collaborate with other stakeholders in the design process.

Hypothesis, Questions and Objectives

The previous motivational context allows us to establish several research questions and specific objectives to achieve. These (Q) questions and (O) objectives are enumerated in a sequential order from which the main hypothesis is derived.

Q1. How can architects leverage mass customization to address the challenges of building renovation of interior spaces? How can architects design cost-effective and disassemble-able digitally fabricated construction systems of partition walls for building renovation and deploy them in web configurators for instance-designers?

O1. Analyze the concept of mass customization and the various approaches to its implementation in the AEC industry, identifying the levels of end-user control over the design and production of buildings, the roles of the stakeholders involved in the process. The aim is to propose a low-key workflow to develop survey-to-production configurators of partition walls for building renovation, identifying the involved stakeholders and their roles, and generic design principles to develop mass-customizable and disassemble-able partition systems.

Q2 What are the relevant criteria to consider when developing MCC systems of partition walls for open building renovation?

O2. Compare the theory, design guidelines and design criteria from the different fields, building renovation, open building and DfD, MCC systems and the technical requirements of partition walls to establish a framework of criteria for the design of open MCC partition wall systems. The aim is to define a framework of criteria for the design phase of the research. These criteria will guide the development of the solutions as well as their evaluation.

Q3 How can digitally fabricated partition wall systems be more reusable? How to transform materials with digital fabrication into parts that can be assembled into components which in turn must be assembled into a partition system?

O3. Identify generalizable design patterns that can guide architects in the process of designing open MCC partition wall systems to achieve a higher level of reusability potential. These design patterns are hinged on the set of previously mentioned criteria but are also related with the selected fabrication methods, the way materials may be joined into components and components into systems.

Q4 How can end-users of web configurators do surveys with sufficient quality so they can be used in MCC systems for customizable and disassemble-able partition systems?

O4. Compare existing methods of collecting geometric survey information commonly used by AEC professionals with currently available smartphone applications for surveying interiors spaces. The aim is to determine if these semi-automated methods of capturing or generating floor plans for non-expert users are sufficiently accurate to use as a basis for generating walls for digital fabrication and if non-expert users able to use these methods reliably to produce sufficiently accurate plans.

The answer to the above questions will allows us to formulate the necessary requirements, methods, and processes to fully address the main question and propose a low-key survey workflow that instance-designers can use effectively to survey their contexts and that provides useful information for meta-designers to build design-to-fabrication workflows.

The main hypothesis of this thesis can thus be formulated. This thesis hypothesizes that MCC unlocks new opportunities for architects to address the challenges of building renovation of interior spaces. In collaboration with other designers and stakeholders in the AEC industry, architects can develop customizable and disassemble-able partition systems and survey-to-production configurators for generic users to co-design solutions for their contexts.

To develop open construction systems for partitions walls, designers can use generic patterns that increase the reusability and modularity of the product system. To implement configurators for building renovation, collecting geometrical features of the context is a key step of the survey stage. Therefore, this thesis proposes a low-key workflow for implementing an interactive survey-to-production configurator, defining the key steps, components, and the distribution of the roles of the actors in the process.

Methodology

This thesis adopted a design inclusive research methodology (Horvath, 2008), which has been previously used by researchers in the development of typologies of joints for open systems buildings (Nijs et al., 2011) and end user interfaces for mass customization of housing design (Niemeijer, 2011). This methodology was adopted because of the need to synthetize basic research from many sources while also evaluating and reflecting on the application of theory through practical design experiments.

Research is divided into three main stages, theoretical research, design, and testing, that were iteratively applied to each of the specific areas of inquiry involved in open building renovation, i.e., design for generic users, MCC and DfD (Figure 1-1). It is from the cyclic process of design, prototyping and observation that generalizable principles are extracted, and solutions tested.

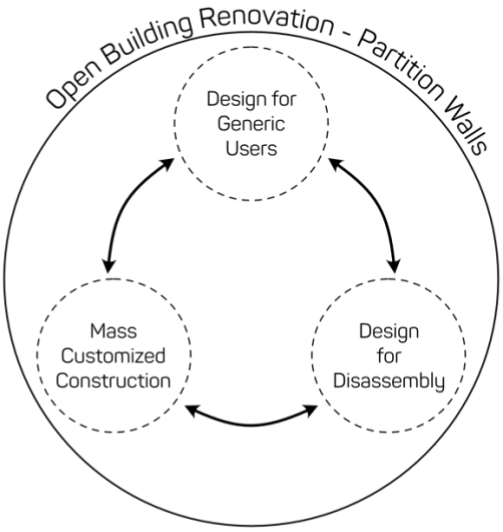


Figure 1-1: Main areas of research

The aim is not to design a product but to use the process of design to produce generalizable knowledge for mass customization construction systems. According to Habraken (2003), innovation in the construction industry cannot be developed in isolation from everyday practice and living patterns. Construction is inherently social in nature, consequently the design of products for that purpose cannot be the result of the direct application of disciplinary theoretical knowledge, requiring a broader view and a consideration of context.

The research process was not linear but involved multiple feedback loops from literature analysis to design experiments, prototyping, parameterizing, and user testing for the above areas. The reflection on the achieved results at each cycle informed the increasing focus over the problem. Figure 1-2 provides a diachronic overview of the research steps, identifying research activities and specific research outputs such as papers and prototypes for each stage.

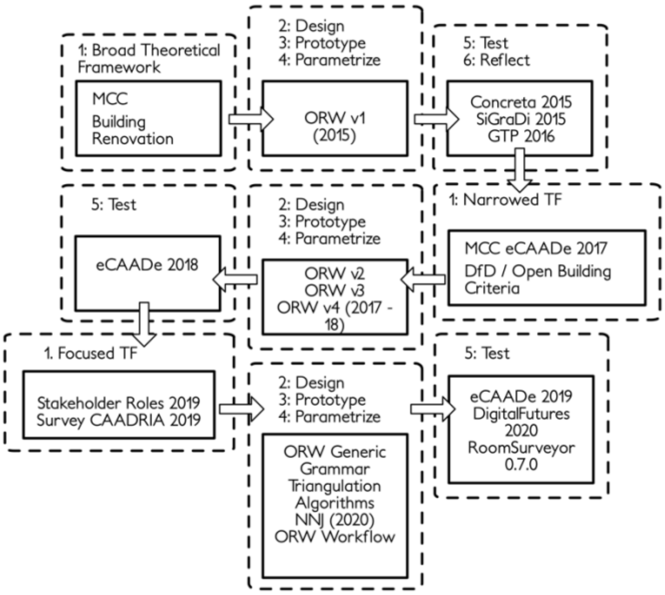


Figure 1-2: Diagram of the research methodology

Although the methodology follows a mostly top-down approach the design stages reverse to a bottom-up strategy where the systems are considered from the materials up to systems, and from particular cases to a generalization of patterns. This *modus operandi* is used across the design of partition wall systems, the development of iterative triangulation algorithms or survey-to-production workflows.

Throughout the text, citations not originally written in English have been translated by the author.

Contributions

The contributions of this thesis can be divided into practical and theoretical and are related with the objectives defined in Hypothesis, Questions and Objectives.

Contribution 1 – is a Theoretical/Practical contribution and consists of a low-key survey-to-production workflow for the implementation of configurators of partition wall systems for building renovation of interior spaces. The workflow is primarily aimed at meta-designers, whatever their background, but can also be useful to other stakeholders particularly those involved in production and construction. The workflow can be used as roadmap of the needed steps from survey to production, either for complete or partial automation of the tasks. It is divided into modular components, each subdivided into a series of steps, that can be developed independently, increasing the opportunities for open collaboration and contributions.

Yet, the workflow is more than a simple process flow and implies a specific organization of roles and responsibilities, and possible organizational structures that are necessary for the practical implementation of these systems.

Contribution 2 – is a theoretical contribution towards the definition of a rigorous framework of design criteria and guidelines for assessing and developing open and disassemble-able digitally fabricated partition wall construction systems for open building renovation.

The analysis of the designs considering the criteria is a contribution to future research aiming to increase reusability of building systems.

Contribution 3 – is a theoretical/practical contribution. The generic grammar is a theoretical contribution to the definition of a generalizable set of design patterns, such as subdivision rules and modularization strategies, for digitally fabricated partition wall systems. These generalizable rules have several practical applications. The first practical application is the use of the generic grammar for developing more specific disassemble-able and mass customizable partition wall construction systems by architects. The grammar enables the possibility of bottom-up design of systems, from materials into components and systems, while keeping a holistic overview of the relations and internal or external constraints of each part of the system.

A second practical contribution is the development of subdivision algorithms for each of the identified patterns that can be used to populate the partition walls with specific systems components. The developed partition wall systems are a third practical contribution that can be used as examples of systems for further design iteration. The T-slot joint is a fourth practical contribution to the toolkit of possible CNC fabricated joint details that can be used in the development of partition wall construction systems.

Contribution 4 – is a theoretical and practical contribution. The iterative triangulation algorithms described in this thesis provide a rigorous framework for developing interactive algorithms for semi-automated survey of interior spaces by generic users. RoomSurvey algorithms are a practical implementation of the algorithms described in this thesis in a

Grasshopper plugin that allows the implementation of low-key interactive survey workflows in online configurators. The resulting surveys are parametrical models of the existing spaces that can be used in design-to-production workflows that depend on the geometrical context.

Furthermore, since the output of these semi-automated survey workflows is a parametric model, there is the possibility of updating the survey and having the changes propagate to the design and production systems.

A further practical contribution consists of the JavaScript apps that facilitate and exemplify approaches for the development of configurators integrating survey processes.

Structure of this thesis

This dissertation intends to provide a concise but smooth description of the developed research, providing the necessary illustrations and diagrams to clarify the argument. It is divided in three parts (Figure 1-3).

Part I focuses on the theoretical framework of each of the areas involved in this research organized in a top-down way: open building renovation, mass customized construction, design for generic users. This part is divided into three chapters each of them focusing on one of these areas, clarifying their scope and the interrelations between each of them.

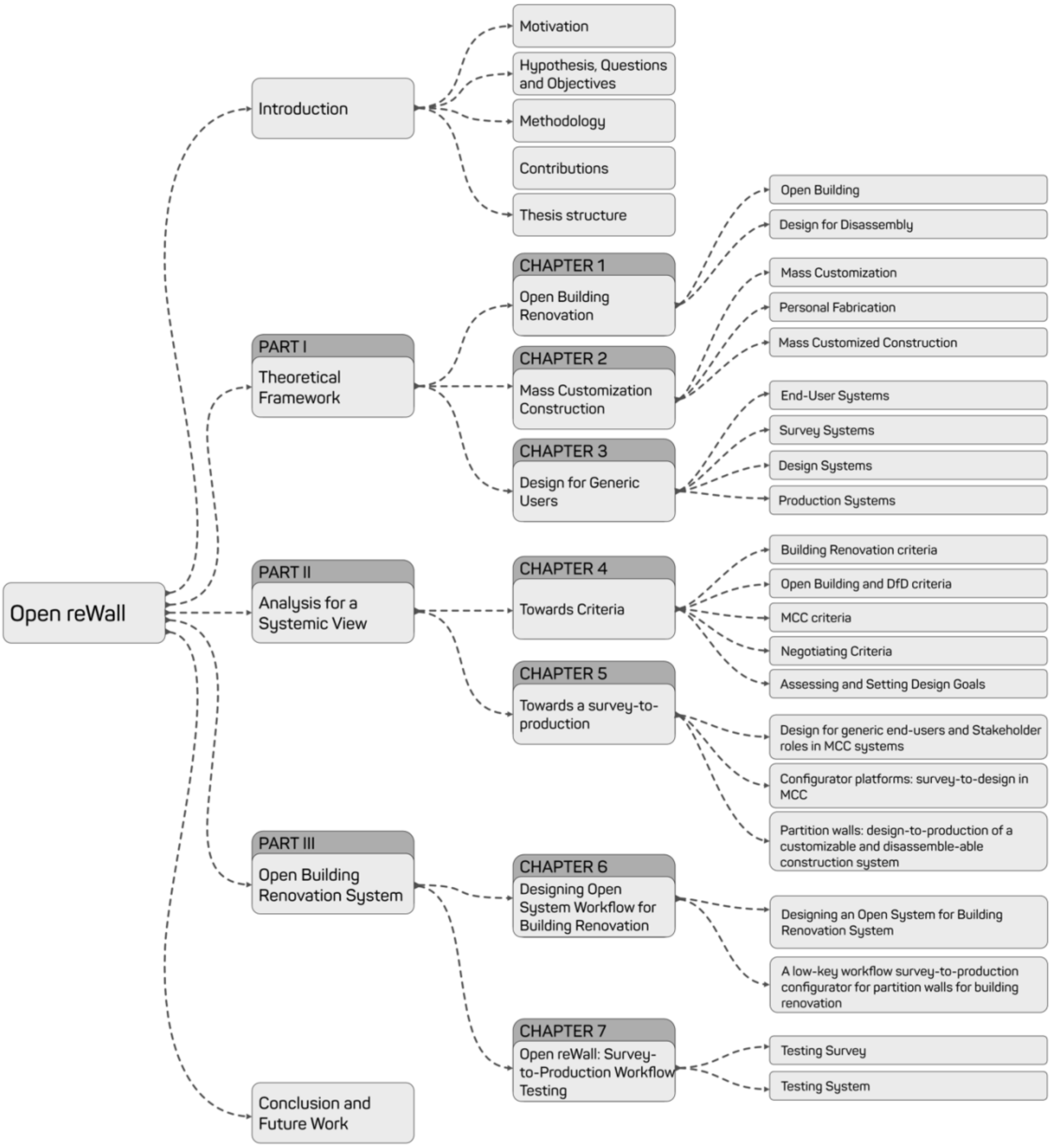


Figure 1-3: Structure of this thesis

Part II consists of a more focused analysis of the aspects described in the first part and is divided into two chapters which and lay the foundation for the work presented in last part. Chapter 4 analyses in detail the contributions from the several different fields of building renovation, DfD, mass customization and light interior partition wall systems to establish criteria for cost-effective and disassemble-able digitally fabricated partition walls systems. Chapter 5 analyses meta and instance-designer roles in MCC systems and existing configurator platforms and workflows that can be used to implement them. It also presents the practical design experiments that fundament the main contributions of this thesis. First, the generic grammar and then the partition wall systems design experiments that originated it are presented.

Part III presents the main contributions of this thesis. Chapter 6 exposes the fundamental research that underpins the proposed survey workflow, focusing in on the iterative algorithms, and the way these can be used to implement survey-to-production workflows. A step-by-step workflow for developing survey-to-production configurators for building renovation is described in detail. This part finishes with chapter 7 where experiments to validate the proposed workflow and generic grammar are described and result presented.

The thesis closes with a presentation of conclusions and achieved result as well as future research directions.

PART 1: THEORETICAL FRAMEWORK

CHAPTER 1 Open Building Renovation

There are multiple levels of intervention actions in the existing building stock, ranging from small maintenance and conservation actions to works involving substantial demolishing and replacement of building parts or adding new volumes to existing constructions. These levels of action are generally related with corresponding levels of administrative control in buildings. A building renovation project may involve many of these levels simultaneously. The processes of transformation of unbuilt land into buildings, or even the demolition and reconstruction of buildings are strongly controlled by municipalities, which require private parties to submit for planning approvals before starting construction.

Across the world, and even between cities in the same country there is a profusion of terms and concepts with similar meanings applied to the field, such as: renovation, remodeling, retrofitting, rehabilitation, adaptive reuse, alteration, expansion, reconstruction, addition, change of use (Lai & Kontokosta, 2019; Vainio, 2011). Most cities or countries deal with this issue by classifying each permit application to be highest level of intervention present in each project.

In the case of Portugal, the taxonomy of types is defined at a national level and comprises the following types: Alteration; Expansion or Addition; Reconstruction; and Conservation. With the introduction of the 2009 legislation on urban rehabilitation (DL nº 307/2009), the term Building Rehabilitation has been ambiguously used to encompass all the previous types including also total demolition followed by the construction of new buildings. This scope of the building rehabilitation stands in contrast with the prevalent definition of building rehabilitation as a set of actions on the built stock that may contribute to improve its performance, safety, functionality, and comfort while respecting the building's architecture, typology, and construction system (Freitas, 2012; Teixeira, 2013b).

In this text, building renovation is used as an umbrella term to encompass building rehabilitation definition and hence specifically excludes actions that involve total demolition of the existing building followed by a new construction, but includes actions that replace parts of the existing building to update or improve their functionality by the introduction of new construction systems, generally referred to as retrofitting, that are nonetheless consonant with the existing structure (Vainio, 2011).

Building renovation accounted for 57% of the total construction market in Europe in 2015, of which 65% are renovations of housing buildings. The annual growth of building stock across Europe has been in the range of 1 to 3% for the past two decades. Durmisevic (2006a) reports that a quarter of the new buildings replace demolished structures. Also, 40% of these buildings were built in the sixties and nearly 90% until the 90s (European Parliament. Directorate General for Internal Policies of the Union., 2016). This has led several researchers to point to the urgency of promoting proper energy retrofitting strategies to reduce the energy consumption in existing buildings (Mestre et al., 2016; Saheb, 2016; Veld, 2015). While other researchers have called for a more carbon focused approach (Luscuere, 2017; Sturgis, 2017). Nevertheless, renovation of buildings has been identified as a cornerstone of the European strategy to address environmental and social challenges.

In Portugal, between 2002 to 2014, there has been an increase in the percentage of renovation in concluded construction works from 18% to 37% nationwide (Figure 1-1), in which, renovation of housing accounted for 56,6% in 2010 and 68,3% in 2015 of all renovation works. This increase occurred in a context of decrease of the overall activity in the construction sector (INE, 2016). The tendency of increasing relevance of building renovation in detriment to new building construction is expected to continue, bringing Portugal closer to the European average (Carvalho, 2013; Freitas, 2012).

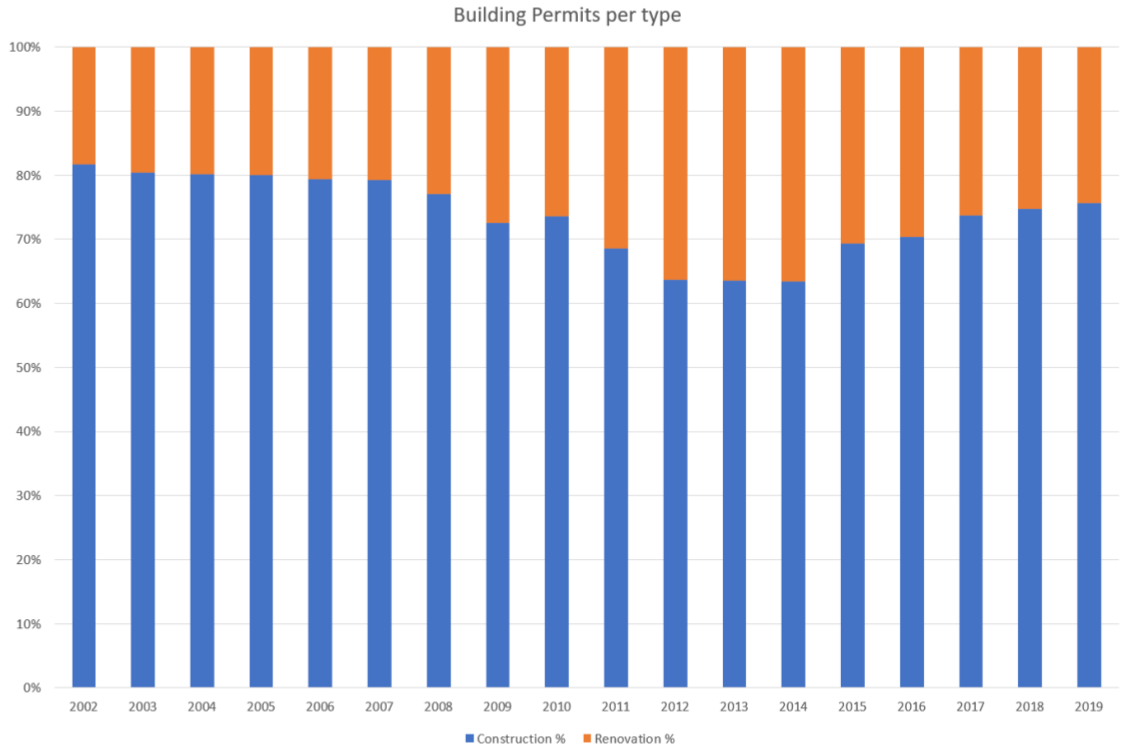


Figure 1-1: Percentage pf building permits per type (New Construction vs Renovation) between 2002 and 2019. Source INE

In the last three years, the national level building permit data seems to indicate the tendency has been reversed, with an increasing proportion of new building permits versus building renovation permits issued by city halls across the country (Instituto Nacional de Estatística, 2020). The statistics for the transactions of buildings nationwide tell the opposite story, showing a steady increase in the number and value of existing buildings vs new buildings, with existing buildings representing 83% of all transactions in the 3rd quarter of 2020 (Figure 1-2).

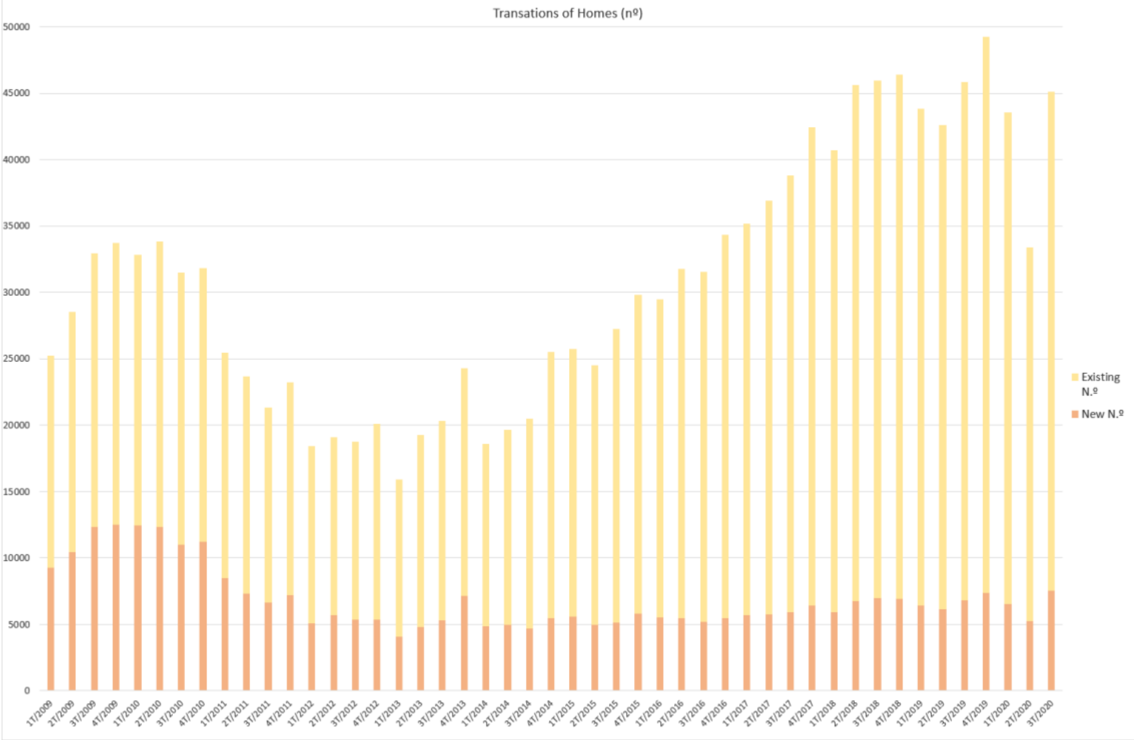


Figure 1-2: Number of transactions of homes between 2009 and 2020. Source INE

The discrepancy may be caused by many factors. Part of the transactions may not be for end-use of the building but for investment. Of the transactions that are meant for end-use, building owners may not conduct any renovation action, conduct those that do not require permit or even conduct the renovations illegally.

It is important to note that not all renovations in Portugal are required to submit for municipal approval. In fact, all interior changes that do not affect the structure or (infra-structure) of the building can be conducted without it. Changes to the internal partitions may occur in all the previous types of intervention except for Conservation works. Furthermore, they may also occur without administrative control. Thus, the existing data on administrative control of building renovation, both the open data and the national statistics, is just a proxy for the total building renovation that effectively occurs.

Based on building permit applications it seems that building renovation is a geographically asymmetric phenomenon. It is higher in the cities and particularly on larger cities such as Porto and Lisbon, and within these cities it has been concentrated on city centers and 19th century expansions, and to a lesser degree, on early 20th century expansions (F. Brandão et al., 2017, 2018). Consequently, building renovation spreads across different building typologies and construction technologies, spanning more than two centuries, which have different requirements and pathologies.

Design and construction in building renovation are piecemeal by nature, requiring high levels of labor on-site and as such not prone to standardized construction methods (D'Oca et al., 2018). The major impediments are the diversity of construction methods, alterations over the life-span of the building, and the pathologies either caused by degradation, lack of maintenance, or natural aging of the materials (Freitas, 2012).

In old buildings, rehabilitation actions are complicated by lack of technical know-how from most of the stakeholders involved but in particular there is a lack of available workforce knowledgeable of traditional construction methods (Freitas, 2012; Teixeira, 2013a). In modern buildings the main obstacles to standardized methods are the division into horizontal properties, which eliminates possible economies of scale. Other important aspect of the renovation work in these types of buildings is the need to intervene while the building is in use. Which further justifies the importance of light construction and disassembly methods that reduce inconveniences such as noise, dust, and the removal of large quantities of debris.

Therefore, when designing a construction system for building renovation less assumptions can be made about the properties and geometries of the interfaces with existing building elements, compared to a system that is designed for new building construction.

At the European level, Veld (2015) states that there are several other industry related factors that inhibit a leaner response from the AEC (Architecture, Engineering and Construction) industry: The building sector is fragmented and unable to offer holistic, cost-effective, high quality solutions; the construction process is layered, involving many actors onsite increasing costs and errors; the building market is supply driven with a discrepancy between offer and end-user demands; the building process is seen by building owners as bureaucratic, financially risky, and long.

Previous research as suggested that a path to overcome these issues is to change the renovation process to an off-site prefabrication process with the potential to reduce cost, waste, time and disturbances while at the same time increasing performance and quality (Mestre et al., 2016; Nijs et al., 2011; Veld, 2015). Further, moving the high-skill work from the site to the factory and leaving only unskilled assembly work to be performed on-site may have several advantages to workers (Kieran & Timberlake, 2003) and to users (Habraken, 1992, 2003).

Recent research has aimed to develop solutions for retrofitting building facades using integrated design-to-fabrication processes to provide high energy-efficient customized prefabricated building components (Veld, 2015; Mestre et al., 2016; Barco et al., 2017) to building owners.

Several European innovation action projects have attempted to tackle the complex issues stated above, proposing either the use of innovative technologies or leveraging existing technologies to build integrated design-to-production systems of plug-and-play construction systems for deep building renovation (D'Oca et al., 2018) . In a review of the efforts of these projects, D'Oca et al (2018) conclude that renovation needs a participative approach involving end-users early in the design process which can contribute to increase trust and reduce conflicts and unexpected changes. They believe that these innovation efforts in building renovation have mostly tackled the problem from a technological standpoint, frequently neglecting social and financial aspects. They further conclude that aggregating demand is an important strategy to reduce investments and social costs.

Building renovation is far more complex than new building construction for several reasons. In contrast to new building construction, building renovation encompasses a diverse set of activities and scopes of intervention on the built fabric. Even within the same country, there can be multiple terms for each of the renovation actions or levels of intervention (Lai & Kontokosta, 2019). Cities have regulation and data collection mechanisms adapted to their specific contexts which hinders information sharing, comparisons and stakeholder action within and across cities (Ku & Gil-Garcia, 2018). Furthermore, Renovation actions are less visible than new building construction, since it occurs at different stages of the building life-cycle and with different depths it may not even be captured by city halls administrative processes (F. Brandão et al., 2018).

Designing for building renovation is also riddled with complexity. If we accept Christopher Alexander (Alexander, 1973) definition of design to be the process of achieving fitness between context and form, the designer's role in designing for building renovation is first determining the form-context boundary. Not only there are multiple context-form boundaries, as Alexander states that there are in any design problem, but the information on the properties of the context is very imprecise.

If in any design problem designers must design *"with a number of nested, overlapped form-context boundaries in mind"*, in building renovation form is not simply "*the part of the world over which we have control"* (Alexander, 1973, p. 18), but might embed parts of the context of which we have little knowledge of during the design phase. As construction work takes place, particularly during demolitions, relevant information may emerge that could lead to changes in the design problem and consequently the form.

Hence, renovating buildings poses a different design problem. The aim is not to design an object over which we have absolute control but to intervene in an existing one introducing different systems to the meet current standards. In practice, this requires a thorough knowledge of the building to be intervened. This knowledge may be obtained through empirical experience, historical research and building surveys (Freitas, 2012).

The historical research, such as proposed by Freitas (2012), is mostly typological and thus for building renovation design practice constitutes a probabilistic sort of information. Coupled with the building survey knowledge it can constitute a very good, educated guess (model) of the real as-is state of the building. Nowadays, most researchers converge to the need of the use of Terrestrial Laser Scanning and/or Photogrammetry as necessary tools to increase the level of detail, accuracy, and precision in the survey. Yet, as-is surveys have several objective limitations (Pătrăucean et al., 2015): (1) High level semantic information such as cost and product specifications are not possible to infer. (e.g., type of paint used); (2) The achievable level of detail in an as-is survey is limited by practical considerations of data collection and can be cast as a tradeoff between cost and sufficient detail; (3) It is not possible to collect geometric data of occluded building elements. Furthermore, deviations between the planned and the as-built geometry may still occur due to errors in construction or changes promoted by stakeholders during the construction process (Tamke et al., 2016).

It is short-sighted to think of renovation as just a short-term goal to meet specific energy consumption targets. Building renovation is a natural and ongoing process in the life of buildings. As needs, technologies and culture changes, buildings are adapted and transformed to meet new requirements or goals (Brand, 1994). It has been shown that more than half of the building lifetime carbon emissions are caused by the materials used in its construction, maintenance, and refurbishment and eventually demolition. Thus, efficient material use is crucial to reduce carbon emissions (Durmisevic & Yeang, 2009; Sassi, 2008; Sturgis, 2017). For instance, Sturgis (2017) demonstrates that deep retrofits of nineteen century housing can be more cost-effective and generate less carbon emissions than demolishing them and building anew to Near Zero Building standards.

Construction activity in general has a very strong impact on local resource consumption such as materials and energy. Renovating or reusing buildings is generally more sustainable than replacing them with new buildings, since less material and energy is used (Sturgis, 2017; *Un Vitruvio ecológico*, 2007).

Reorganizing interior spaces is one of the most frequent forms of adaptation to new uses, thus partitioning and interior finishes are the most often replaced components over the life-cycle of a building, however the partitions are usually constructed with overly permanent constructive processes or that cannot be reused, either as a constructive system that maintains its functionality but in new combinations, or as materials that can be reused for other purposes (Durmisevic, 2006b; Durmisevic & Yeang, 2009).

Reusing partition walls in building renovation can have several advantages in terms of waste generation, energy and resource consumption and cost over the building lifetime (Durmisevic, 2006a; Sturgis, 2017). For this to happen, partitions must be demountable, reusable, and serviceable. DfD (Crowther, 2009a; Durmisevic & Yeang, 2009) is a strategy that addresses the design of buildings, systems or components that are demountable and reusable with minimal interference with the supports, and at a lower level can be decomposed into basic materials for reuse or recycling.

These goals are in fact complementary to the proponents of generative systems and digital fabrication, but as Habraken (2003) suggests, construction is both cultural and technical and to successfully change it, the solutions must involve all actors, architects, builders, and users, and focus not on the longer lasting layers, such as the building structure, but on the fit-out systems.

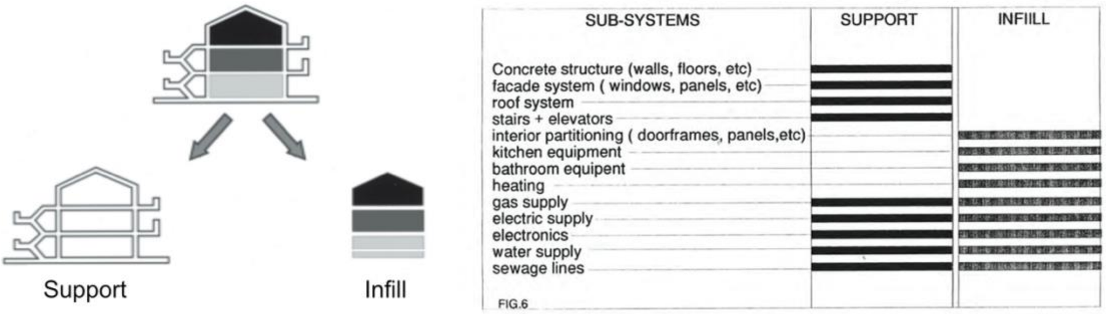
1.1 Open Building

Renovating buildings is more sustainable than to demolish and rebuild them to a higher standard (Sturgis, 2017). Maintaining and reusing the existing structure, where possible, significantly reduces the material and energy inputs in construction. Nevertheless, a greater focus has been placed in the research of solutions to improve the efficiency of material use and waste minimization in the construction process, or development of recycling processes at the demolition stage of the building life-cycle (Crowther, 2009a; Durmisevic & Yeang, 2009; Sassi, 2008), than on solutions that are capable of disassembly and reuse during the use phase of the building.

Embedding adaptability in building design through the separation of building components according to their service life expectancy – support and infill - was proposed by Habraken and the SAR (*Sitchting Architecten Research*) group in the sixties (Habraken, 2000) and evolved during the eighties into what became known as the philosophy of open building (Habraken, 2003). For Habraken, open building is a response to the need for flexibility to in built environment to accommodate changing user needs.

John Habraken ideas where first laid out in his 1961[1] book - *Supports: an alternative to mass housing* – originally published in Dutch and translated to English in 1972. In his book, Habraken stated that the responsibility of the individual for his environment represents an essential condition to the health of that built environment (Habraken & Teicher, 2000). Habraken criticizes the strategy of simplification of construction with the aim of maximizing industrial production, which leads to the exclusion of human social and psychological needs in housing design (Habraken, 2000). For Habraken the problem is not industrialization of construction but the dimensional standardization of components and design (Habraken, 1992). Based on these insights, he develops the principle of separation of *support and infill* as a way of disconnecting the diverse levels of action of the stakeholders in the built environment. He further stated that the control over the design of that built environment should be distributed in a balanced way between the community and the individual.

Frequently misinterpreted, *Support* for Habraken is not the building structure although it includes it. Support includes all building elements which make up the common framework of the building such as façades, structure, roof, common services, and distribution spaces such as hallways, stairs, and entry halls. Infill includes all the elements that are exclusively private. In a nutshell the frontier between support and infill is correlated with that of private and condominium property (Figure 1-3).



SUB-SYSTEMS	SUPPORT	INFIILL
Concrete structure (walls, floors, etc)	■	
facade system (windows, panels, etc)	■	
roof system	■	
stairs + elevators	■	
interior partitioning (doorframes, panels,etc)		▨
kitchen equipment		▨
bathroom equipent		▨
heating		▨
gas supply	■	▨
electric supply	■	▨
electronics	■	▨
water supply	■	▨
sewage lines	■	▨

FIG.6

Figure 1-3: Support and Infill (Kamo, 2000; Habraken, 1992)

The SAR foundation, of which Habraken was director between 1964 and 1975, is a reference for having established alternatives to urban land use and practical solutions to the design of housing following the principles of separation of support and infill (Bosma et al., 2000). This work is latter continued by the Open Building Foundation, founded in 1984 by 13 signatories such as De Vries, Karel Dekker and Age van Randen, and whose manifesto is based on the ideas of Habraken. Similarly, in 1986 the OBOM research center is founded at TU Delft, directed by Van Randen, dedicated to researching building systems and technological solutions to increase

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[1] The original title is *De Dragers en de Mensen, het einde van de massawoningbouw* published by Scheltema & Holkema

the implementation of open building philosophy. In 1996, the Open Building Network was created - the CIB W104 Open Building Implementation – part of the international Council for Research and Innovation in Building and Construction (Kendall, 2015b).

Open building philosophy is based on several ideas (Kendall, 2015b; Kendall & Teicher, 2000): (1) There are distinct levels of intervention in the built environment; (2) There is a need to distribute the control over the design of these levels amongst all stakeholders; (3) Having interfaces between technical systems allows independent replacement over the building lifecycle; (4) The built environment is constantly changing in a never-ending design process.

Similar ideas of separation of the building by layers where later proposed by Francis Duffy (Duffy, 1990), and developed by Stewart Brand (Brand, 1994) into the six S's: Site, Structure, Skin, Services, Space plan and Stuff (Figure 1-4).

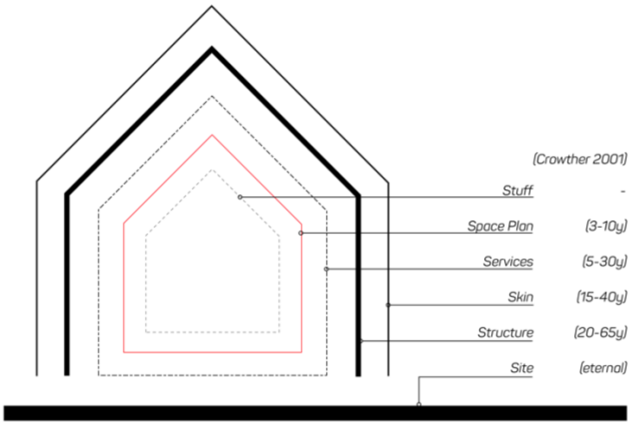

Figure 1-4: Shearing Layers of Change (adapted from Brand 1994) with layer change frequencies determined by Crowther (2001)

Within this framework, partition walls are part of the space plan, which according to Crowther (2009a) is replaced every 3-10 years. Furthermore, these components represent 41% of the material inputs of all non-load bearing construction components over 60 years (Addis & Schouten, 2004).

1.2 Design for Disassembly and industrialized partition construction systems

From the previously described developments in open building and the theory of layers it is possible to argue for a different approach to the design of buildings, that facilitates the deconstruction process to decrease the impacts of the renovation cycles of shorter lasting layers on longer lasting layers and to increase the range of possible outcomes for the layers that are removed from the building (Crowther, 2001).

DfD aims to provide evidence-based recommendations and strategies to be implemented in the design process of products to increment first and foremost their reuse potential (Addis & Schouten, 2004). As such, it prioritizes product and building designs that enable the reuse of building systems, components, and materials, in this order, over recycling and down-cycling (Durmisevic & Yeang, 2009; Sassi, 2004). It can be considered a subset of a model of environmentally sustainable construction and requires understanding the building as set of layers with different service lives, as it was proposed by Brand (1994).

DfD takes full circle a design philosophy that is commonly used in manufacturing of products – Design for Manufacturing and Assembly (DfMA) – which has been pointed as a fundamental next step for the AEC industry: "*In future industrialized building processes, DfMA needs to be applied methodically at early stages, because the development of prefabricated components is, in fact, product design.*" (Scheurer & Stehling, 2020, p. 44). Ultimately, DfD can be considered a strategy to close the material loop in the construction cycle and it aims to tackle the challenges that the deconstruction process poses (Rios et al., 2015; Sassi, 2008).

Crucially, DfD aims to provide a design level strategy to increase deconstruction of buildings versus their demolition, thereby increasing the range of possible outcomes at the renovation / disassembly stage (Figure 1-5). Designers and the design process have been found to be a major challenge to a wider adoption of deconstruction versus demolition (Srour et al., 2012). Other important issues that hinder deconstruction are: (1) selective demolishing is more costly, (2) requires more time and labour, (3) can be unsafe for workers and (4) it is difficult to be performed by machines (D'Oca et al., 2018; Rios et al., 2015), (5) and materials and building components have increasingly complex or irreversible connections (Crowther, 2001).

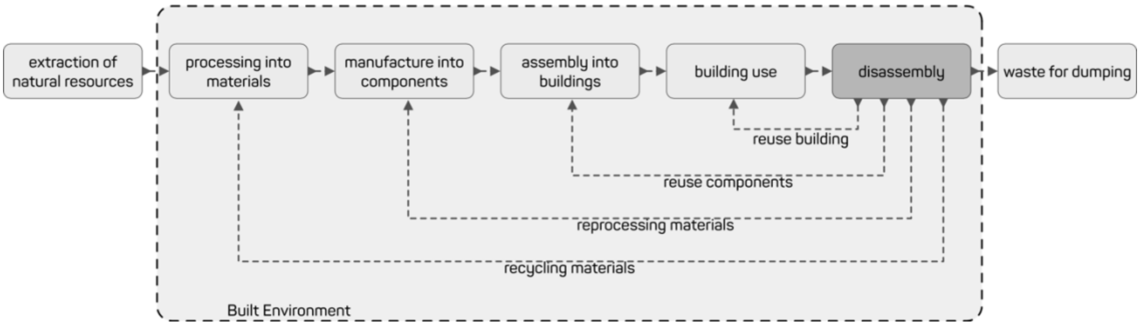

Figure 1-5: Possible End-of-Life scenarios if disassembly replaces demolition in the built environment (Crowther 2001)

Crowther (2009) identified a broad set of principles for designing buildings or construction systems that are demountable. They can be summarized as: (1) reversibility of assemblies and sub-assemblies into basic materials; (2) avoiding chemical connections between different materials; (3) minimize the number and types of different components and connectors; (4) use lightweight recyclable or recycled materials; (5) prefabricate subassemblies; (6) increase interchangeability; (7) use construction technologies that are compatible with standard building practice and common tools; (8) increase serviceability; and (9) document the construction process. Therefore, the essential feature of demountable systems is the nature of the interfaces between systems, components, and materials.

Even if there is an increased initial cost to disassemble-able systems, Durmisevic (2006a) demonstrates that these systems have significant economic advantages over the building life time and that partition walls in particular can have a large reuse potential. This high reuse potential is a result of the disproportion between the partition's technical service life (i.e., the durability of the materials, subassemblies, connections) and the use life-cycle of the spatial systems (i.e., the layout of the building). Yet, these benefits are difficult to perceive by clients and building stakeholders in general which makes DfD difficult to implement at the project level (Adams, Osmani, Thorpe, & Hobbs, 2017; D'Oca et al., 2018).

Adams et al. (2017) states that clients have a pivotal and largely unexplored role in driving the adoption of circular economy concepts, such as DfD, in the AEC industry, but for this to happen support from the construction supply chain is necessary. Geldermans et al (2019) argue that without including the end-user in the design process replicability of the these concepts cannot be achieved on a larger scale. Andrade and Bragança (2019) claim that early design stages are critical for implementing sustainable design strategies and it is important to integrate adaptability criteria at these stages.

BAMB (Building as Material Banks) is a recent EU funded project whose central idea is that buildings should be seen as material banks for future reuse. To achieve this goal the BAMB project proposed the adoption of passports for materials, products and systems that may contain information on value, characteristics, information on assembly and disassembly, etc. (Luscuere, 2016, 2017).

Yet, the reuse potential is only effective if there is a second-hand market for building components or the building owners reuse building parts as they move to new houses as if it were furniture, i.e., partition walls, doors, etc. Several marketplaces for building products have emerged in the last few years such as RotorDC[2] in Belgium, or Enviromate[3] in the UK (Figure 1-6)

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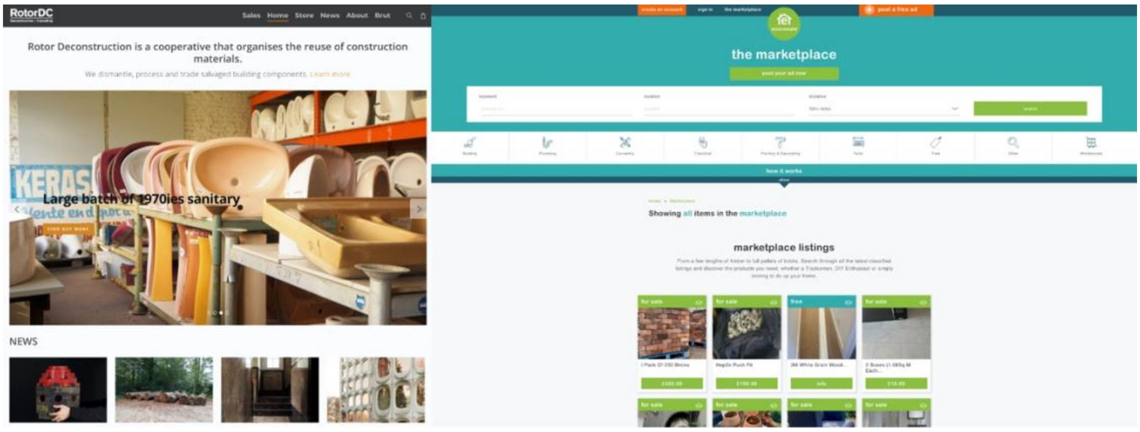
[2] Available in https://rotordc.com

[3] Available in https://www.enviromate.co.uk



Rotor Deconstruction is a cooperative that organises the reuse of construction materials.

We dismantle, process and trade salvaged building components. Learn more

Figure 1-6: RotorDC (left) and Enviromate (right) marketplaces

Among other important outcomes of the BAMB project is a roadmap of important changes in design culture, value definition and collaboration that need to take place in the future to achieve a circular built environment. Amongst the changes in design culture are: (1) the need to redefine the role of building and product designers; (2) the need for industry wide convergence on agreed standards of connections or interfaces; (3) An alignment of product and building design; and (4) creation of design guidelines and tools to evaluate the transformation capacity and reuse potential of the building and its components in early design stages[4]. Regarding future action highlights are the need of an open industrialization and bringing the manufacturing of building products closer to the building designer and the end-user using digital fabrication.

For these reasons, there has been substantial research on demountable infill systems (Kendall, 1996; Lawrence, 2003; Nijs et al., 2011), yet these efforts have so far mainly focused on new buildings, or in energy renovation of building envelops (Barco et al., 2017; Mestre et al., 2016; Veld, 2015).

The Matura System (Habraken, 1992; Kendall, 1996) is an early exception that was developed specifically for the renovation of mass housing by John Habraken and the Ahrend group, yet it revolves around a polystyrene tile – the Matrix tile - and a baseboard profile. AdjustMEMBRANE (Mendonça & Macieira, 2014) or the smart partition system (Chien & Wang, 2014) are examples of modular demountable partitions, while not specifically developed with building renovation in mind. These systems rely on modular coordination and many assumptions are made on the dimensions and properties of the supports, either floors, ceilings, or existing walls. Also, these systems are meant to be assembled by specialized construction technicians and not building owners.

The Dynamic Wall (Paduart, 2015) is an example of a recently developed demountable and reusable partition system for refurbishment of existing buildings. Dynamic Wall relies on

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[4] https://www.bamb2020.eu/topics/blueprint/vision/design/

standard components and modular coordination. It uses simple construction methods with mostly off-the-self solutions for connections. Yet it is not clear how adaptation to a variety of different spatial configurations is achieved.

Open building encourages industrialization of building but also a direct relation of the manufacturer with the building owner (Habraken, 2003). This implies a redistribution of design control across all actors involved in the construction process. The distribution of design, and consequently of production control, is also a characteristic of the mass-customization (MC) paradigm. In fact, several authors have established a connection between open building philosophy and MC (Kendall, 2010; Lawrence, 2003; Nijs et al., 2011), claiming that the use of adequate reversible connections between materials and building subsystems is an enabler of industrialization and MCC. Furthermore, Kendall identifies “*designing the commons*” as a future challenge of open building, which can be related with the research conducted in the processes of open innovation in general (von Hippel, 2005) and in particular with personal fabrication (Gershenfeld, 2005) and open-source architecture (Ratti & Claudel, 2015).

CHAPTER 2 Mass Customization Construction

As parametric design and digital fabrication become increasingly established in both the practice and research, alternate paradigms of production, such as mass customization (MC) or personal fabrication (PF), emerge as viable models for architecture and the building industry (Kolarevic, 2013, 2015) and specifically to building renovation (Barco et al., 2017). The application of the MC paradigm in manufacturing has been extensively researched with the purpose of improving customer satisfaction and brand fidelity, by allowing the user to participate in the design of the product. For the building construction industry, whose products are mostly prototypical in nature, it seems to be a fitting paradigm (Kieran & Timberlake 2003).

PF is an emergent alternative that is the result of widely available information and means of production. It empowers users to take the design and fabrication of objects, and eventually houses, into their hands (Gershenfeld, 2005).

A central issue to both concepts is the control of production and design. In the following section we first review the state of both MC and PF concepts and then how these have been implemented by architects and the building industry in theory and practice. To assist this process a mapping method is used, that captures the production and design control level of both PF and MC.

Joseph Pine II (1993) believes that the MC paradigm requires different organizational structures and values to the prevailing industrial paradigm of the 20th century. Stanley Davis (1987) also speaks of opposing organizational structures, the industrial hierarchical organization versus the network that promotes a flat organization, or the industrial product focus versus the post-industrial client focus. Thus, the transition to MC requires systemic change to organizations and products, and ultimately to the way customers procure products.

2.1 Mass Customization

MC is a production paradigm and also a business strategy that was introduced by Stanley Davis (1987) in his book “Future Perfect”. He defined it as the possibility of mass-producing customized goods, combining the advantages of mass production – low price, stable quality, and availability – with craft production advantages – accommodating personal requirements or preferences. The idea that there was a change in the production paradigm away from Mass Production was already present in Alvin Toffler’s books Future Shock (1970) and more clearly in The Third Wave (1980). The last book is noteworthy for introducing the concept of prosumer, part producer part consumer.

Historically, the main enablers for the emergence of MC paradigm were the digitization of design, production, and sale of products, particularly over the web, and their integration with CNC machines. The specific enabling technologies were the integration of CAD (Computer Aided Design), CAE (Computer Aided Engineering) and CAM (Computer Aided Manufacturing) with flexible automated machines on the factory, and the advent of Internet (Fogliatto et al., 2012).

Other important enablers of MC were manufacturing management advances such as Just-in-Time manufacturing (JIT), a component of the Toyota Production System (TPS), introduced to the West in 1977 (Sugimori et al., 1977). JIT eventually came to be known as "lean production", a term introduced by John Krafcik (1988) and later developed by Womack, Jones and Roos (Womack et al., 1990). In fact, both lean production and MC share the same references in the work of Peter Drucker ([1973] 2008) and his advocating for "flexible mass production", and previously on John Diebold's book Automation (1952) where he labels the existing automated production machinery as inflexible and unfit for small or medium production runs.

MC, according to S. Davis (1987), is not limited to manufacturing management. The emergent possibility is that minute changes to the product, to satisfy a defined market segment, are possible without machine downtime. This would emphasize the role of marketing and customer relations in establishing customer's needs. Stanley Davis foresaw a tendency to "disintermediate" the relation between producer and consumer, which eventually was made easier with the advent of the Internet. This disintermediation would allow that some of the final decisions about the product or even some of the work could be handed down to the consumer. In this he saw a parallel with Alvin Toffler (1980) prosumer. Pervasive information technology and networks combined with an integrated file-to-factory process would allow "*bring[ing] customized products within the reach of the average person*"[5] (S. Davis, 1989, p. 19).

MC as originally proposed by S. Davis is considered visionary in the sense that he sees MC as the ability to provide individually designed products to customers at mass production levels of efficiency (S. Davis, 1987). In this sense, MC is understood as a complete combination of the volume of mass production with the diversity and individuality of pre-industrial production paradigms (Figure 2-1). A more practical definition was first proposed by Pine (1993) which defines MC as the ability to provide diversity that meets specific needs of individual customers (Fogliatto et al., 2012; Kaplan & Haenlein, 2006; Silveira et al., 2001). In the more practical approach, concessions are made on the degree of variety and on the cost efficiency, grounded on the fact that personalization is perceived by customers as a desirable feature (Piller, 2004; von Hippel, 2005).

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[5] An idea which S. Davis attributes to Alvin Tofler

Da Silveira et al. (2001) eventually proposed a dual definition model of visionary and practical MC, which was further developed by Kaplan and Haenlein (2006). This model exposes the provisional nature of the practical definition. Both definitions are similar in that they consider MC to be a *"strategy that creates value by some form of company-customer interaction"* (Kaplan & Haenlein, 2006, p. 176/7). The main difference between both definitions is the stage of the operations level at which this interaction takes place – the design stage or fabrication / assembly stage. Nevertheless, most researchers agree that MC influence is systemic across all stages of the product value chain from design to sale.

According to Baranauskas et al (2020), there are three distinct stages in the evolution of the practical implementation of MC coincident with the decades since its inception: traditional MC 1987-2000, electronic MC (e-MC) or mass personalization 2000-2010, and electronic mass customization and personalization (e-MCP) 2010-2020 (Figure 2-1). These stages are characterized by the emergence of different technological tools that enable increasing levels of customization, bringing visionary MC closer to reality: pre-internet, web commerce platforms, data mining and 3d printing.

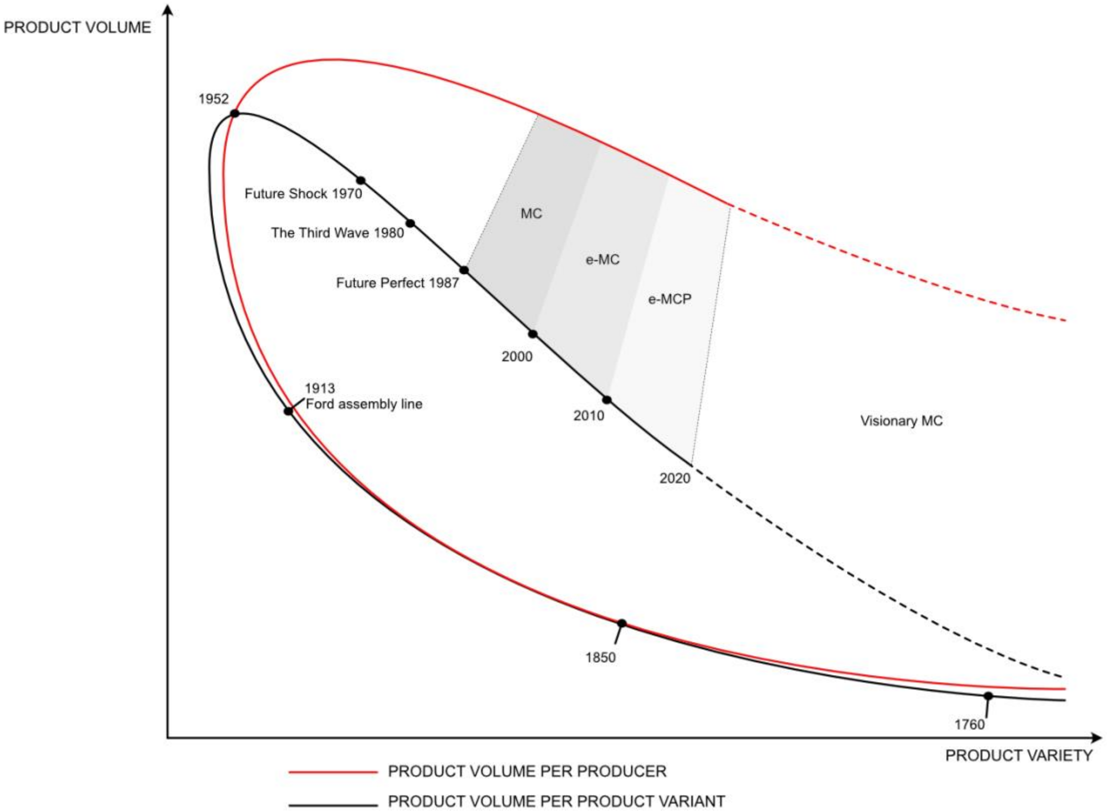

Figure 2-1: Historical background and mass customization. Adapted from Koren (2010), Baranauskas (2020)

The first period is characterized by a strong focus on manufacturing and engineering issues, research on success factors and transition from mass production (S. Davis, 1987; Duray et al., 2000; Gilmore & Pine II, 1997; Kotha, 1996; Pine II, 1993). The second period is characterized by the emergence of e-commerce, web platforms and product platforms and their combination into configurators (Jiao et al., 2007; Kaplan & Haenlein, 2006; Piller, 2004; Piller et al., 2005; von Hippel, 2001). While in the last decade there has been an increasing focus on personalization techniques, involving Big Data, Machine Learning and Artificial Intelligence, and open-source approaches to the design and personalization (Buffington, 2011; P. Jiang et al., 2016; Koren et al., 2015; Tien, 2006; Zhang et al., 2019).

Over the last decade, MC has become more interdisciplinary, which coupled with ongoing trends of digitization, globalization and sustainability, led to the emergence of new concept versions (Baranauskas et al., 2020): Mass Personalization (Marsh, 2012), Electronic MC (Kaplan & Haenlein, 2006), Generative Customization (Buffington, 2011), Mass-individualization (Koren et al 2015), Smart Customization (Zhang et al., 2019). These concepts fit in the Practical MC and Visionary MC continuum, attempting to provide paths towards the "market-of-one" objective by bringing MC to the design level, either through purely technological (Buffington, 2011; Zhang et al., 2019) or socio-technical means (P. Jiang et al., 2016). Despite that, as Baranauskas (2020) bibliographical analysis found, the practical MC concept still has very strong grounding.

Furthermore, there is a wide agreement that MC is "customer centric", that is, the technologies are applied with the aim of better satisfying a more diverse set of customer needs by involving the end-user of the product in its design or specification, as opposed to a focus on a particular technology mix (Fogliatto et al., 2012; Kaplan & Haenlein, 2006; Piller, 2004). This is effectively a co-design process in which manufacturers relegate design control and consequently some fabrication control over the product (Toffler, 1980; von Hippel, 2005). Hence, there is a strong basis to support the dual definition model as opposed to definitions based on enabling technologies. Also, as we will soon show, the dual definition model is useful to clarify different approaches to MC in architecture.

2.1.1 Levels of MC

From its dual definition, MC can be understood as a domain and, naturally, one of the implications is that there is a relation between the level of customization that is possible for a product in a given MC system and the point of the production cycle at which the costumer interacts with the manufacturer (Duray et al., 2000; MacCarthy et al., 2003; Rudberg & Wikner, 2004; Tien, 2006).

The idea that there are growing levels of customization was put forth by Pine (Gilmore & Pine II, 1997; 1993), as a consequence of different methods to provide customized products. Pine (1997) suggested that the methods may be classified according to the stage of the value chain they affect. The author used the Product-Process Matrix to map MC putting it into the context of volume (low to high) and diversity (customized or standardized) of production.

Later Gilmore and Pine (1997) introduced four approaches to MC: (1) collaborative; (2) adaptive; (3) cosmetic; and (4) transparent. These different strategies to introduce MC emerged out of the acknowledgement that not all customers wish to fumble with options and that many companies were facing increased costs while implementing a MC model. A collaborative approach would introduce some form of support in selection, helping the consumer who would otherwise be able to articulate what suits his needs. An adaptive approach standardizes the design of the product in such a way that the consumer can customize it. In a cosmetic approach the product is standard but presented differently. In the transparent approach the product is customized without making it explicit.

Duray et al. (2000) argued that to achieve MC it is necessary to include each customer specification in the product design. For this to be possible, they argue, the product must have a modular design. They further concluded that higher degrees of customization are related with specific types of product modularization and an earlier involvement of the user in the product value chain (Figure 2-2). Modularity, as is understood by Duray (2000), is a property of products that results from their subdivision into components that may be combined in different ways to create customized assemblies of components. They borrow their definition from Ulrich and Tung (1991) typology of modularity (Figure 2-3). Duray (2000) proposed a two-dimensional matrix to classify the levels of customization, being its two axes the point of customer involvement and type of modularity.

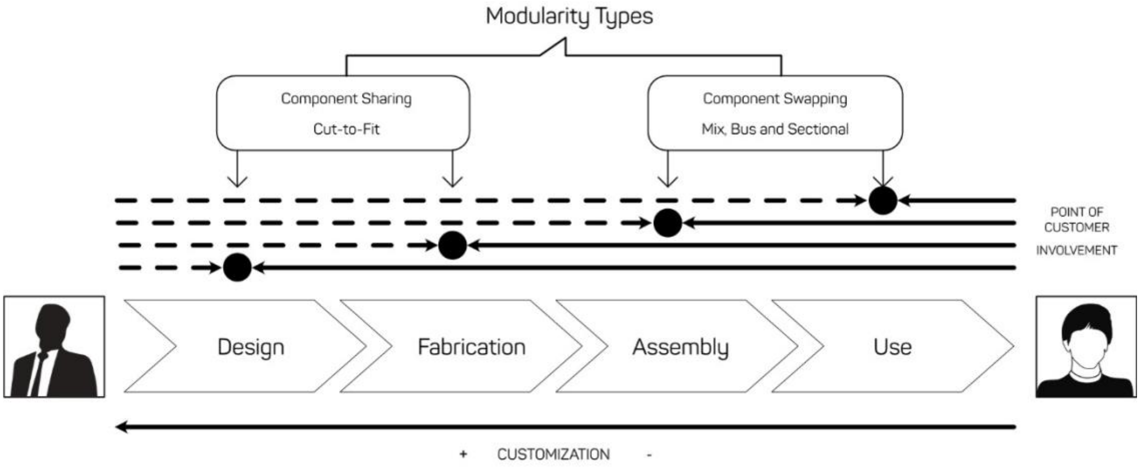

Figure 2-2:Relation of Modularity with the point of customer involvement in the value chain. Adapted from Duray et al (2000), Rudberg and Wikner (2004) and Tien et al (2004)

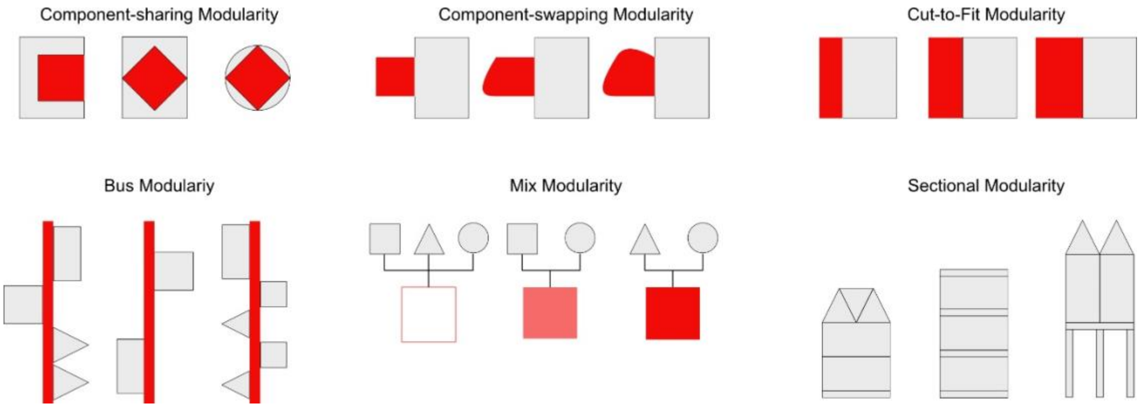

Figure 2-3: Typology of Modularity. Adapted from Ulrich and Tung (1991)

Tien et al. (2006; 2004) proposes a linear progression of level of MC in terms of the customer order penetration point, that is at which stage the order interferes with the supply chain: customer, retailer, assembly, manufacturer, supplier. Like previous authors, Tien (2004) sees customization as continuous domain, whose level affects the design of the product and its production.

Table 2-1: Comparison of MC levels and definitions across authors regarding the customer order penetration point

Customer Order Penetration Point	Pine and Gilmore (1997)	Definition of MC (Kaplan 2006)	Levels of MC (Tien 2006)	Buffington 2011	Koren 2015	Zhang et al 2019	Enablers (cumulative)
Customer	Pure Standardization		Mass Production				
Retailer	Customized Standardization		Minor Customization				Marketing Modularity
Assembler	Tailored Customization	Practical MC	Partial MC	MC	MC	Traditional MC	CAM, Robots, CAD/JIT
Manufacturer	Pure Customization	Practical MC	MC		MC	Customer-Driven MC	Co-Design, Product Platform (BIM)
Supplier		Visionary MC	Real-Time MC	Generative MC	Mass Individualization	Data-driven MC	Data Mining, AI, Open Design, AR, VR Generative Design Cobots

Table 2-1 maps the previously discussed definitions and levels of MC to the level of customer involvement in the product specification and specific enabling technologies discussed by the authors. There has been an increasing focus on concept definitions that interfere with the supplier level, i.e., the design level of the product, supported by technological developments in enablers.

2.1.2 MC enablers

Enablers are methodologies, processes and technologies that can be used to put MC in practice (Fogliatto et al., 2012). According to Fogliatto et al. (2012), processes can be divided into four stages, related with specific subsystems of an MC system: (1) order elicitation; (2) design; (3) manufacturing; and (4) supply chain coordination. Technologies can be described as solutions for addressing specific implementation challenges of subsystems, automation of processes and their coordination into a larger whole MC system, and can be divided into Information, Design and Manufacturing Technologies. The design and elicitation technologies combined create a configurator (Fogliatto et al., 2012) , also referred to as a toolkit (Piller et al., 2005; von Hippel, 2001), that transfers design related activities to users, providing toolkits that enable them to configure solutions for their specific problems engaging in a learn-by-doing process (Figure 2-4). Lastly, methodologies mostly deal with approaches to the implementation of MC systems in practice.

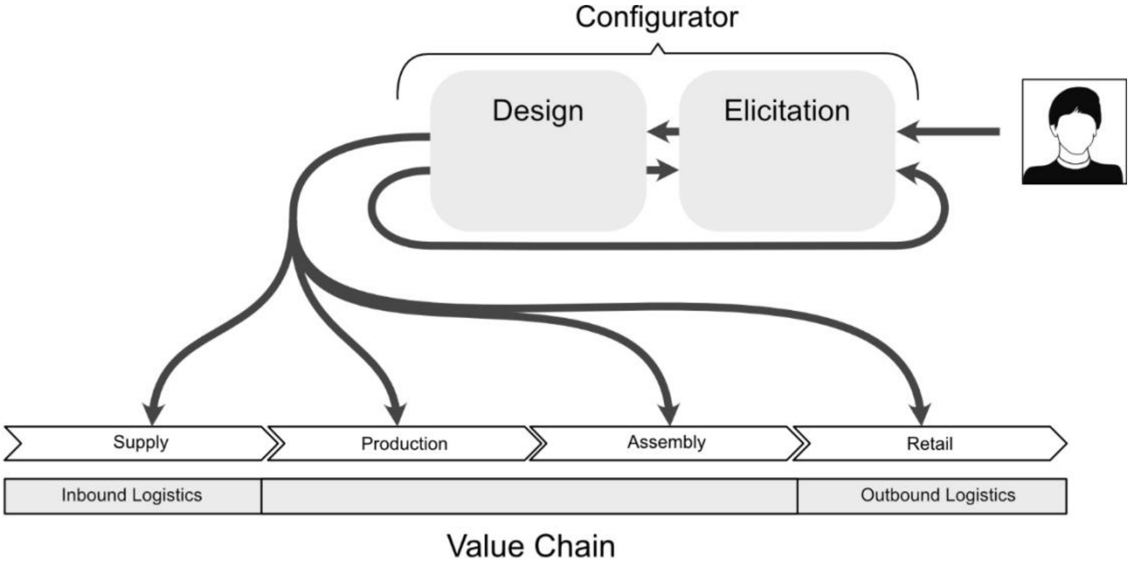

Figure 2-4: Effects of the outputs of a configurator in a value chain. Adapted from Tien et al (2004) and Kaplan and Haenlein (2006)

The goal of order elicitation or personalization subsystem is to arrive at a product specification that fulfills the client's needs within the scope of the producer capabilities. The goal of the design subsystem is to generate a valid product configuration. As explained in the previous section, the outputs of a design system, and by extension of a configurator, may affect the value chain on different levels. Furthermore, configurators are specific to a product/service type and production system.

There are three important reasons why manufacturers transfer design activities to users: (1) user need-related information is hard and costly to transfer to manufacturer's designers; (2) users can achieve faster learning by doing; and (3) users don't have a clear definition of what they need (von Hippel, 2001). A properly designed toolkit will allow users to leverage manufacturer designer's solution knowledge and apply it to their specific needs engaging in an iterative process.

According to von Hippel (2001), properly designed toolkits or configurators will: (1) Allow users to complete several cycles of learn-by-doing; (2) ensure the solution space encompasses designs that respond to the user needs; (3) be user-friendly, that is, it uses a language the user is familiar with; (4) contain a library of commonly used modules so the user can focus on the what is specific to his/her case; and (5) ensure that any product that is designed by the user must be producible without the need of revision.

Introducing configurators, as well as MC, requires the product to be reconfigured and several approaches have been proposed. Concepts such as product families, product platforms, modularity and interfaces are often discussed as necessary approaches for the implementation of MC Systems (Fogliatto et al., 2012; Khalili-Araghi & Kolarevic, 2020; Mikkola & Gassmann, 2003). Mikkola and Gassmann (2003) discuss product architecture as an arrangement of functional elements into several building blocks with specified interfaces. As discussed in the previous section, similar ideas have long been proposed by architects such as John Habraken (2003), the open building philosophy, and the proponents of DfD methodology.

Configurators aim to go beyond simple elicitation strategies based on providing choices and variables of the product. As product complexity increases these approaches can quickly led to overloading the customer with options, thus increasing complexity, effort, and perceived risk from the customer perspective. This effect is known in the literature as “mass confusion” (Pine in Teresko, 1994) and may deter customers from engaging in co-design activities (Piller et al., 2005). Piller et al (2005) identify three categories of problems a consumer might face in a co-design process that may cause this undesired effect: (1) burden of choice; (2) difficulty in matching needs with product specification; and (3) information gap[6] regarding product and process. The authors identify three approaches to tackle the problem: (1) dedicated configurators with appropriate interface design and usability, representation and visualization techniques and the restriction of choice; (2) strong branding; (3) communities for customer co-design around configurators. The first and third approach are contingent on deploying adequate elicitation approaches to identify the context of the design problem to solve and cast it into the configurator design domain.

2.2 Personal Fabrication

The emancipation of the artist from the artisan, that took place during the Renaissance, and later the transformation of the craftsmen into unskilled labour, with the introduction of the mechanized tools of the Industrial Revolution, sheds a different light on the history of manufacturing. One of increasing specialization and separation of roles of using, designing and

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[6] Uncertainty in the process, difficulty in establishing quality and performance standards to evaluate the product

producing, and a devaluation of making into a mere mechanical procedure (Carpo, 2001; Gershenfeld, 2005; Picon, 2016). The evolution from mechanization to automation led to computers and from there back to machines directed by computers that manufacture other machines. What these machines could do was only limited by the expressiveness of the programs. As Gershenfeld (2005) points out, the literacy for the machine, the designer and the user came to mean three different things.

Bringing a design into a digital representation, digitization of the drawing, either as a 2D or 3D representation provides access to either digital tools of production (e.g.: CNC, 3D printing, etc.) or mass production. A machine can be Numerically Controlled (NC) or Computer Numerically Controlled (CNC) and still only produce one product in large quantities. This process can be personal if the design is only meant to be produced once, that is, the prototype is the product. Traditionally, PF was only possible using manual crafts since the mechanized tools of mass production required a certain scale to become cost effective.

The connection of a Personal Computer with the machine allows variation of the design to be feed into the machine without stopping the production process. As this connection is virtually instantaneous the only difference becomes the time it takes to produce the product (Kolarevic, 2001a). This is as we have seen an enabler of MC, where variation of a set of characteristics of the product is possible without incurring in added costs. Yet in MC, there is still a mass production volume of a product, developed by a producer, in which specific dimensional properties, physical characteristics or specifications are open for the consumer to change. As Gershenfeld (2005, p. 44) notes, *"the expressive power of machines that make things has remained firmly on the manufacturing rather than the consumer side"*.

A completely different thing is to design and produce only one product. Originally the production of one object with machines was the realm of prototyping. That is what 3D-printing was originally called, rapid prototyping. Inevitably the first field of application of rapid prototyping became product development. The development of multipurpose digital fabrication tools, their reduction in price, their capacity to work with multiple materials in ever increasing precision, started to change prototyping tools into short run production tools (Anderson, 2012) and pave the way for truly personal fabrication.

In 2005, Neil Gershenfeld proclaimed a coming revolution of the digitization of fabrication, bringing the programmability of the digital into the physical world. The conditions for its emergence are increasingly affordable digital fabrication and open access to knowledge, made easier and widespread by information technology. In the future, Gershenfeld (2005) envisions material assemblers that will be capable of assembling and disassembling objects from and into basic components – Personal Fabricators. A Personal Fabricator is a machine that can reproduce itself or other machines or objects with form, function, sensing and logic. So, Personal Fabrication is the process of operating such machines, providing them with the descriptions of objects and the digital materials necessary to produce or disassemble them. The capacity to deconstruct objects into basic components (i.e.: the digital materials) from the information the object contains sets the Personal Fabricator apart from existing machines (Gershenfeld, 2005).

Personal Fabricators are visionary machines, focus of the research conducted at the Centre for Bits and Atoms (CBA), founded by Gershenfeld in 2001, at the MIT. Meanwhile, Gershenfeld proposes a practical approach using the “proto-personal” digital fabrication tools of today - CNC routers, laser cutters, and 3D printers – which are already widely available, or large-scale 3D printers capable of producing large size building parts which are becoming available. To spread this vision, he started the FabLab project in 2003.

FabLabs (Gershenfeld, 2005) are currently a global network of local laboratories, run by universities, city halls, or private companies, that seek to foster invention by facilitating access to digital fabrication tools. They provide a set of activities involving teaching of technology, developing solutions to local problems, startup incubation, research, and development in diverse areas from architecture to robotics. To join the network the requirements are open access, a minimum set of fabrication tools, participation in the global network and abide by the Fab Charter. The network of FabLabs has grown exponentially[7], into a global social movement (Walter-Herrmann, 2013) convergent with the “Maker Movement” (Anderson, 2012).

The FabLab and PF concept open the possibility to question the separation of making and planning by bringing 1:1 prototyping into the design stage. Designers can benefit from the type of learning-by-doing activities that are enabled in its context by leveraging design research methods, such as “*design through research*” (Cross, 2006), “*design inclusive research*” (Horvath, 2007) or “*research by design*” (Hauberg, 2011), that aim to bring user experience, design, and idea generation together. Haldrup (2018) argues that these characteristics of FabLabs make them right setting for engaging in dialogues across social spheres and disciplinary boundaries.

Architectural offices and design research groups alike have since increasingly adopted digital fabrication tools, introducing prototyping into their workflows (Marble, 2012). The increasing availability of digital fabrication tools and their connection with digital design allowed the exploration of the expression of the digital on the material and vice-versa, through programming and construction in what Gramazio & Kohler (2008b) call a new “*digital materiality*”. In this process, other boundaries have also become blurred, the separation of the traditional roles of architect, engineer and builder, the difference between the prototype and

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[7] by January 2020 there were 1998 registered on https://fablabs.io

the product and consequently the questioning of the role of the architect as a provider of services.

Stevens and Nelson (2015) contend that as digital fabrication and design technologies use becomes widespread, they become a new form of architecture vernacular – a digital vernacular, whose emphasis is on developing work with foundational origins on historical and present vernacular context that evolves over time rather than complexity without limits or expression without ethics. They further contend that only digital fabrication tools that are open-source, economically viable and serve a diverse group of stakeholders with different backgrounds and skills can be included in the scope of the digital vernacular. In their book, they exclude robotic arms or large-scale 3D printing, but naturally that scope is a moving target.

Gershenfeld's (2005) view is that eventually personal fabricators will be like the personal computers of today, democratizing the means of production. These machines are still far from reaching a mass market as the PC did, but 3D printing and other digital fabrication technologies, combined with the collaborative nature of the Internet, are already making it easier for the makers that Andersen (2012) speaks off to prototype businesses, evolving into niche market companies or growing from its maker roots into mass-market companies.

But what Anderson (2012) speaks off is still far from the PF idea Gershenfeld (2005) described. Digital fabrication technologies and open innovation, open-source hardware and software combined with online collaboration, are mainly allowing to prototype businesses and products faster and more democratically, kickstarting the successful ones into mass production or mass-customization models. Truly PF only happens when the means of production are in the hands of the consumer, either to print food or fabricate clothes. For that to happen intuitive digital design tools must be developed instead of "*state-of-the-art engineering software with obscure "user interfaces"* (Gershenfeld, 2005, p. 46).

In this context, PF and MC depart from opposing views regarding production control but not necessarily so on the design control since both intend to achieve design democratization. Both paradigms aim to provide end-users with more control of the design of their products. MC systems seek to capture open innovation and PF aims to foster it by empowering users to solve their needs. For both goals to be achieved design tools need to evolve, embedding the technical complexities, so non-technical users can leverage them for design.

2.3 Mass Customized Construction

Digital design and fabrication tools have been adopted in design practice and construction (Clayton, 1995). Architects and other building professionals are increasingly working on interactive digital representations of objects through information modelling software that gives prominence to the collaborative and decision-making aspects of the design process (Carpo 2011; Marble 2012). Parametric and algorithmic design methods have become more accessible and widespread in architecture with the emergence of more intuitive design specific programming languages connected with familiar CAD packages, e.g. Grasshopper or Dynamo. Also, programming as a competence and skill has become more widespread (Blikstein, 2013).This in turn has nurtured the interest in fabrication methods that are capable of materializing more complex or highly variable forms (Naboni & Paoletti, 2015).

Digital fabrication tools have also became more pervasive as a result of a reduction in price and of the development of open-hardware initiatives, such as RepRap (R. Jones et al., 2009), Global Village Construction Set, or open-source robotic arms such as the AR3 (Annin, 2018), which demonstrate a prevalent interest in these tools. Other important factors are the increasing complexity of building systems and material types, the increasing cost of work and the growing demands of environmental performance.

A set of conditions have contributed to the emergence of the paradigm we define as Mass Customized Construction (MCC).

At the turn of the century, all the above aspects combined have led several authors to state that the conditions are set for a larger adoption of design-to-production workflows, that connect digital design and production in a seamless chain. These authors argued for the adoption of MC by the AEC industry (Kieran & Timberlake, 2003; Kolarevic, 2001a; Larson et al., 2001).

The first reference of the MC concept by an architect is attributed to William Mitchell (1999)[8], but this author had long been convinced of the expressive power of computers for design and its fabrication. In fact, although the MC term was not used before, through the 90s several architects started using computers in design to their logical potential of designing non-standard series of architectural forms (Carpo, 2017). Also, some architects, such as Greg Lynn or Bernard Cache, had been promoting the idea that these non-standard designs could be produced with existing fabrication tools in a file-to-factory process which could provide the *"ability to mass-produce irregular building components with the same facility as standardized*

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[8] Although Mario Carpo points to the text "Antitectonics: The Poetics of Virtuality", also by William Mitchell and published in the previous year, as the first instance, the text does not actuality contain the MC expression.

parts" (Kolarevic, 2001b). This was a new production paradigm for a new era where the standard was no longer needed in architectural expression (Kolarevic, 2005)[9].

Concurrently, Larson (2000), Duarte (2001), or Kieran and Timberlake (2003) were considering that MC offered the opportunity to provide combinatorial variation in mass-produced housing driven by client's needs, bringing together the ideas of Habraken and Negroponte. Implementing this paradigm in the AEC industry would require using digital design and fabrication tools, coupled with the internet, to create design engines for instance-designers (clients or their architects) to customize their mass-produced house. For these authors, the challenge is not to produce variety but how to meaningfully connect variation with context (Kolarevic & Duarte, 2019a) in an economic, social, and environmentally sustainable way. The outcome would be design democratization (Kolarevic & Duarte, 2019a).

For architects to work on this paradigm they must design the system on a meta-level (Duarte, 2008). Which entails some separation of the roles of design between the designer of the system – system designer (Habraken, 2003) or meta-designer (Kolarevic, 2015) and the user of the system – the instance-designer (Habraken, 2003; Kolarevic, 2015).

Most authors believe that MC can be applied to products and services (S. Davis, 1987; Fogliatto et al., 2012; Pine II, 1993; Silveira et al., 2001; Tien, 2006). Though, it is worth mentioning Kaplan and Haenlein (2006) objection that services are inherently customized, since two of their key qualities are perishability and inseparability, i.e.: they must be consumed as they are produced and necessarily involve the customer as a co-producer. This objection is important since architects provide services, not products, which are traditionally offered on a personal one-to-one basis. While the architect work can involve or result in physical artifacts which can be used to iterate or communicate the service, the actual product is built by others. Thus, architects that engage in MCC have either acted as instance-designers, collaborated with a manufacturer to become building sub-system/component designer, such as in the Instant House (Sass & Botha, 2006) or integrated with engineers and contractors to develop MCC systems such as Benros and Duarte (2009).

The adoption of MCC would also entail the change of roles to other stakeholders in the AEC industry. Kieran and Timberlake (2003), provide the automobile, naval or aeronautical industries as necessary organizational models. While, Larson (2004) provides the computer industry as a role model, stating that builders should become assemblers, developers would become system

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[9] In 2005, Kolarevic , in his book Digital Morphogenesis, was already pointing to the correlation of the digital with the "blobby" aesthetics as *"sidetracking the critical discourse into the more immediate territory of formal expression and away from more fundamental possibilities that are opening up"*

integrators and manufacturers should *“agree on interfaces standards to become tier-one suppliers of components”* (2004, p. 187).

2.3.1 Open-Source Architecture

Proponents of the adoption of MCC claim that this will bring about the democratization of architectural design (Kolarevic & Duarte, 2019a). However, this democratization is limited to the range of customization the manufacturers, or the designers of these systems choose to offer. Open-source architecture (OSArc) (Ratti et al., 2011; Ratti & Claudel, 2015) seeks to overcome these limitations extending the MCC theory with features of the community driven open-source movement. Its supporters argue that the progress of digital technologies has put into question the idea of authorship in architecture. Thus, there is a new opportunity for involving the user in the design process and for the architect to influence the evolution of built environment.

They adopt the idea of incremental socially driven innovation in construction advocated by Habraken (2003) and propose the adoption of a process inspired on the notion of vernacular evolution of building solutions, accelerated by digital technologies that allow instantaneous collaboration. They call for the development of a digital framework, a mixture of Wikipedia and Amazon, to allow the actors in the AEC process to interact, evolve and deliver design solutions (Ratti & Claudel, 2015).

Several other authors have taken cues from the hardware and software industry, such as the House_n project led by Kent Larson which sought to model the prefabricated house industry after the computer industry, the Open-Source Building (House_n, 2003). However, the idea was brought to the fore by an Op’Ed Carlo Ratti was invited to write for Domus on the subject. Instead, he decided to orchestrate collaboratively written Wikipedia article which is still available today (Ratti et al., 2011).

OSArc aim is to completely revolutionize every step of the AEC process: design, construction, funding, standards, and engagement. OSArc builds upon the body of experiences and ideas generated since the sixties on user participation in architecture, urbanism, and construction, with important references on Habraken, Christopher Alexander, Cedric Price, Negroponte and Stewart Brand.

The OSArc movement derives from the open-source software (OSS) movement an economic, funding, organizational and licensing model for architecture. Naturally driven by the success of OSS movement in “incubating” many of the symbols of today’s society: Linux, Wikipedia, Wordpress, etc. These projects have inspired the development of many similar efforts in other areas from computer hardware to design.

In fact, several open-source projects, such as the Wikihouse (Parvin, 2013) or Open Structures[10], attest that there is a growing interest in leveraging digital fabrication tools to develop open-source construction systems to solve real problems in the AEC industry. In the case of the WikiHouse project the system is meant to be cut from flat panels with a 3-axis CNC mill and can be used to build small houses.

2.3.2 Design and production control

From the preceding description OSArc shares methods, processes, and technologies with MCC, extending it with a specific philosophical position on the openness of the systems. This suggests an overlap with the visionary view on MC which promises design level user control. Hence it is crucial to understand how architects surrender design control to arrive at what visionary MCC effectively means. To achieve it we map the concepts and the most relevant works in the field in relation to production and design control. As we have seen, design and production control are continuous and orthogonal dimensions. Thus we use a bi-dimensional map, based on Sanders (2006) methodology of mapping the design research, to chart along these dimensions the concepts of MC and PF in relation to relevant research and practice (Figure 2-5).

Design control is mapped along the vertical axis and ranging from absolute control by architects or the AEC industry, at the top of the map, to absolute control by building owners or customers. Production control is mapped to the horizontal axis going from manufacturer total control on the left-hand side (e.g.: mass produced housing), to user fabrication on the right-hand side (e.g., self-built houses). This creates four quadrants: (1) Manufacture/expert designed and produced; (2) Manufacture/expert design and owner produced; (3) customer designed, and manufacture produced; and (4) owner designed and produced (Brandao et al., 2017).

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[10] https://openstructures.net

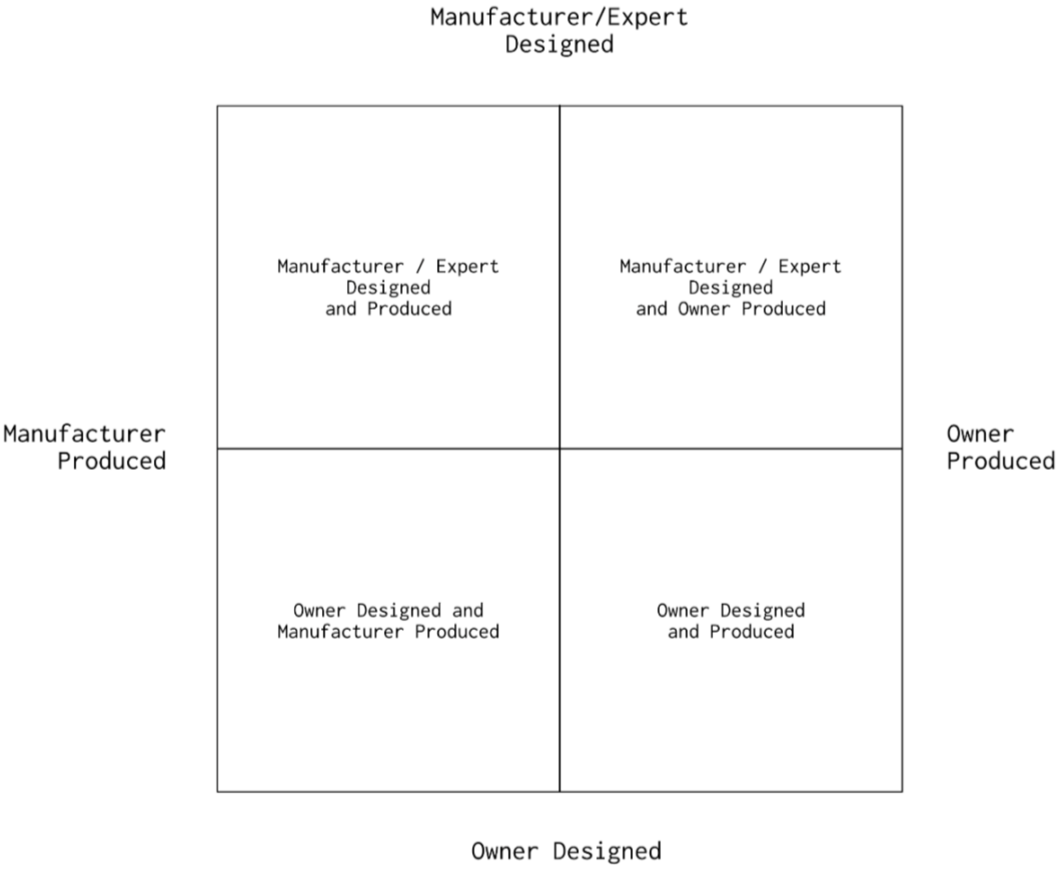
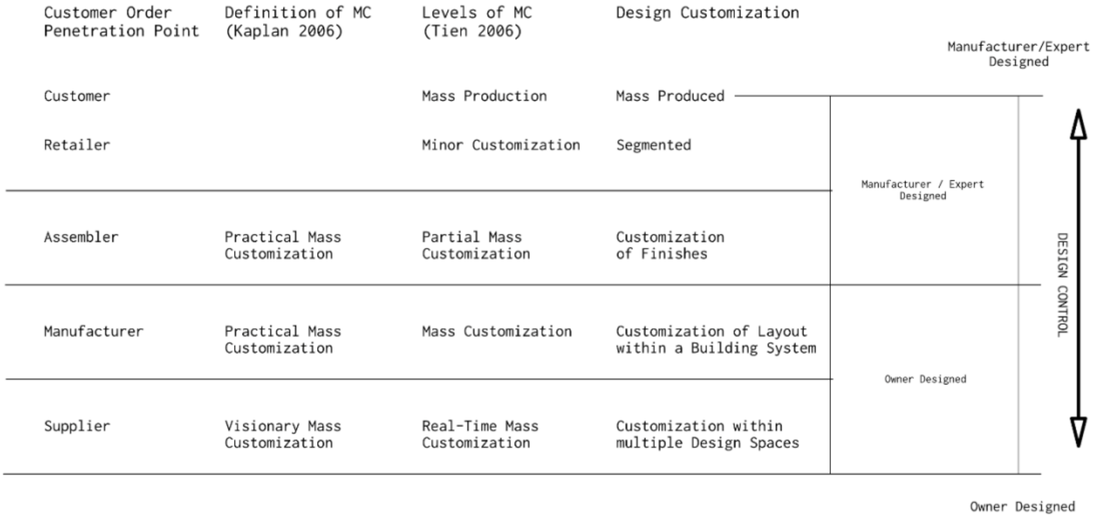


Figure 2-5: Conceptual map of MCC (Brandão et al 2017)

There are several advantages of this mapping methodology: (1) the possibility to compare the concept of MC with alternatives such as Personal Fabrication; (2) the possibility to expose relative differences in degree of customization; and (3) and capture variations of design and production control in industries where these activities are not vertically integrated, e.g., the AEC industry.

The levels and the definition of MC can be related with the control of design and production. In Figure 2-6, the levels of MC proposed by Tien (2004) are related with definition of MC as proposed by Kaplan and Haenlein (2006) and with the level of design customization in the building industry.

The practical definition of MC by Kaplan (Kaplan & Haenlein, 2006) is coincident with Partial MC and MC levels defined by Tien et al (2004), while Real-Time MC (RTMC) is comparable with the visionary definition of MC by the same author but with some limitations. For Tien, RTMC is instantaneous production and delivery of customer designed products. Since design is a service, real-time delivery of customized solutions is attainable by the adoption of digital design methods, and consequently only limited by the complexity of the computational configuration process and computational processing power available. Yet for building products, even if digital fabrication may significantly reduce the time involved from design to producing building components, RTMC is still a visionary concept.



Customer Order Penetration Point	Definition of MC (Kaplan 2006)	Levels of MC (Tien 2006)	Design Customization
Customer		Mass Production	Mass Produced
Retailer		Minor Customization	Segmented
Assembler	Practical Mass Customization	Partial Mass Customization	Customization of Finishes
Manufacturer	Practical Mass Customization	Mass Customization	Customization of Layout within a Building System
Supplier	Visionary Mass Customization	Real-Time Mass Customization	Customization within multiple Design Spaces

Figure 2-6: Design control levels (Brandão et al 2017).

Design customization in a mass-produced building occurs aftermarket - the customer can only inhabit the building, and any renovation the inhabitant chooses to do is itself another process. Customization at the retailer level is when the would-be end-user is offered different types to choose from (e.g., apartments with different numbers of rooms in a multifamily housing building or houses in different styles from a prefabricated building manufacturer). None of these cases can be considered MC.

Relinquishing design control at the assembler level is giving end-users all the previous level freedoms plus the potential to swap finishes or add components in a modular system (e.g., adding a window). While design changes that affect the fabrication stage are related with alterations to the layout of the building. Which in turn have consequences on the manufactured building parts but may only occur within a given building system. At this level MC design solution space is finite and all possible solutions belong to the same design space (Kolarevic, 2013; Piller, 2004)[11]. Lastly, an end-user has design control at the supplier level if it is possible to choose amongst design spaces and consequently different building systems and different rulesets.

There are two critical observations to understand how the production axis is organized: (1) it focuses strictly on the core tasks involved in the production of products, specifically excluding design or engineering[12]; and (2) the midpoint is where the production control moves from being

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[11] In theoretical terms, systems at this stage can already be infinite if continuous variation is allowed, but in most practical applications this is generally constrained to a subset of discrete values.

[12] In a way the left part of the graph is a dually symmetrical version of the CODP map by Rudberg and Wikner (2004). Naturally all the observations of these authors regarding the optimality of the diagonal hold.

on the manufacturer side to the owner/customer side (Figure 2-7). At that point, tasks that are part of the manufacturer operations level start to be assumed by the customer: first the assembly (i.e., joining or installing previously manufactured parts or components into a new whole), then the fabrication (i.e., transforming inputs into outputs). On the left side, the manufacturer loses absolute control of the manufacturing process when the customer is given the possibility to make decisions that affect one of the stages of the operations level - first the assembly then the fabrication. For clarity, a new map with the gradients of control is provided in Figure 2-7.

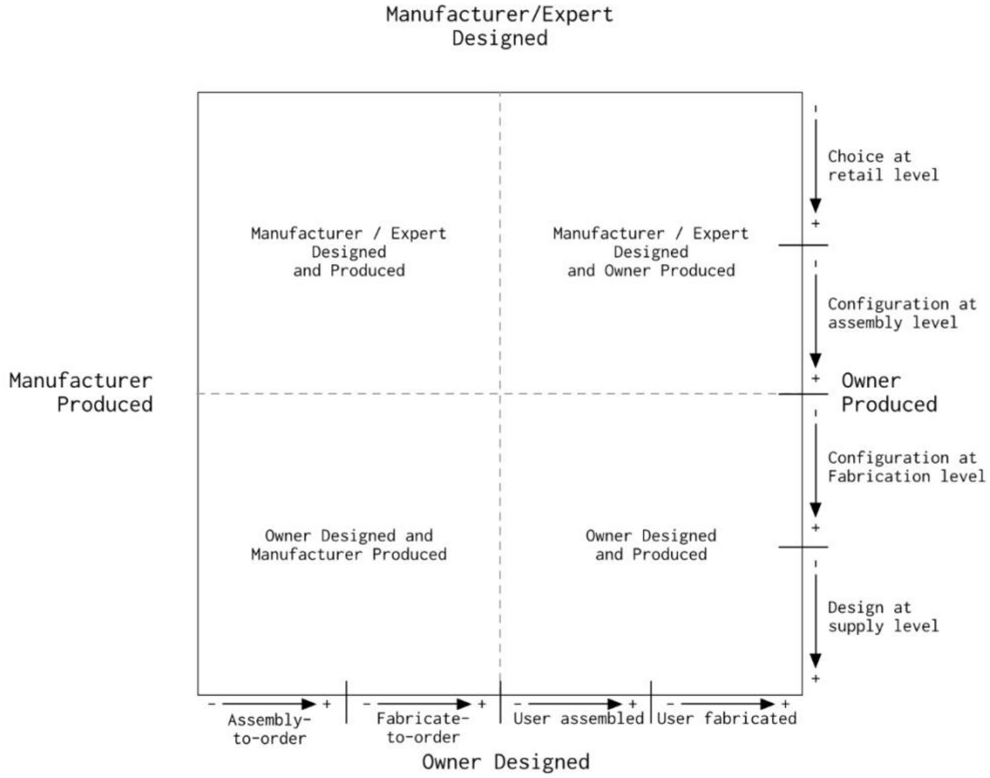

Figure 2-7: Gradients of design and production control

Using the map to position the concepts of MC and PF reveals that they do not overlap (Figure 2-8). To contextualize the discussion, conventional construction and mass production spaces are also identified. Any pure mass production system offers no real design control and thus can be seen as a line from the top-left corner which may stretch to user assembled systems following the logic of the kit-of-parts.

Conventional construction practice, as opposed to industrialized offsite prefabrication (Smith, 2011), can span the domain of the design control. Since architects almost always work for clients, buildings that are completely designer controlled are rare, likewise there will always be some level of design control exercised by architects. On the other hand, multi-family housing is a perfect example of choice being offered at the retail level, where the architect's client is not the end building owner and the variation that is offered is based on some form of market segmentation.

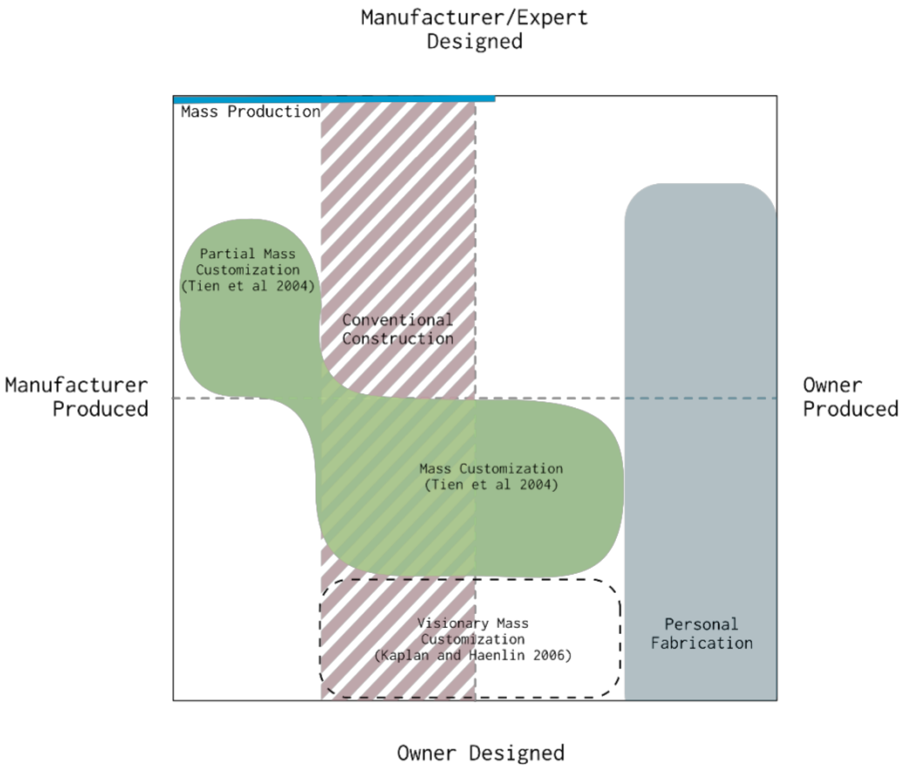

Figure 2-8: MC and PF concepts compared with mass production and conventional construction processes.

Any MCC system requires company-customer interaction, thus there cannot be MC if the building is owner-built and assembled or if there is no level of owner design and production control. The opposite is true for PF, the tools of production are only on the owner side if these are used for fabrication and assembly of products with some level of owner design control (Gershenfeld, 2005, p. 4). Hence, PF is limited to the right forth of the production axis, but it may span nearly all the design axis.

When there is a split between the architect and the client forms of delivering service emerge. The three levels of MC of Figure 2-6 - (1) Partial MC; (2) MC; and (3) Visionary MC - are roughly organized along a diagonal from the top-left corner to the middle of the bottom of the map. Customization in Partial MC only interferes with the assembly stage of production, which implies that building parts have lower ranges of variation, frequently limited to changes in options or components from a predefined modular dimensional kit. Thus, there is less owner design control. In MC, owner design control interferes with fabrication and assembly of parts, since interference with the building dimensions has consequences on the fabrication of parts.

While MC theory does not discuss the possibility of owner assembled systems, Sass's Instant House (2006) is an example of such a system, hence MC might extend beyond the middle axis.

To understand what visionary MC in architecture may be, it is crucial to understand how architects may surrender design control. It is evident that the architect is in total control of the design of a building when all the decisions are taken by himself. An example of this is the architect's own house, where he is at once the client and the architect. At the other end the client is in total control of the design decisions without any interference of the architect. It could be argued that at this point if there is no service being rendered there can't possibly be a client to begin with, so the owner is taking the role of the architect to himself. A self-designed home could be an example of this. The similarity of the two ends of the spectrum is evident. The only thing setting it apart is the expertise: the architect-client vs the owner-designer. It is what lies between these two extremes that is of interest to this discussion of MCC.

Duarte's Malagueira Grammar is an example of MC in design that offers topological customization. The grammar can change the topological relations of the rooms within a building type – *casa-pátio* designed by Siza. In this sense, Malagueira grammar is typologically limited. If the customizer wants to step outside the bounds of this building typology, he will have to edit the rules of the system. Furthermore, while programming Malagueira grammar, Duarte also encapsulated the building system as well. This of course means that any valid design generated by grammar can be built with a casa-patio building system.

If the design system could be capable of traversing the typological limits it might not be possible to build the designs with the *casa-pátio* building system. In that instance there would be a need for a design system capable of at least searching existing building systems that could build the design. Another possibility would be that the design system could be capable of innovation, that is, evolving the building system to make the design buildable. This is the ultimate capacity of designers: breaking rules and inventing solutions to their designs that meet specific needs. If there can be visionary MC in architecture, that is, MC at the design stage, it must be capable of taking the role of the architect in this sense.

Thus, as seen in Figure 2-6, Visionary MC can only occur at the lower quarter of the design control axis, which in the context of architecture implies the owner is able to customize the building across multiple design languages and construction systems, including the possibility of generation of new hybrid or creative languages or systems. Over the production axis, it might still be produced and assembled by a manufacturer or, like MC, have the assembly stage performed by the owners.

As seen in the previous section, OSArc shares methods with MC, but the requirement for evolving solutions in tandem by all AEC stakeholders implies that owners must take a higher level of design control than is possible within a specific design language like Malagueira discursive grammar. The number of design iterations the WikiHouse project has gone through between 2011 and today is a good case in point. As the Foundation seeks to expand the scope of the building system from small cabins to multi-story buildings, new systems have emerged to respond to those specific needs. Thus, OSArc is likely coincident with Visionary MC along the design control domain, although lower design control can also be possible (Figure 2-9).

Along the production domain, OSArc can allow owner fabrication and assembly but other stakeholders must be involved, the same condition implies that owner control of fabrication and assembly by manufacturers is needed (Figure 2-9).

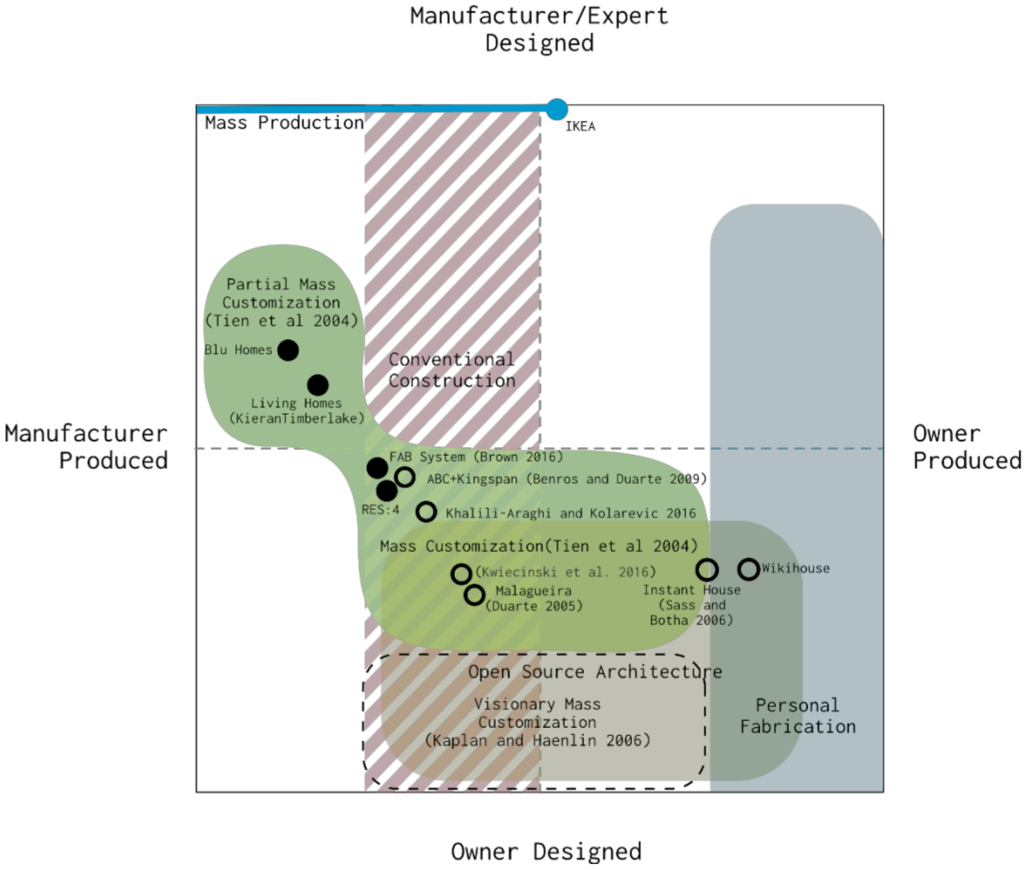

Figure 2-9: Mapping concepts and examples of research (circumferences) and practice (circles).

Lastly, some MC practical implementations in the housing that have been discussed in the literature are included in the map as examples (Kolarevic, 2015). Research cases are discussed and compared in the next section. Some examples are prefabricated housing manufacturers such as Blu Homes[13] and Living Homes[14] or design-build firms like Housebrand[15] or Resolution: 4 Architecture[16]. Both BluHomes and LivingHomes offer prefabricated models which the

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[13] Available at https://www.bluhomes.com/

[14] Available at https://www.plantprefab.com/livinghomes/

[15] Available at https://www.housebrand.ca/

[16] Available at https://www.re4a.com/prefab

prospective owners may select and customize in a website. Changes are only possible to interior or exterior finishes and thus these examples can be placed withing the partial MC domain (Figure 2-9).

The design-build firms use predefined modular "languages" either based on modular components or modular spaces that can be recombined to fit specific owner needs. Housebrand FAB system is design-to-fabrication modular system for the renovation of interior spaces of North American suburb single-family houses (Brown, 2016). Resolution: 4 Architecture uses a predefined set of modular space typologies, e.g. kitchen units, bathroom, etc., that can be recombined into different spatial arrangements mostly to design detached single-family homes (Tanney, 2019). The degree of customization of these systems fits into the MC area, but it is important to note that the owner design control is mediated by the architects and is also not clear what methods are used to implement the design systems (Figure 2-9).

In this section we have seen that OSArc is aligned with visionary MCC, which is the domain where control over design is exchanged between users and designers. Since OSArc extends MCC methods, processes, and tools it is crucial to expand the analysis of existing and proposed MCC systems to determine how they may be extended to enter the visionary MCC space. Furthermore, it is important to determine how the specific challenges of open building renovation may be addressed with MCC systems.

CHAPTER 3 Designing for Generic Users

Designing buildings for generic clients is a problem that architects have recurrently sought to address since the beginning of the 20th century (C. Davis, 2005; Kieran & Timberlake, 2003). The idea of design democratization using digital frameworks to provide context specific solutions to generic clients has recently taken on a new life with developments in MCC systems in architecture (Kolarevic & Duarte, 2019b). These authors have sought to leverage computational methods to address these century old challenges, arguing that these systems can produce context specific solutions that link variation with the physical, socio-cultural, technological, and individual context of the user (Kolarevic & Duarte, 2019a).

A system in this context is understood as a set of interacting components that are assembled to achieve a specific task, with clearly defined inputs and outputs, connections, hierarchy and interaction with the environment (Aguilar, 1973). Designing a system is the process of defining its architecture, characterized by a given structure, components, interfaces and input and output data (A. Friedman et al., 2013). Thus, these systems are computational models implemented in digital computers that automate the design and production of architecture, and as seen in the previous section, the fact that systems are designed means that a separation emerges between conceiving the system and the act of using it.

As argued by Von Hippel (2005, p. 147), the goal of the system is to embed specialist knowledge to empower non-expert end-users to instantiate designs that are adequate to their needs. End-users are thus prosumers that engage in co-design activities.

Larson, Tapia and Duarte (2001) established the main components of a MCC system, which consisted of a preference engine, a design system and a production system. For these authors, a preference engine is an interface that captures user preferences to produce a specification, the design system generates solutions that meet the specifications and the site survey, and a production system produces the components for onsite assembly or directly produces the building onsite. More recently, Duarte (2008, 2019) redefined the preference engine as one of the components of the design system, that seeks to "formulate" the problem from contextual data. Other subcomponents are evaluation, search, and generation subsystems.

Larry Sass (2006; 2006) expanded the definition of a design system to include a design detail sub-system, a construction grammar, that is capable of translating a concept design into a set of components that are producible by 3-axis CNC mills or laser cutters. Sass's system bound the detail design system with a specific digital fabrication technology. Sass's approach creates some ambiguity in Larson et al conceptual model of MC by showing that construction systems can also be subject to design[17]. Is detail-design embedded in the Duarte generation system or a duplicate sequential design system before production? Sass model follows the second approach.

As discussed in the previous chapter, the configurator is a tool to transfer design related activities to users. One of those design activities is the collection of information regarding user and design context, which in building renovation includes the survey of the existing building location, urban and regulatory context, shape, preservation state, history, materials, etc.

Lastly, independently of the specific structure and architecture of the digital framework, decisions will always be required about which designs it can generate and which methods are used to empower the user to find solutions that meet his/her requirements by either directly or indirectly manipulating the models. While there are interrelations between the methods used to implement these design systems and the user interfaces that are possible, each of these aspects is discussed separately in the following sections.

3.1 End-User Systems

The need for end-user involvement in the design of mass housing has been identified since the sixties by authors such as John Habraken (1961, 1972), Christopher Alexander (1973), Yona Friedman (1971; 1969), or Nicholas Negroponte (1969, 1972). Alexander theories in particular have been influential in the development of computer languages, object oriented design, and wikis (Cunningham & Mehaffy, 2013; B. Jiang, 2019; Salingaros, 2000). Negroponte or Friedman specifically proposed the use of computer systems to empower the user to participate in the design of his/her environment, which was a core aim of the research conducted at the Architecture Machine Group (ArcMac) (Ameijde, 2019).

The most striking example of that ArcMac research is YONA: Architecture-by-Yourself (Weinzapfel & Negroponte, 1976). It is a computer implementation of Friedman's graph theory applied to the design of housing[18] (Y. Friedman, 1980, 2006). In YONA, the lightpen interface, originally developed by Ivan Sutherland for the SktechPad, was replaced with a touch sensitive display tablet allowing users to manipulate the graph nodes by touching the screen, thereby *"eliminating one of the more serious barriers between naïve users and the machine"* (Weinzapfel & Negroponte, 1976, p. 75).

By a combination of an unobtrusive interface (tablet) and a flexible infrastructure (graphs), Nicholas Negroponte aimed to provide a non-paternalistic process of design to non-expert

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[17] Other authors have also equated construction systems to production systems, such as Benros et al (2011). We find this a fuzzy classification that mixes methods and tools of production with aspects that related with the materialization of form.

[18] Toward a Scientific Architecture was originally published in 1971, translated to English in 1980.

designers. Yet, it recognized that since these users lack practical design experience, they require some sort of assistance in the process of design by means of a workflow or a clear step-by-step strategy. Negroponte goal was not so much to provide solutions for design democratization but to use the specific case study as a limit condition for computer aided design techniques, because *"the user is demanding, the problem is hard and the product is personal, one-of-a-kind design"(Weinzapfel & Negroponte, 1976, p. 74).*

A similarly hard problem was taken on by Habraken and the Arend group with the development of the Matura system, between 1985 and 2000, an infill system for customized renovation of mass housing (Kendall, 1996, 2015a). Unlike Negroponte, the Matura system was meant to be applied in practice and was composed of a construction system and a computer system, the MaturaCAD.

The second iteration of MaturaCAD was a parametric design library and interface for architects to operate in tandem with users to customize their apartments. When the design was settled, the system would prepare the documentation for prefabrication and organize the supply of components for onsite assembly, or at least that was the aim (Kendall, 2015b).

Both these early examples place the user in the designer role with a direct interaction with the design by manipulation of graphic representations either mediated or not by an expert. In the MaturaCAD these graphic representations are geometric proxies of building elements, much like Building Information Modelling (BIM), while in YONA the objects are bubbles representing spaces.

The idea of design democratization using digital frameworks to provide context specific solutions to generic clients, was revived by the work of Duarte (2001) and Larson (2000). While developing his PhD thesis, Duarte proposed a framework comprised of shape grammars that encoded Siza's Malagueira, an interpreter, and a website (Duarte, 2000a, 2000b; Duarte et al., 2000). The framework was meant to enhance the architects' ability to find solutions to client requirements in a predefined design universe.

Between 2000 and 2003, Duarte participates in the House_n research project at MIT, with Kent Larson and Jarno Suominem, whose main aim was to develop an integrated system for designing and producing customized prefabricated housing. Likely influenced by this, his PhD thesis starts referring to his framework as a mass-customization system, with which a user could, unassisted by a designer, generate his own designs solutions. The elicitation of user preferences for generation of the design was achieved with an extensive form regarding cost, typological, morphological, spatiality, topology, and proportion requirements. The determination of urban context is limited to the selection of 4 orientations and position of the plot in the block. The geometry of the plot is predetermined (Duarte, 2001; Duarte & Correia, 2006).

Later, Duarte and Correia (2006) develop an application – PROGRAMA - to generate design briefs for Malagueira Grammar from user provided replies in a form. PROGRAMA had a web version and PC version and was composed of 2 parts: the user interface and a rule system. The rule system controlled the interactive workflow of the user interface and generated a design brief based on user input. Thus, Duarte implementation only allowed indirect manipulation of the design by the user and since search and optimization systems are used to select solution candidates there isn't a direct connection between parameters and the resulting design.

Likely due to Duarte participation, the first iteration of the preference system of the House_n project follows Duarte's template: an exhaustive online query that aims to reproduce the client-architect dialogue (Larson et al., 2001). Later the interface solution was extended to include a co-design environment involving an interactive digital table mixing virtual reality and scale models of the building components. This environment was meant to be used after the initial program was established using the questionary, and an initial solution was generated by the design system. The clients could them iterate the solution by changing the design or start the process again. Computational critics were also proposed to assist clients in designing their houses using predefined components (Larson et al., 2004; Mcleish, 2003).

The i-Prefab Home system UI was also based on an initial questionnaire to determine client requirements, but unlike House_n, it tried to match those requirements against a library of existing prefab designs in a specific geographical area. If a match was found the user was given the option to do some customizations and view some images and the budget. Unlike the House_n system, it was developed as a website (Huang & Krawczyk, 2006).

Both the House_n and the i-Prefab offer a much more constrained form of user control. And while the co-design iteration of House_n seems to expand that control, profile building and recommendation mechanisms counteract it.

Niemeijer (2011) retook the classical direct manipulation approach proposed by Negroponte and Habraken. He argued that to achieve *"true mass customization in the building industry"* (Niemeijer, 2011, p. 83) end-users should be able to modify their own solutions directly on a design interface. He identified some obstacles for this to be possible: (1) users lack knowledge of building regulations and codes; (2) users lack design experience; and (3) CAD interfaces are not aimed at end-users. He argued that the first two issues are easily addressed with constraint checking, i.e., albeit a user may not know if a given design is legal, an automated constraint checking system can quicky verify the design against existing regulations or specific design constraints.

Niemeijer (2011) tested constraint checking of a design and constraint creation from natural language, either legislative or design based, using Natural Language Processing. He implemented a prototype of a design interface in a BIM software with a constraint checking mechanism, but he only tested the prototype with researchers and not with end-users of the intended system.

Khalili-Araghi and Kolarevic (2016, 2020) built on Niemeyer's work and proposed a dimensional customization system for prefabricated housing using dimensional constraints set in a BIM model. The proposed interaction by non-expert end users is by dragging building elements in a 2d plan or by editing their dimensions within a BIM software. Like Niemeyer the system was not tested with non-expert end users. Yet the results of YONA research (Weinzapfel & Negroponte, 1976) already suggest that non-expert users may need step-by-step guiding in the co-design process, using toolkits or configurators to avoid the burden of choice (Piller et al., 2005; von Hippel, 2005).

The Wikihouse project was started in September 2011 by Alastair Parvin and Nick Ierodiaconou, of Architecture 00, as a CNC cut construction system aiming to disrupt "*architecture's economic equation*" (Parvin, 2013, p. 94) that prevents a large chunk of the world's population from accessing architectural services. Several attempts of computer implementations where made, the first as a plugin in Sketchup, then as grasshopper model of the Wren version, and the latter as a JavaScript custom application – Buildx[19]. Each of these implementations has specific characteristics regarding interaction, but they mostly limit user inputs to the overall dimensions of the building. Yet, contrary to all other cases, the parametric models have been widely shared allowing anyone to use or change them.

John Brown (Brown, 2016, 2019) provided an interesting conceptual contribution on how to address the mass-confusion problem. His Future Adaptive Building (FAB) system is a reconfigurable infill system that caters specifically for seniors. The system is composed by FABmodular, a system of prefabricated modular cabinetry, FABstudio, a web platform for interior design, social interaction, house management and health monitoring and FAB+, a set of medical addons that can be integrated into the FABmodular system. The FABStudio includes community features that allow users to interact and assist each other in the design process of their houses.

HOPLA (Kwiecinski & Duarte, 2019; Kwieciński & Markusiewicz, 2018) is a design interface for a shape grammar, that allows users to change and explore the organization of their house by dragging markers on a touch table. The idea bears some similarities with House_n interface implementation but has a different underlying design system. The authors conducted user testing with non-expert users in two different contexts. Their results shown that non-expert

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[19] https://demo.buildx.cc

users were mostly satisfied with the process of customizing their houses and obtaining immediate design and cost feedback.

Another recent development is the emergence of configurator platforms such as DynaMaker, ShapeDiver or Swarm. These platforms provide a base implementation of an interface that is automatically customized for specific model's inputs, thus allowing designers to distribute their models online or insert them into webpages. ShapeDiver and Swarm are specifically developed to allow the deployment of Grasshopper for Rhino visual programming environment (VPL) models, on the web or inside other designer applications, respectively.

The map in Figure 3-1 positions the above cases in terms of the level of end-user design control afforded by their design interfaces considering the previous analysis.

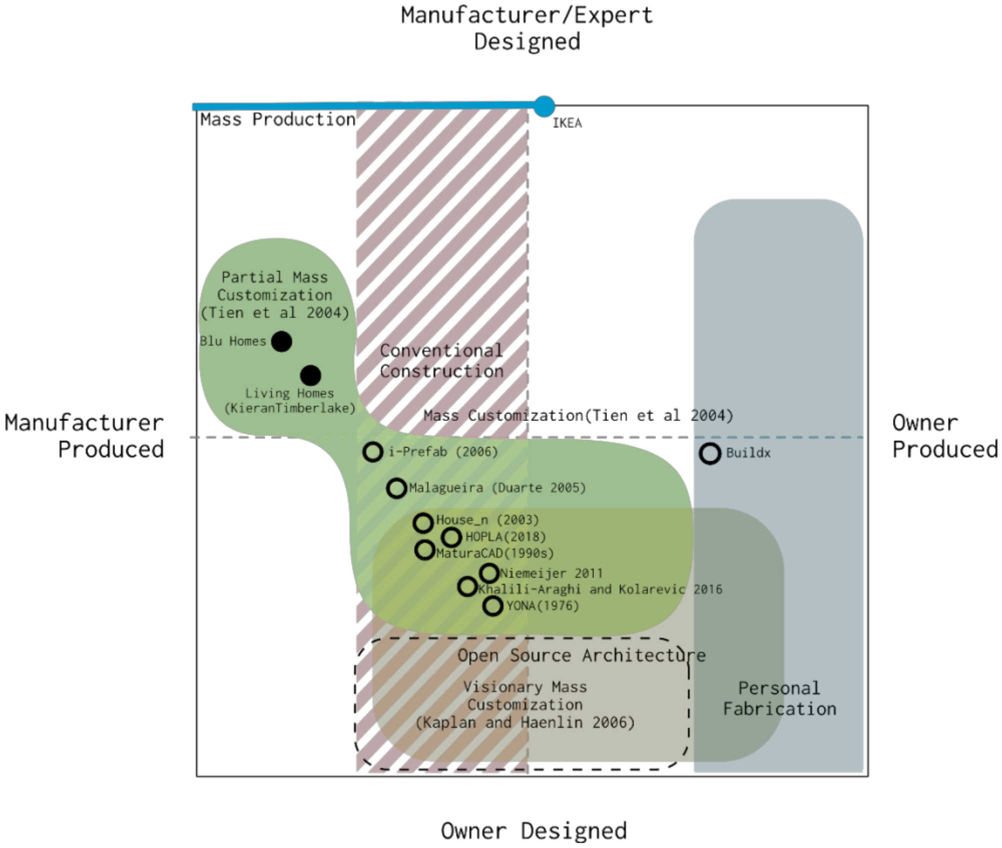

Figure 3-1: User input systems design and production control in research (circumferences) and practice (circles).

In summary, we identify in the literature two approaches to allow users to manipulate designs: (1) direct, by pushing and pulling geometry or physical surrogates; and (2) indirect by picking options and dragging sliders in menus. YONA, MaturaCAD and more recently Niemijer and Khalili-Araghi and Kolarevic try to follow a direct approach. HOPLA offers a less direct control of geometry, replacing it with control of space markers, perhaps a contingency of the design system being used, that clearly reduces the scope of design control. House_n interface sits between HOPLA and the previous group, by using markers for infill components (Mcleish, 2003).

A second level of control is exercised or not by establishing a direct correlation between inputs and the resulting design. A degree of disconnect might always be needed because of having constraints introduced by the meta-designer. Yet implementations that introduce search systems, like Malagueira, HOPLA or House_n will necessarily amplify that disconnect. Another lower level of disconnect is the use of modular components with standard dimensions.

3.2 Survey Systems

As stated in the introduction of the present chapter, design systems require information about user context to generate valid and user specific solutions, which can be divided into user preferences and context information. The previous section mostly focuses on user preferences, yet geometrical and semantical information about the physical context is also critical. Most of the previously reviewed cases deal with new buildings where the building context is simply the shape of the plot, building orientation and urban insertion, e.g., Duarte Malagueira Discursive Grammar (Duarte, 2001). In the Malagueira Grammar (2001) the allowed variations to the geometrical context are limited since it was mostly intended to be used in the Malagueira neighborhood.

In the case of renovation of the architecture of interior spaces, the geometrical contextual problem is more complex and cannot be reduced to a set of quadrangular shapes. In the MaturaCAD Infill System, the survey of interior plans was performed by the architects involved in the customization process following the conventional methods of architectural surveys. Later work in MCC systems dealing with configuration of infills, such Niemeijer or Brown, also does not provide any advances regarding systematization of building surveys. In fact, in the reviewed literature, we failed to find a reference to any solution to this problem.

Yet, observation of practical examples of simple configurators in use show examples of attempts to solve the problem, e.g., in many IKEA’s configurators the first step is a survey of the existing space. The process starts with selecting a similar shape and completes with some measurements of the orthogonal walls. This process suffices for simple shapes where there is a guarantee of orthogonality but for more complex contexts such as kitchens, the existing tools cannot ensure the quality of the survey.

The succeeding question is whether end-users should do building surveys. Clearly, since MCC systems automate design processes and in building renovation a geometrical survey is a sine-qua-non first step to design, then the real question is how end-users can do these surveys with sufficient quality so they can be used in MCC systems. Naturally, it is not sufficient to determine if end-users can do surveys with meaningful precision. Instead, the methods to achieve it must be capable of integration with existing configurators platforms and the commonly used tools to develop design-to-production workflows.

3.3 Design Systems

Design systems are essentially machines that automate design using rules and formalisms to describe potential transformations enacted in response to specific contextual data (Duarte, 2008). A design system is frequently a style-specific, context-specific or customized language of designs described with a domain-specific language (Beirão & Duarte, 2018), i.e., the description of the process or the algorithm by which designs of a given family are generated. Alternatively, Kolarevic calls them metadesigns (Kolarevic, 2019).

The process of developing metadesigns is widely referred to as computational design, an activity which requires an intersection of computational thinking and doing, i.e., a specific literacy in design and computation necessary to develop tools to be used by others (Denning, 2017; Oxman, 2006; Terzidis, 2006). Design systems for MCC by building owners or end-users are a subset of design systems where the target community has little or no expert knowledge of design. In this review, we specifically focus on design systems that are intended to be operated by non-expert users.

Within the Design systems for MCC subset, researchers have focused on systems that automate the design of mass-housing, apartments or single-family housing (Benros & Duarte, 2009; Duarte, 2001; Eloy, 2012; Khalili-Araghi & Kolarevic, 2016; Kwiecinski et al., 2016; Niemeijer, 2011), or on cost-effective building solutions for specific contexts using digitally fabricated construction systems (Brasil & Franco, 2019; Elsayed et al., 2017; Finch & Marriage, 2019; Gámez et al., 2015; Parvin, 2013; Sass, 2006; Stoutjesdijk, 2013; Vincent & Backheuser, 2019). Crucially, while the first group is also concerned with affordable housing solutions, it leverages conventional or prefabricated construction systems to achieve cost-effectiveness. This thesis is concerned with the second group while for completeness, the first group is included in this review.

With a few exceptions, such as Benros and Duarte (2011; 2009), researchers of the first group have focused on the house layout and organization and aspects correlated with the concept design stage, while the second group dealt with considerations that are typical of the detail design stage of traditional architectural design processes. To facilitate the discussion about design systems we call the first Concept Design Systems (CDS), that generate a house design from user contextual data, and Detail Design Systems (DDS), that generate building specifications for fabrication and assembly. Evidently there are feedback relations between what is buildable with a given construction system and the spaces that may be designed; thus, researchers frequently embed in CDS building systems constraints.

To create a functional design system for MC three steps are needed: (1) define its scope by precisely identifying the type of objects on which the system is intended to operate; (2) identify which types of variation are provided by the system, which should ideally match those that are required by its' users; and (3) select an adequate method to encode the required variation (Kolarevic & Duarte, 2019a).

The first step can be achieved by focusing on a specific type of building or a specific building subsystem. The second step requires defining on a metalevel the topologic relations between the specific parts of the selected object family, e.g., a chair, a wall, a house, keeping in mind that each part of that object may be itself an instance of another class of objects, e.g., a chair contains legs which may be assembled with screws. Then, it must be decided what are the ranges of admissible variation and how these are exposed to the user. The third step requires selecting a specific method or combination of these to organize the dependencies and relations between the parts of the system (Kolarevic & Duarte, 2019a). Two main methods of implementing these systems have been described in the literature: parametric design (Woodbury, 2010) and ruled-based design systems, such as shape-grammars (Stiny & Gips, 1972).

Rule-based systems allow for higher level of design variation, specifically topological variation, but are harder to implement in practice because they can run into shape recognition problems. A common way of circumventing the issue is to transform the rule-based system into several parametric models thereby allowing for topological variation (Kolarevic & Duarte, 2019a). Examples of design systems in the context of mass customization of housing using shape grammars are the already mentioned Malagueira Discursive Grammar (Duarte, 2001), the Instant House (Sass & Botha, 2006), Relief Housing for Haiti (Benros et al., 2011), the Rabo de Bacalhau Grammar for renovation of a specific apartment typology in Lisbon (Eloy, 2012), or the Wood Mass Customized Housing (Kwiecinski et al., 2016).

Parametric design systems are widely adopted due to the development of design specific programming or scripting languages, e.g., Processing, Grasshopper or Dynamo, and can provide infinite variation within a specific topological structure. Examples of the implementation of these systems using parametric design are the ABC+Kingspan (Benros & Duarte, 2009) Constrain specification (Niemeijer, 2011), Khalili-Araghi and Kolarevic dimensional customization (2016, 2020) or the Wikihouse[20].

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[20] Several different versions of the Wikihouse system have been developed since 2011 and different models of these versions have been implemented in Grasshopper or as a plugin for Sketchup.

Positioning the identified cases in research on the map reveals that they are all in the first forth below the production axis and all are roughly within the MC area except for the WikiHouse (Parvin 2013a), which sits in the PF area, and the Instant House (Lawrence Sass and Botha 2006) which is ambiguously placed between PF and MC (Figure 3-2). In fact, most DDS research could be positioned similarly. CDS research mostly fits into the MC area right of the design control axis, and we can identify 3 groups. The first group are parametric systems that only offer modular variation, as is the case with Benros and Duarte (2009). The second group offers more user design control by providing either topologic and modular variation with a limited envelope (Benros et al., 2011; Kwiecinski et al., 2016) or dimensional variation within a fixed topology, e.g. Kolarevic work (2016, 2020).

It is instructive to ponder on the differences between the cases in this group as they seem to provide variation that is orthogonal. The first two are shape grammars that operate over a constrained envelope, thereby providing houses that will be in the same cost range with different topology. The latter case is a parametric system that could offer the same topology but with widely different building morphology, surface area, and overall cost.

The last group contains cases that can offer dimensional variation and topologic variation, as is the case with Duarte (2001) and Eloy (2012) shape-grammars and Niemeijer parametric system. Niemeijer (2011) achieves topologic variation by allowing users to interactively add, remove and move partitions in a design, while ensuring the designs are valid with a constraint checking system.

In building renovation dimensional variation is required, since it is not possible to ensure that the pre-existing building will fit to a specific modular system, thus only the cases in this group provide an adequate model of CDS for MC in building renovation.

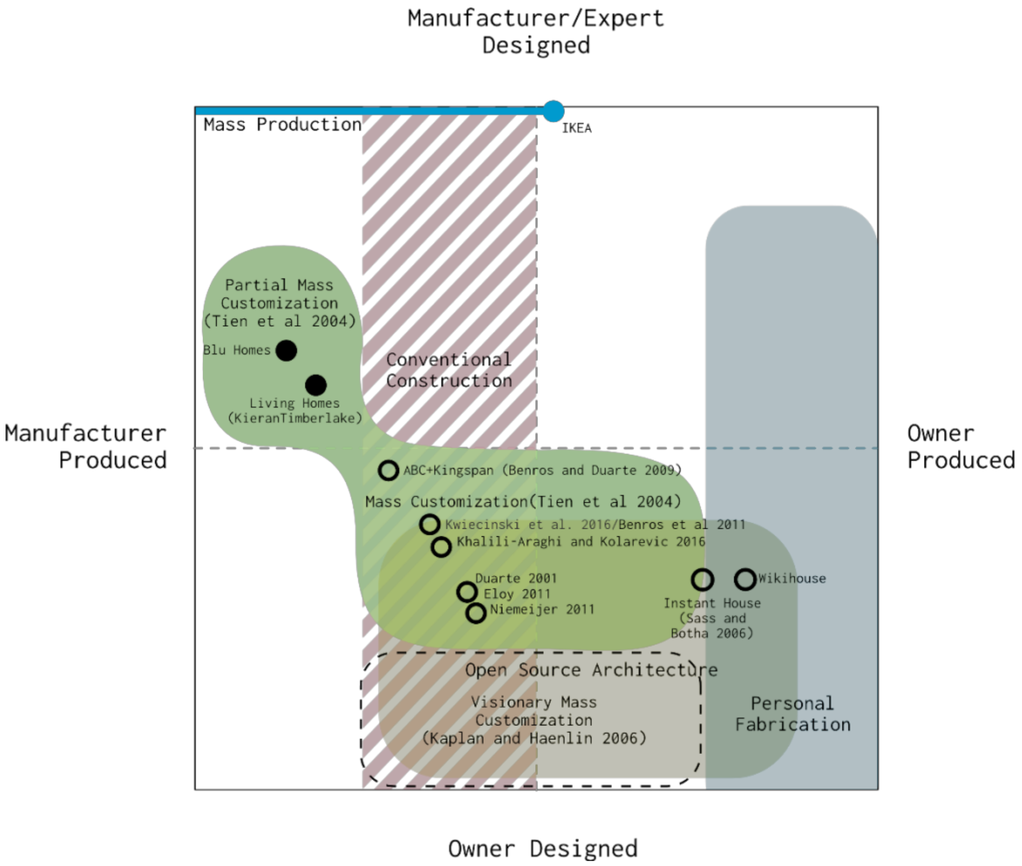

Figure 3-2: User input systems design and production control in research (circumferences) and practice (circles).

A common feature of shape-grammar CDS implementations is that the user does not directly design solutions but instead provides information that is interpreted by the system to generate solutions. A small selection of solutions is presented to the user who may then iterate by changing the initial parameters. Parametric systems have traditionally taken a more direct approach allowing the user to directly manipulate geometry or continuously change it by manipulating numeric values and options (Niemeijer, 2011; Khalili-Araghi & Kolarevic, 2016, 2020). Thus, contrary to most parametric systems, in these implementations of rule-based systems there isn't necessarily direct feedback between changing a choice and a specific output.

While none of the reviewed cases can reach Visionary MC space, we can foresee that Niemeijer system could easily achieve that by removing architect-specified constraints, while for shape grammars the concept of Generic Grammars (Beirão & Duarte, 2018) could also be an adequate solution. The rudiments of a generic grammar in DDS are already present in first subdivision rules of the Instant House, although it is questionable if those specific subdivision types are generalizable beyond simple small houses. Using a modular design system composed of multiple independent CDS and DDS could further increase expressive power of the design system.

Most issues in the implementation of an MCC design system are related with the balance of user design or production control. Increasing user design control is related with increasing: complexity of the system implementation; increasing difficulty for computational designers to ensure quality from aesthetic, functional, performance, environmental and structural point of view across the domain of solutions; increasing difficulty for the end-user to select solutions within the range (Kolarevic & Duarte, 2019a).

The first issue can be addressed with workflows and design system modularization, such as separating the generation of a house concept design from the generation of the construction components the building will be built of, as exemplified by Sass's Instant House (2006; 2006). The quality issue has been addressed with optimization and simulation systems (Duarte, 2005b; Kolarevic & Malkawi, 2005), but also implementing constraint checking (Niemeijer, 2011). The last issue has been discussed in the previous section.

Issues of sustainability are scarcely discussed by either CDS or DDS researchers before 2010. Benros et al (2011) suggested that mass customized solutions are more sustainable while Parvin (2013) pitched the Wikihouse as a sustainable and affordable solution to the housing problem. Later, Hosey et al (2015) argued that digitally fabricated systems, particularly those with reversible joints, can be a more adequate response to the construction energy problem if DfD principles are followed. But they do not detail these principles or how they should be implemented in DDS. Other authors that address the issue of the environmental impact of digital fabrication have found that it is mostly negligible when compared to the material production stage (Agustí-Juan & Habert, 2017).

In summary, the continuous dimensional variation that building renovation requires can be achieved with rule-based systems or parametric systems. Also, it is possible to anticipate that both types of systems could be used to provide design level control at visionary MCC levels using a modular system architecture. Such system architecture can also reduce the implementation complexity resultant from increased user design control.

3.4 Production Systems

A production system attempts to capture the processes involved in fabrication and assembly of building components, systems, or entire buildings. Yet the choice of building production technology and the level of automation is a design decision that is bound with technological limitations, costs, and ethical issues (Sass & Botha, 2006; Kolarevic & Duarte, 2019a). In fact, as is implicit from the map we presented in the previous section, design systems that generate building descriptions may be coupled with automated processes of production and assembly, automated production and manual assembly or manual production and assembly. While DDS can be implemented separately from production systems, most are developed for specific production systems or in tandem with them.

Within fully automated systems of production it is worth mentioning the possibility that the production and assembly steps are intertwined into a single indivisible step, as is the case with 3d printing (Duarte, 2019), or the result of a single universal machine with different end-effectors that is capable of both fabrication and assembly tasks (Gramazio & Kohler, 2008a; Willman et al., 2017).

Production systems may be still separated according to the digital fabrication process involved. A frequently used classification system is the type of transformation the machine performs on the input material: (1) subtractive, for processes that change the input material by removing parts of it; or (2) additive, for the processes that aggregate material to produce a larger part (Burry & Burry, 2016). We call this a process classification.

Some authors have proposed adding two other categories: (1) formative processes, for transformations that only change the shape of the material without adding or removing parts of it; and (2) joining processes, for operations that join parts with long term processes such as welding (Hauschild et al., 2011). Joining processes have seen a rise in interest by architects with the increasing use of robotic arms, but these processes have been generally classified under the additive category (Gramazio & Kohler, 2008a; Willman et al., 2017).

An alternative classification system was proposed by Iwamoto (2009) which categorizes digital fabrication processes by type of tectonic technique: (1) Sectioning; (2)Tessellating; (3) Folding; (4) Contouring; and (5)Forming. Sectioning is essentially a post rationalization process that takes a 3-dimentional volume and extracts planar sections. The sections may be all parallel, or some mix of 2d or 3d plane orthogonal or non-orthogonal plane intersections. Tessellating is a method of subdividing a surface into pieces, frequently planar, that when jointed together form a continuous surface without gaps or overlaps. Folding is the process of bending a 2d material into a 3-dimensional form. Contouring is akin to carving but limited to 2-dimensional subtractive operations. Forming or casting is producing objects by pouring liquids or deforming solids into molds.

Another important aspect of digital fabrication technology is the number of axes a machine may move on, which determines the geometrical complexity that is attainable with a given fabrication process. The most common machines are limited to moving the tool in 3-axis, e.g., CNC mills or 3D printers, while robotic arms can move in either 6 or 7 axes.

A tectonic classification is illustrative and can be useful for understanding how digital fabrication techniques relate to a particular design materialization or how these digital fabrication techniques may be leveraged to achieve specific material effects. Yet, it is reductive since fabrication processes are best described by the capabilities of the used tool/machine and multiple fabrication techniques may be needed to produce even a simple building. Furthermore, the same machine can be used to produce several tectonic effects. A process classification is particularly useful for describing fabrication affordances and may be related with sustainability issues but is problematic when classifying robotic arms fabrication processes which are dependent on the end effector. It also does not capture the limitations of the movement of the tool. Thus, we adopt a process classification prepending the freedom movement, e.g., 3-axis subtractive for 3- axis CNC mills or 6-axis additive for robotic arms with 3d printing end-effectors.

Although the classification above empowers designers to select appropriate fabrication methods for specific goals, selecting a specific fabrication system should also be considered in terms of the possible workflows integrating design, fabrication and assembly, and the accessibility of the tools and materials.

The interest in integrating design and fabrication has grown significantly since the nineties, kickstarted by the work of authors such as Bernard Cache, Greg Lynn, Frank Gehry or Gramazio and Kohler, whose work is considered equally relevant to MC in architecture (Kolarevic, 2019). Some of these authors established one-off seamless design-to-production workflows for MCC of specific building components or building types. Creating digital workflows integrating digital design with digital fabrication is frequently seen as a competitive advantage (Hauschild et al., 2011) or a creative opportunity (Burger, 2012) for architectural offices. Yet, after almost 30 years since the first experiments, the design-to-fabrication workflows are only now starting to go beyond research pavilions (Scheurer et al., 2014).

Scheurer considers that simply adopting integrated project delivery and digital design tools like BIM is not enough, and a revision of the workflow is needed to consider fabrication and assembly at the beginning of the design process. Also, adoption of industrialized offsite prefabrication requires changes to the conventional construction workflow to allow parallelization of production processes, which in turn demands shared conventions on interfaces between systems and processes. Expressing parametric models of building systems in terms of their envelopes is key and eliminates the need to re-draw the model at each stage of the building process as precision or site conditions change (Scheurer & Stehling, 2020).

Other more technical roadblocks pointed by Scheurer (2014) are technologic limitations, e.g., automatic feature detection only being feasible for simple geometries, and workflow limitations, e.g., more complex geometries require either manual work or custom CAD-CAM interfaces for a-priori known fabrication machines. Lastly, developing systems for assembly by end-users requires rethinking traditional design workflows to clarify how the steps may be divided between expert designers and non-expert designers, and which extra steps may be needed to ensure the design outcomes are within a specific scope (Hoftijzer, 2017).

DDS systems identified in the previous section unanimously adopt 3-axis subtractive digital fabrication methods coupled with manual onsite assembly, which can be considered a reasonable option in cost-effective and do it yourself (DIY) contexts but fail to leverage the opportunities for factory pre-assembly of parts thereby shifting the complexity from the fabrication stage to the site.

The selection of materials is inextricably linked with the fabrication processes. Beyond the fact that some fabrication processes are only viable with specific materials, it is important to note that the cost and accessibility of the process are also important factors to consider when selecting a given process / material combination (Stevens & Nelson, 2015). Regarding material selection and fabrication process, Scheurer considers that building with wood-based products should be preferred because it is a light and circular material with a long tradition of offsite prefabrication and widespread use of digital fabrication (Scheurer & Stehling, 2020).

In fact, if wood materials are sourced from sustainability managed forests, they are in fact negative in carbon emissions (C. Jones & Hammond, 2019). Yet, Hammond (2019) points that to truly achieve those benefits the end-of-life is critical. Carbon storage can only be applied to wood materials that effectively become end-products.

By using wood derivates, architects can also benefit from the tradition of wood joining techniques adapted to be fabricated with CNCs (Menges et al., 2017; Robeller et al., 2014; Schimek et al., 2010).

Naturally occurring materials have been, up until the beginning of the industrial revolution, the main resources of building construction. Using manual labour and craftsmanship, knowledge acquired by experience and transmitted from master to apprentice, these materials were transformed and organized in material systems to suit specific applications within the built form. There was an evident relation between the material, its properties, the available tools, and the specific functions it played within the building. Wood, "*the structurally most capable insulating building material*" (Menges et al. 2017), is a good example of this. This empirical knowledge was iterated by generations of builders and its evolution is closely related with the evolution of constructive systems. Form and mater were deeply intertwined.

The revolution in production processes - or in the tools to make things - brought by the Industrial Revolution, progressively severed the relation of the building craftsman with the sourcing and transformation processes of raw materials into building materials. This process coupled with the evolution of material science, drove the material processes further away from the architect, the master builder, and effectively transformed the role of building craftsman into skilled assembler.

As David Ruy (2016) points out, it can be argued, like the Rem Koolhaas '*Elements*' exhibition at 2014 Venice Biennale suggests, that architects themselves have been cornered into a role of compilers of technologies and building solutions. In fact, the separation between material science, building design and building construction has never been so acute. This specialization of knowledge into different disciplines hinders the development of effective solutions to a more sustainable way of building. These solutions will inevitably involve materials that are renewable, recyclable and with low embedded energy such as wood and cork. And they will also require rethinking the processes of design and building.

The integration of digital design and digital fabrication promotes an engagement with the material which requires transdisciplinary approaches. Digital fabrication tools are becoming increasingly accessible to the architectural practice, which in turn is bringing prototypes into the toolbox of the architect and reducing the prototypical nature of the building site. This promise of acting on "*the stuff of things*"(Gershenfeld, 2005), doesn't imply that the architect will be redeemed from its current condition of assembler into a new world of originality. The very transdisciplinary nature of the process and the need to comply with regulations or the building code, stand in the way of invention. And as Picon (2016) correctly points out multiple paths lie ahead both for the authorship / copyright or the nature of the relations between the construction industry players. More likely than not the collaborative nature of construction will intensify, motivated by increasing complexity and demands of the built form.

In this part it was shown that building renovation is a complex cyclic process within an expanding and increasingly diverse corpus, and with a varied set of stakeholders. Researchers call for involving the user in the design process to increase trust and reduce conflicts. However, architectural design services delivered in the traditional sense for interior renovations are frequently too costly and not legally required. Furthermore, delivering these design services in building renovation requires added survey steps to better understand the design context. Yet, added precision does not prevent the need for adjustments in the construction phase, which are mostly caused by unforeseeable circumstances during the design stage. What is needed is a flexible and updateable representation of context that can be linked with design-to-production workflows to deliver custom co-designed solutions affordably.

Renovating, when possible, is generally more sustainable than demolishing and building again since less material is used in the process. Researchers have argued for the adoption of closed loop approaches in design and construction based on the principles of open building using strategies such as DfD. These authors have proposed principles for the development of construction systems and have identified MCC as an adequate paradigm to enable industrialization of construction. Yet, research and examples of digitally fabricated construction systems do not seem to adhere to the principles of open building and DfD, particularly in what regards to the reusability of non-standard systems. Also, the complexity of the assembly stage seems to be increased rather than reduced in these types of systems. So, it is important to know how the criteria of DfD, building renovation, and MCC can be reconciled to arrive at a framework of criteria for customizable and disassemble-able partition wall systems for MCC systems. Furthermore, this framework of criteria must be translated into actionable design principles for architects to design upon.

It was shown that MCC is a paradigm evolving from developments in the integration of digital design and fabrication processes. We have seen that to implement MCC it is necessary to develop configurators that allow instance-designers to co-design solutions by providing their preferences and information about their contexts to the MCC system. In the case of building renovation, this implies providing surveys of the space to be intervened. Yet, how can the users of these systems perform as-is surveys of their contexts with sufficient quality for design-to-production workflows?

Researchers in open building argue for industrialization of buildings and a direct relation between manufacturers and building owners. The redistribution of design control is the first step towards systematization which is itself driven by social habits. In Chapter 2, MCC is posited as systematic form of distribution of control yet to provide end-users with control at the design level it is necessary to deliver MCC at the visionary level. OSArc suggests that to achieve such goal a more open approach to MCC system architecture is required. In Chapter 3, some insights are provided on how this might be achieved, namely selecting interactive methods that allow continuous dimensional variation, direct design manipulation and can be assembled in modular systems architectures.

Incremental innovation is according to Habraken the process by which AEC sector evolves. Disruptive innovation or systems that attempt to capture the entire workflow from design to production are extremely difficult to implement and have all historically failed. Most of the MCC systems discussed in the previous section fall into the closed prefabrication category. Thus, for MCC to be widely adopted in practice it needs to reconcile with existing actor roles and processes in the AEC sector.

Open systems on the other hand, define specific interfaces through which the connections with the context happen. Yet, designing the commons is a major challenge that cannot be addressed by a single author. It requires shared frameworks and workflows to become generally accepted.

PART 2: ANALYSIS FOR A SYSTEMIC VIEW OF BUILDING RENOVATION

To answer the previously described questions, concerning the issues of implementing MCC in building renovation, the integration of disparate views from different domains concerning the design of systems and the implementation of MCC in practice, it is necessary to adopt a systemic view.

Most of the concepts we will discuss are derived from a systemic view which all the cited authors either explicitly or implicitly adopt. A systemic view argues that solutions to complex problems are not the result of the sum of solutions to each of the multiple subproblems. Instead, a more holistic approach which accepts the problem in all its complexity is adopted thus acknowledging that systems have complex feedback relations at multiple levels.

We can think of all entities as hierarchical nested systems, which at any scale can be separated into a set of components, which in turn are themselves systems (Simon, 1962; Alexander, 1973; Schilling, 2000). Each component may be a part of multiple systems simultaneously (Schilling, 2000) and each system exists in a context to which it responds and adapts (Alexander, 1973). If a system is a solution to a problem, its context is the definition of the problem. Thus, Alexander states that fitness is the degree to which context and system are mutually acceptable. However, the definition of the context is itself a design problem for artificial systems (Alexander, 1973). In any case, systems evolve to respond to contextual pressures but may never actually achieve a perfect fit (Schilling, 2000). Lastly, as systems evolve, they change their context (Alexander, 1973; Schilling, 2000).

The need for a more holistic approach in addressing the issues of developing systems that seek to be more sustainable is acknowledged by several authors (Adams, Osmani, Thorpe, & Thornback, 2017; Crowther, 1999b). It features preeminently in Durmisevic thesis which proposes that design methodologies must consider all aspects of the problem from the onset, instead of the traditional top-down progression (Durmisevic, 2006b). Those methodologies frequently require integrating knowledge from multiple disciplinary domains.

Klein et al. argue that transdisciplinarity is a research strategy that can cross disciplinary boundaries to achieve a holistic view. It is a *"form of learning and problem solving involving cooperation among different parts of society and academia in order to meet complex challenges* *of society"*(Klein et al., 2001, p. 7). This strategy was adopted in the following discussion of criteria to include diverse viewpoints from researchers and practitioners with different agendas, stakes, and positions in the AEC industry.

In Part 2 we address the three questions that were previously identified in the theoretical framework. In Chapter 4, the disciplinary views of the several identified areas of research are clarified, compared, and reconciled into a common framework of criteria for the design of partition wall systems for building renovation. In Chapter 5, we look at which workflows are latent and emerging, amongst computational designers and proponents of design-to-production systems and how these may be reconciled with practice. To address the issue of the integration of as-is surveys in design-to-production workflows we compare several methods of survey with semi-automated workflows available in mobile apps for generic clients, to determine if these methods could be adequate for design-to-production workflows and if end-users can use them. Lastly, we describe the design research with digitally fabricated joinery and partition systems which was conducted with the aim of finding generalizable principles for disassemble-able and mass-customizable partition wall construction systems.

CHAPTER 4 Towards framework of criteria for customizable and disassemble-able partition systems

In this section, we establish a set of criteria for designing and evaluating DfD and mass-customizable partition walls for building renovation, that can be digitally fabricated and assembled by generic users. Contemporary societal challenges dictate these systems must also address the sustainability issues at the level of material waste, without forgoing cultural values of the buildings that are renovated, rehabilitated, or refurbished.

To achieve our goal, we first look at the theory, criteria or design guidelines which have been proposed in each area: building renovation, open building and DfD, MCC systems. We briefly define the scope of application of disassemble-able partitions and their functional and technical requirements, although these are already well defined in standards issued by the CEN and guidelines defined by EOTA (2019). We aim to summarize a consensual set of criteria, or identify trade-offs between them, and ultimately contribute to the definition of criteria for the development of customizable and disassemble-able partition wall systems for MCC systems, focusing on architectural aspects such as their capacity for reuse, ease of assembly or modularity.

This analysis will allow us to define a preliminary set of criteria which is then tested in exploratory interviews with industry and academia experts in each respective field. The 8 interviews have been conducted with experts with experience in different areas of the AEC industry: construction, engineering, and architecture, both in academia and practice; to ensure that a wider gamut of points-of-view is captured. From the analysis of the literature on these concurring aspects, a framework of criteria is derived for the design phase of the constructive system.

4.1 Building Renovation Criteria

Several authors have identified the need to develop building renovation methodologies and criteria for common building stock (Casanovas, 2007; Eloy, 2012; Freitas, 2012; Teixeira, 2013a). Either to ensure preservation of cultural and historic values or the commonality of intervention strategies.

Portuguese authors identified several factors that should lead to an increase in relevance of building renovation such as: (1) the abundance of the existing buildings, particularly housing, in need of rehabilitation; (2) the stabilization of population growth; and (3) existing houses far exceeding the number of families. The tendency of increasing relevance of building renovation in detriment to new building construction is expected to continue, bringing Portugal closer to the European average (Carvalho, 2013; Eloy, 2012; Freitas, 2012; Teixeira, 2013a).

While the proposed methodologies and criteria were developed with specific case studies in Lisbon (Eloy, 2012) or Porto (Coimbra & Romão, 2013; Freitas, 2012; Teixeira, 2013a) they can be considered generic, e.g., Eloy's methodology was applied in Kwiecinsky et al (2016) and Teixeira's methodology is closely related with Casanovas RehabiMed (2007) and the Cartas. Coimbra and Romão (2013) only propose a methodology, using Shape Grammars as a tool, and no explicit criteria are defined. Eloy's methodology focuses on the concept design stage and the needed reorganization of the floorplan in the rehabilitation of houses. Her methodology defines evaluation criteria which are focused on the performance of the spatial organization. Thus, this methodology does not contribute to the definition of criteria for construction systems, as opposed to the work of Freitas or Teixeira.

Both Teixeira and Freitas propose intervention methodologies that start with a preliminary survey stage, and whose output is a diagnostic report that sets the stage for the projects. This preliminary stage must be scaled according to the type and scope of the intervention, but mainly serves to build knowledge of the existing structure when this is not available.

4.1.1 Teixeira Criteria

For Teixeira, interior partition walls are considered a medium intervention on the building which falls under the scope and type of a rehabilitation action. Teixeira's criteria are not specific to this type of intervention and should be viewed with sufficient flexibility to allow for adaptation to particular cases (Teixeira, 2013a, p. 563).

Teixeira's (2013a) criteria are based on a review of a large body of theoretical and prescriptive knowledge[21]. Although it was proposed as an intervention methodology for Porto historical center, its' authors consider the methodology and criteria as a generic tool for intervention on built heritage, either monumental or common building stock (Teixeira, 2013b; Teixeira & Póvoas, 2012). Nevertheless, their recommendations are specific to buildings built with traditional materials and construction techniques.

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[21] The prescriptive knowledge in this case refers to the recommendations of the Cartas and successive congresses since the 1904 International Congress of Architects, such as the Athens Charter for the Restoration of Historic Monuments of 1931, the 1964 Venice Charter, the 1975 European Charter of the Architectural Heritage, 1983 Appleton Charter, the 1987 Washington Charter, the 1995 Lisbon Charter, or the 2000 Krakow Charter.

Teixeira (2013a) defines a set of 12 intervention criteria:

JT1. **Knowledge of the pre-existing building:** a survey including but not limited to a geometrical, photographic, historical, structural aspects must precede the intervention.

JT2. **Preservation of the pre-existing:** It is preferable: "*to repair than to demolish, but in case there is a demolition, it should be selective; to repair than to replace, but in case it is replaced, it is preferable to reuse.*" (Teixeira, 2013, p. 565).

JT3. **Adaptation to the context:** Any intervention should respect the typological and morphological characteristics of the architectonic context. Thus, adjusting spatial requirements to the existing structure and maintaining original uses is preferable.

JT4. **Integration with context**: Harmonious integrations should be favored in detriment to confrontation or rupture with context.

JT5. **Improving existing conditions:** The interventions should contribute to improve or update the quality of buildings to current standards of comfort, hygiene, structural and fire safety.

JT6. **Proportionality of normative demands**: proportionality between the scope of the intervention and the normative and performative requirements

JT7. **Reversibility of interventions and retrofits:** Sufficient degree of reversibility of the interventions must be ensured and to this end the adopted solutions must be as close as possible to the existing ones in terms of material properties. Irreversible solutions are those that cause damage to original structure if removed. Reparations should be done with original materials and techniques (this includes change of elements within a given system such as a beam in a wooden floor)

JT8. **Preservation of pre-existing interventions:** If a previous intervention holds historical value, it should be maintained.

JT9. **Compatibility of materials and construction systems:** Reusing existing systems and materials should be privileged. If repairing or replacement is necessary, the original methods should be privileged, otherwise compatible techniques and materials should be used.

JT10. **Visibility of the intervention:** New elements or parts should be visibly different from the original, in both materials and languages, nevertheless maintaining the harmony of the ensemble.

JT11. **Population participation**: participation of users should be encouraged in the project decisions that affect them, and if possible, they should participate in the renovation of their own houses conducting simple or small tasks.

JT12. **Documentation of the intervention**: all changes must be documented, stored, or published

For the specific case of changes to functional organization of interior spaces, which requires demolishing existing partitions walls and introducing new ones, Teixeira considers that the new elements should be distinguishable from the existing ones yet integrate harmoniously and use compatible materials. This recommendation is inherited from the Venice Charter (Teixeira, 2013a, p. 581).

Teixeira does not define performance criteria, static, acoustic, or thermal, for partition walls, yet admits those types of improvements are relevant for the exterior envelope of the building.

4.1.2 Freitas Criteria

Freitas principles for rehabilitation of old buildings (2012, p. 24) are in agreement with those proposed by Teixeira, and originate from similar sources, i.e., the cartas and ICOMOS recommendations. Yet, for the sake of completeness these are summarized below:

VF1. **Minimize intervention**: Only indispensable interventions should be conducted, and the scope of the intervention should be minimized while ensuring safety and durability.

VF2. **Proportionality of safety and functionality demands**: Changes of use should adapt functionality demands to the existing building. Normative safety demands should be replaced, when necessary, with other methods to ensure safety requirements.

VF3. **Physical and chemical compatibility of materials**: Materials introduced by the intervention should be compatible with the existing materials.

VF4. **Reversibility of interventions**: The interventions should be reversible, particularly on built heritage, allowing to reinstate the building to a previous condition. The aim is to not compromise future uses, and the possibility of the replacement of the current intervention in the future with more efficient and durable ones.

VF5. **Respect for the pre-existing building**, its history and original construction techniques.

Freitas' criteria can easily be mapped to Teixeira's criteria: VF3 and VF4 are identical to JT9 and JT7 respectively, VF2 maps to both JT5 and JT6, VF1 is related with JT2, lastly VF5 can be related with the ideas expressed in JT3 and JT9. Hence, there is a clear agreement in terms of approaches to the intervention on existing buildings by researchers in this area. Reversibility of interventions clearly points to the need of thinking in terms of interfaces between systems and their capacity for disassembly. Which combined with the visibility criteria (JT10) offers a resolution to the apparent contradiction between open building and building renovation experts regarding the evolution of the space plan building layers. Lastly, criterium JT11 emphasizes the need of user involvement in the design process, and if the tasks are small, in the construction also.

4.2 Open Building and Design for Disassembly criteria

The philosophy of open building evolved from John Habraken theories of the separation of support and infill, which already lays out some criteria for the design of industrialized construction systems, such as their separation by control and use life-cycle, the standardization of interfaces between technical systems instead of dimensions of the components (Habraken, 1992).

For Habraken, open building is a response to the need for flexibility in the built environment to accommodate changing user needs. The building is seen as a system whose parts must change at different rates depending on the levels of control. Habraken proposes the separation of the building into two layers, which he argues, is a strategy that is already present in vernacular construction (Habraken, 1992).

As discussed in Chapter 1, Duffy (1990) and Brand (1994) have independently argued for a division into an increased number of layers, related with the different functional systems of a building and their differing changing rates. Brand specifically considered a functional division into six layers, known as the six S's: Site, Structure, Skin, Services, Space plan and Stuff (Brand, 1994). These authors argue that there is a need for a greater differentiation in the layers of the building to respond to different use life-cycle of each system and its maintenance needs.

Crowther (1999a, 2001) proposed that the ideas of time-based building layers can have a major impact on the design and analysis of building deconstruction and be a key piece in a model of sustainable construction. He proposed the adoption of the concept of DfD in AEC as a strategy to achieve a circular economy in construction and defined design criteria to achieve it (Crowther, 2009a). Within this layers framework, partition walls are part of the space plan, which according to Crowther (2009a) is replaced every 3-10 years. Furthermore, these components represent 41% of the material inputs of all non-load bearing construction components over 60 years (Addis & Schouten, 2004).

Concurrently, Elma Durmisevic devised systematic methodologies to evaluate and design buildings and systems with increased capacity to change (Durmisevic, 2006b). Expanding on the work of Age van Randen since the foundation of the Open Building Network, she proposes that there is no fixed number of layers but instead these should be determined at the design stage depending on the use scenario, its functional decomposition, the durability of the selected materials, and the end-of-life scenario. Thus, the specification and arrangement of materials are the critical issue to achieve DfD.

Even if there is an increased initial cost to DfD systems, Durmisevic (2006a) demonstrates that these systems have significant economic advantages over the building lifetime and that partition walls in particular can have a large reuse potential. This high reuse potential is a result of the disproportion between the partition's technical service life (i.e., the durability of the materials, subassemblies, connections) and the use life-cycle of the spatial systems (i.e. the layout of the building).

4.2.1 Crowther DfD criteria

Crowther proposed DfD as a strategy to increase the rate of reuse of building materials in construction. This strategy implies implementing technological change at the design stage but this must be accompanied by cultural change (Crowther, 1999a). He identifies 4 possible routes for reuse in buildings: (1) reuse of the whole building in a different location; (2) reuse some components of the building in another building or in the same building in a different configuration; (3) reuse the materials and components in new products; and (4) recycling the materials into new materials. The environmental impact reduces as the level of reuse increases and there are different design criteria to achieve each of the levels of reuse (Crowther, 1999a).

Crowther proposes a set of design criteria for each level of reuse (Table 4-1) and recommends aiming at the highest level possible, because future reuse scenarios cannot be accurately foreseen (Crowther, 2009b, p. 229). To compile a list of criteria Crowther collected information from several sources such as: guidelines in DfD in Industrial Design; architectural technology experiments by authors such as Cedric Price, Habraken or the Japanese Metabolists and vernacular construction; research on buildability; research on building maintenance and research into deconstruction.

Table 4-1: Crowther design criteria for Design for Disassembly in AEC. Adapted from Crowther 2001; 2009.

	Criteria	**Material Recycling**	**Component remanufacture**	**Component reuse**	**Building relocation**
PC1	Use recycled and recyclable materials	◉	◉	.	.
PC2	Minimise the number of different types of material	◉	◉	.	.
PC3	Avoid toxic and hazardous materials	◉	◉	.	.
PC4	Avoid composite materials and make inseparable subassemblies from the same material	◉	◉	.	.
PC5	Avoid secondary finishes to materials	◉	◉	.	.
PC6	Provide identification of material types	◉	◉	.	.
PC7	Minimise the number of different types of components	.	○	◉	◉
PC8	Use mechanical not chemical connections	.	◉	◉	◉
PC9	Use an open building system not a closed one	.	.	◉	○
PC10	Use modular design	.	.	◉	○
PC11	Design to use common tools, equipment and builing practice	.	○	◉	◉
PC12	Separate the structure from the cladding and partition walls for parallel disassembly	.	.	◉	○
PC13	Provide access to all parts and connection points	○	○	◉	◉
PC14	Make components sized to suit the means of handling	.	○	◉	◉
PC15	Provide a means of handling and locating	.	.	◉	◉
PC16	Provide realistic tolerances for assembly and disassembly	.	.	◉	◉
PC17	Use a minimum number of connectors	.	○	◉	◉
PC18	Use a minimum number of different types of connectors	.	○	◉	◉
PC19	Design joints and components to withstand repeated use	.	.	◉	◉
PC20	Allow for parallel disassembly	○	○	◉	○
PC21	Provide identification of component type	.	○	◉	○
PC22	Use a standard structural grid for set outs	.	.	.	◉
PC23	Use prefabrication and mass production	.	.	◉	◉
PC24	Use lightweight materials and components	◉	◉	◉	◉
PC25	Identify points of disassembly	.	○	◉	◉
PC26	Provide spare parts and on site storage for during disassembly	.	.	.	◉
PC27	Sustain all information of component and materials	.	.	.	◉

Reuse of building components is the focus of this work, yet criteria for lower levels of reuse should also be considered, since these will necessarily be end-of-life scenarios eventually, e.g., criterium 1 using recycled and recyclable materials (Crowther, 2009b, p. 231). Furthermore, Crowther states that these principles are generic and should be adapted to the conditions of the project at hand, the evolving context of the industry, and, particularly when dealing with contradictory criteria, they should be considered in the larger framework of the conceptual model for sustainable construction (Kilbert, 1994).

After removing criteria that are not relevant to component reuse or any of the lower levels of reuse, a set of 24 criteria remain that are either highly relevant to component reuse or highly relevant to one or both previous levels.

4.2.2 Durmisevic DfD criteria

For Durmisevic the goal of sustainable design should be to *"design transformable building structures made of components assembled in a systematic order suitable for maintenance and replaceability of single parts"* (Durmisevic, 2006b, p. 86). Thus, DfD is placed as the key methodology by which sustainable design is achieved in its three dimensions of structural, spatial, and material circular transformation. Independence and exchangeability are the crucial design criteria that should be applied to all levels of the building.

The author claims that the concepts of exchangeability and independence are applicable at several levels: the building, system, and component levels. More specifically, while the use life-cycle of a given sub-system such as a façade may be 20 years, specific parts or materials may have shorter technical life-cycles that may require maintenance or replacement actions sooner. This implies a certain degree of recursiveness in the material independence logic as we descend the hierarchical dependency tree. While this process could lead to indefinite number of independent materials, ultimately design efforts should be concentrated on the systems and components that exhibit a large disproportion between their use life-cycle and their technical life-cycle (Durmisevic, 2006b).

To implement DfD in AEC, Durmisevic proposed a sequence of steps to identify opportunities for redesign: (1) Determine the long and short-term use scenarios for the building; (2) Identify the materials to be used to provide the desired functionalities; (3) determine which parts of the solution are sensitive for disassembly using a life-cycle coordination matrix; (4) establish the hierarchical tree of material levels determined by the frequency of change of each of the parts; (5) design or re-design the integration of parts with different use and technical life-cycles; and (6) evaluate the designed solution.

The above can be seen as a reconfiguration of the design process. Conventional design practice follows a top-down sequence of stages, starting at the higher more abstract level of the functional building configuration, ensuing to the technical composition of the system level, and finishing at the physical aspects of the component level. According to Durmisevic (Durmisevic, 2006b), an integrated DfD approach should consider the physical and technical domains right from the start.

Durmisevic design criteria are integrated in the larger scope of the previously described methodology and derived from the high-level criteria of independence and exchangeability. Instead of relating them with the reuse scenarios, Durmisevic organizes the criteria according to their relevance for the building, system, or material levels, for a given short- and long-term use scenarios (Durmisevic, 2006b). Within the context of this thesis, we are concerned with systems that have a shorter use life-cycle that their technical life-cycle, i.e., that are replaced before they are technically obsolescent. Thus, they have a high reuse potential if they are designed to be reused. Table 4-2 summarizes these criteria for the system and component levels.

Table 4-2: Durmisevic criteria for use life-cycle < technical life-cycle systems and components. Adapted from Durmisevic 2006.

	Criteria	System level	Material level
ED1	Develop life-cycle coordination matrix in order to define the point of disassembly	◉	
ED2	Design complex strutures which can change functionality in the course of time	◉	
ED3	Design base element as an intermedier between systems, components and elements	◉	◉
ED4	Design base element of each system and components	◉	
ED5	Optimize the strutural grid to materials in order to make the most efficient use of material properties and therefore use less material	◉	
ED6	Provide sufficient information about the building/systems configurations, ther reconfiguration possibilities and their capacity for reconfiguration, reuse, recycling	◉	◉
ED7	Define material levels following the functional decomposition	◉	
ED8	Cluster materials into subassemblies according to their functionality, use life cycle, material, technical life cycle.	◉	
ED9	Create separation between the elements with different functional and life cycle expectances by using separate construction systems	◉	
ED10	Define an open hierarchical structure by avoiding functional and assembly relations between different functional groups.	◉	
ED11	Design and open building system whose elements are independent and exchangeable	◉	
ED12	Use modular dimensional systems that are compatible with other systems	◉	
ED13	Base element / intermediary should be the most durable elements with the clusters	◉	◉
ED14	Use pre-assembled asemblies for faster and easier construction on the building site, and two-phase disassembly processes. (better material flow control)	◉	
ED15	Subdivide the building into sections that can be independently produced and assembled	◉	◉
ED16	Define building systems suitable for repetitive manufaturing processes while retaining variation and irregularity (MC)	◉	
ED17	Connections between independent clusters should be suitable for easy decomposition and reuse.	◉	◉
ED18	Use light weight components which are easy to handle and transport	◉	
ED19	Use small size components which are part of larger assembly in order to increase the possibility for variations	◉	
ED20	Design connections between changeable components to withstand multiple disassembly and reuse, by using well engineered base elements and intermediary between changeable components	◉	◉
ED21	Use minimum number of diferent types of fastners and connection geometries	◉	◉
ED22	Provide tolerances to allow disassembly of individual parts	◉	◉
ED23	Parallel assembly to allow disassembly of a single part or faster disassembly		◉
ED24	Keep all components separated avoiding penetration into other component or system		◉
ED25	Mechanical connections should replace chemical connections		◉
ED26	Provide intermediary between base elements which belong to diferent clusters		◉
ED27	The clusters should be assembled in a systematical order that is suitable for maintenance and replaceability		◉
ED28	Assembly sequences should be designed with respect to type of material, its performance and life-cycle		◉
ED29	The connections within the Cluster should be suitable for recovery or recycling of a single part		◉
ED30	Provide material information		◉
ED31	Avoid composite materials unless recyclable		◉

4.2.3 Reconciling Design for Disassembly guidelines

DfD authors have proposed largely coincident design guidelines, yet there are some divergencies in aspects such as the use of mass production, the way components and systems should be separated and the level to which functional independence should be applied.

Crowther's criterion PC23 specifically requires a "*system of mass production*". Crowther's view on modular standardization is further reinforced by a requirement of compatibility both at a functional and dimensional level (PC10 - (Crowther, 2009b, p. 232)). While Durmisevic also expresses a similar requirement (ED12), ED16 directs to a MCC system. In the context of building renovation, complete dimensional standardization is not possible, thus some level of dimensional flexibility will always be necessary. The key seems to be finding the appropriate balance between dimensional standardization and custom component dimensions.

Durmisevic extends the concept of functional and material independence to the material level. This requirement is not as clearly defined in Crowther's guidelines, which proposes that inseparable parts within components should be made of the same material (PC4). In the set of Durmisevic criteria that are not present in Crowther, the majority is related with strategies Durmisevic proposed to achieve such independence, specifically criteria ED1-4, ED7-8, ED13, ED26 and ED29. Both approaches are in fact complementary and should be selected taking into consideration which connections are site and factory (dis)assembled (ED14).

Yet, increasing material and functional independence has tradeoffs with some of Crowther criteria which are not foreseen by Durmisevic such as reducing material types (PC2), reducing number of different types of components (PC7), and number of connectors (PC17). Another criterion with tradeoffs which is foreseen by both authors is reducing types of connectors (PC18 / ED21).

Criteria ED19 and ED24 have no match with Crowther's criteria. ED24 is slightly related with the independence criteria but is more related with the ease and sequences of assembly and disassembly. D19 directly relates component size with flexibility for adaptation. Maximizing ED19 and making components as small as possible increases the number of reusable components of standard size. Yet, there is a possible tradeoff with ED5 since reducing the component size increases the proportion of production waste to finished component.

Beyond the previously identified criteria proposed by Crowther, there are 3 groups of criteria related with information (PC21 and PC25) practical issues (PC15, PC26 and PC11) and environmental issues (PC1, PC3, PC5), that have no direct equivalent in Durmisevic framework. The information criteria proposed by Crowther in PC27 are already wider in scope, requiring that information should be kept in a registry of assembly/disassembly sequences. PC21 extends the requirement to physical component identification that should ideally be electronically readable (Crowther, 2009b, p. 234).

Some criteria concerned with practical issues like PC26 and PC15 are already adopted in specific areas of construction practice, e.g., PC26 is frequently applied in practice for ceramic tiles. PC11, on the other hand is concerned with simplicity and compatibility of new systems with low-tech tools and standard building practices. Lastly, within the environmental group are included aspects such as favoring recyclable and recycled materials, avoiding toxic or hazardous materials, which are nowadays part of Life Cycle Assessment (LCA) methodologies and evaluation standards such as the EN 15804+A2 (Sustainability of Construction Works -

Environmental Product Declarations - Core Rules for the Product Category of Construction Products, 2019). PC5 can be mapped to Durmisevic material independence criteria.

4.3 Mass Customization Construction Criteria

MC is a *"strategy that creates value by some form of company-customer interaction at the fabrication/assembly stage of the operations level to create customized products with production cost and monetary price similar to those of mass-produced products."* (Kaplan & Haenlein, 2006, p. 176). This interaction is concentrated on the manufacturing point of a product life-cycle, more specifically at its fabrication or assembly stage. To do this, manufacturers relegate design control and consequently some fabrication control over the product. In practice, it has been achieved by product modularization, which allows some level of interchangeability of the product parts.

The product is no longer an indivisible whole but an assembly of independent components that can be swapped at the assembly stage or customized at the fabrication stage to meet user requirements. Thus, interchangeability and modularity of components are important criteria to develop MCC systems. This was immediately understood by some of the pioneers of MCC, such as Kent Larson (2000) or Kieran and Timberlake (2003) which defined criteria that construction systems and production processes should have to be mass-customizable.

4.3.1 Modularity in product systems

Modularity as understood by researchers in MC does not necessarily imply component dimensional and formal standardization. But it has been demonstrated that there is a connection between higher component standardization and higher production efficiency even in mass customizers (Duray et al., 2000). Conversely, interchangeability does imply standardization of connections or interfaces, both dimensionally and formally. Components will need to share matching features to be combined in different configurations. Higher interchangeability implies that a given component may be replaced or connected with a higher number of other components. Similarly, higher modularity is related with higher recombination capacity (Schilling, 2000).

In fact, the concept of modularity is used across many different fields with slightly different meanings (Salvador, 2007), so a rigorous definition of the meaning of modularity in MC is needed. Salvador addressed this issue and proposed that modularity is a property of products systems and not of a specific product (2007, p. 226), and thus is related with the capacity to differentiate products by reconfiguring them.

A module is then a part assembly or a singular component that can be either assembled or fabricated first and independently of the product instance. Consequently, a module is by definition separable (2007, p. 226) and for Salvador this also extends to the possibility of disassembly. *Component separability* is a property of a modular system whose degree is related with the ease of assembly/disassembly.

But component separability is not sufficient to define a module of a system since to form a stable assembly it must have some form of establishing a connection with other components of the system. A second property of a modular system is *component combinability* which is maximized if (1) each of the modules is interchangeable with any other module of the system; and (2) each module is a stand-alone version of the product (Salvador, 2007, p. 226). This leads to the definition of modularity in terms of component separability and combinability:

"In the domain of tangible, assembled artifacts a product system is modular to the extent that its separable components, or modules, are combinable." (Salvador, 2007, p. 229).

Component combinability involves the concepts of interface standardization and packaged function binding. As previously stated, a component is only "*connectable*" with another if they share a common physical interface, but this requirement is not sufficient. They must also share a common agreement on the set of functions each component performs. This problem is frequently solved by matching interface standards with specific sets of functions (Salvador, 2007, p. 232).

Lastly, Salvador still admits the possibility of "*weak modularity"* for product systems that have common components, usually referred to in the literature as component commonality (i.e.(Ulrich & Tung, 1991)), but these cannot be easily disassembled (Salvador, 2007, p. 233). This is the case when two components are glued together, or in construction, when tiles or bricks are laid using mortar. The original components have a very high degree of commonality (and combinability) but are no longer separable after they are assembled without damaging or destroying the component.

4.3.2 Kent Larson Criteria

Kent Larson is one of the first authors to propose that MCC may be an appropriate paradigm to address the challenges of productivity, quality, and user choice in building construction (Larson, 2000). At the MIT, he was the principal investigator of the House_n research consortium, during which he published a series of position articles defining principles and methods for mass customization of housing (Larson, 2000; Larson et al., 2001, 2004). In these articles, he proposes a systemic view of the building as a set of subsystems or components that are connected to a common platform and between themselves (Larson et al., 2004, pp. 188, 199). The separation of chassis and infill approach closely follows Habraken's proposals of the separation of support and infill (Habraken, 1972) and of industrialized construction (Habraken, 2003).

Larson and his team propose a "*standardized platform*", the chassis, and a user customizable infill which connects "*in standard ways to the chassis*" (Larson et al., 2004, p. 188). These interfaces or joints of component-to-component and chassis-to-component should have industry wide acceptance (Larson et al., 2004, p. 190). In the spirit of open-source, designers and engineers across organizations and countries should *"share knowledge and details and agree on common design rules"* (Larson et al., 2004, p. 189).

The above criteria are achieved by "*principles of modularity (where interface between systems are standardized)*" (Larson et al., 2004, p. 198) and *automation of fabrication processes* that seeks to address *"a shortage of skilled construction labour"* (Larson et al., 2004, p. 189). Both criteria would also allow for "*tighter tolerances* and *faster onsite assembly"* processes, further minimizing field labour (Larson et al., 2004, p. 189).

They recognize a balance must be established between *integration of several functions* in a module (Larson et al., 2004, p. 189) and *disentanglement of systems* to facilitate change "*during design or use without affecting the performance of the larger system.*" (Larson et al., 2004, p. 188). Other identified criteria are the need for *customization* and "*to efficiently accommodate new technologies and change over time"* (Larson et al., 2004, p. 188).

KL1. Separation of chassis and infill (Larson et al., 2001, 2004)
KL2. Customization of infill / Standardization of platform (Larson et al., 2004, p. 188)
KL3. Interoperable components across manufacturers (Larson et al., 2004, p. 188)
KL4. Standardized connections component-to-component and chassis-to-components (Larson et al., 2004, p. 190)
KL5. Open-source (Larson et al., 2004, p. 189)
KL6. Disentanglement of systems and components (Larson et al., 2004, p. 188)
KL7. Flexibility - provide the possibility to upgrade (Larson et al., 2004, p. 188)
KL8. Speed up onsite assembly by minimizing field labour: (Larson et al., 2004, p. 188) (Larson et al., 2004, p. 189)
KL9. Modularity (Larson et al., 2004, p. 198)
KL10. Automated fabrication processes: (Larson et al., 2004, p. 198)
KL11. Integration of several functions in one module: (Larson et al., 2004, p. 189)

4.3.3 Kieran Timberlake Criteria

Stephan Kieran and James Timberlake book Refabricating Architecture (2003) can be read as a manifesto for a more customizable and industrialized architecture, that departs from the Modern Movement view of mass production. The book lays out principles, criteria and methods that would allow the implementation of MCC in a quasi-propagandistic way, frequently drawing comparisons with the design and production methodologies adopted in car, computer, aviation, or shipbuilding industries.

A core design task for these authors is to reduce the complexity of the on-site assembly by aggregating parts into preassembled modules. This would serve the purpose of achieving *"higher quality, better features, less time to fabricate, and lower cost: more art and craft, not less."* (Kieran & Timberlake, 2003, p. 79).

The previous design challenge requires a clear subdivision of the building into modules**.** Working with a modular system requires a framework for understanding the whole and this is "*the originating act of the design process*" (Kieran & Timberlake, 2003, p. 64). Digital technologies allow the coordination of these efforts across teams that may then focus on designing specific modules, it would also allow the possibility of simultaneous production of the modules, a process that the authors compare to quilting (Kieran & Timberlake, 2003, p. 56).

The key criteria to consider in deciding how to divide the building into modules are exchangeability (Kieran & Timberlake, 2003, p. 77)*,* that must be provided where there are: (1) "*difference[s] in life cycles in construction and technology, between dumb and smart"* (Kieran & Timberlake, 2003, p. 77)*;* (2) reduce the number of components for final assembly at the site (Kieran & Timberlake, 2003, p. 47)*;* **(**3) reduce number of joints or interfaces, which will provide "*more precise tolerances and better working conditions with less accumulation of parts in the final assembly area"* (Kieran & Timberlake, 2003, p. 87); and (4) non-linear assembly (Kieran & Timberlake, 2003, p. 75).

For these authors the purpose of modular joining is manufacturing efficiency, dependent on **"***geography, on the location of the plant where the materials are actually joined"* (Kieran & Timberlake, 2003, p. 93), more than to reduce the number of parts in a module. Yet, they consider that there is also the opportunity to redesign these modules into monolithic components, thereby reducing weight and number of parts (Kieran & Timberlake, 2003, p. 80).

Another important criterion when considering the subdivision into modules is integration of functions, instead of dividing the modules according to trades and functions (Kieran & Timberlake, 2003, p. 91).

This modular logic operates at several nested levels which in turn implies that there are different types of joints depending on where these modules are assembled, the authors speak of connection and system joints (Kieran & Timberlake, 2003, p. 101).

KT1. **Reduce the number of parts per module by redesigning them into monolithic elements** (Kieran & Timberlake, 2003, p. 80)
KT2. **Exchangeability** (Kieran & Timberlake, 2003, p. 77)
KT3. **Modules defined by life-cycle** (Kieran & Timberlake, 2003, p. 77)
KT4. **Reduce the number of components:** (Kieran & Timberlake, 2003, p. 47) (Kieran & Timberlake, 2003, p. 96)
KT5. **Reduce number of joints or interfaces** (Kieran & Timberlake, 2003, p. 87)
KT6. **Modularity for manufacturing efficiency** (Kieran & Timberlake, 2003, p. 93)
KT7. **Non-linear assembly** (Kieran & Timberlake, 2003, p. 75)
KT8. **Simultaneous production of components** (Kieran & Timberlake, 2003, p. 56)
KT9. **Integrate functions** (Kieran & Timberlake, 2003, p. 91)
KT10. **Site and factory joints** (Kieran & Timberlake, 2003, p. 101)

4.3.4 Merging Mass Customization Construction criteria

MCC enables the possibility of delivering customized solutions to specific contexts efficiently. Its authors also have a large set of overlapping criteria. Integrating several functions within one module is discussed by both authors (KT9, KL11), as is its' tradeoff criteria of disentangling systems (KT3, KL6) for exchangeability in design, production, and future change (KT2, KL7). Separation of chassis/infill (KL1), interoperable component across manufacturers (KL3), standardized interfaces (KL4), open-source (KL5) and modularity (KL9) can be considered strategies to achieve exchangeability (KT2). Likewise, reducing the number of components (KT4) and interfaces (KT5), and defining site and factory joints (KT10) and non-linear assembly sequences are all strategies to minimize field labor (KL8).

Although the concepts of open-source (KL5) and chassis-infill (KL2) are not explicitly discussed by Kieran and Timberlake as a criterion, there really is no disagreement since open-source for Larson is limited to the interface and chassis standards. Shared interface standards are also discussed by Kieran and Timberlake, but instead of the chassis and infill approach, they discuss several different strategies present in different industries to divide the products into modules, e.g., “*grand blocks*” or “*smart modules*” of the shipbuilding industry.

The term *module* is sparingly used by Larson and strictly to signify spatial structural units, which is more in line with the conventional meaning within architectural circles (Rocha et al., 2015). The term *component* is interchangeably used with module and is also used to signify either complex assemblies of parts or the parts themselves. Kieran and Timberlake mostly use the term module for the latter meaning, while the expression "*grand blocks*" is used to signify large building components which offer support for "*smart modules*". Thus, while the terms are different the concepts behind them are the same.

The fundamental difference between both authors lies in how the decision on the modular framework is made. For Larson this something that is arrived at by industry consensus, while for Kieran and Timberlake this is something that the "*tier 1*" product manufacturer can decide.

4.4 Negotiating criteria for customizable and disassemble able partition wall systems

In the previous sections we reviewed the criteria that have been proposed by different authors in different research areas, and which represent a summary of different approaches to the problem we set out to address. Clearly there are multiple points of contact between these several views which are immediately evident. In this sub-chapter we analyze and reconcile the differing perspectives and propose a preliminary synthesis of criteria.

4.4.1 Partition Wall Systems

Interior partition walls are one of the building sub-systems that is part of the space plan level. Yet, partition wall systems perform several functions within a building and there are different construction systems available in the market used both for interior and exterior enclosure. It is thus necessary to clarify the functional and technical characteristics that are specific of interior partition walls to be able to arrive at criteria for customizable and disassemble-able partition wall systems.

There are several approaches, with various detail and complexity, to organize and subdivide the building into systems, components, and parts. ISO 12006-2 provides a framework for classification systems for the built environment which have been adopted by several classification systems, e.g. OmniClass or UniClass. The OmniClass 2012 classification system provides an elements functional classification table which is sufficiently detailed and congruent with the layers subdivision logic proposed by Brand (Figure 4-1). An element is considered a "*major component, assembly or construction entity part which, in itself or in combination with other parts, fulfills a predominant function of the construction entity.*" (ISO 12006-2:2015, 2015)

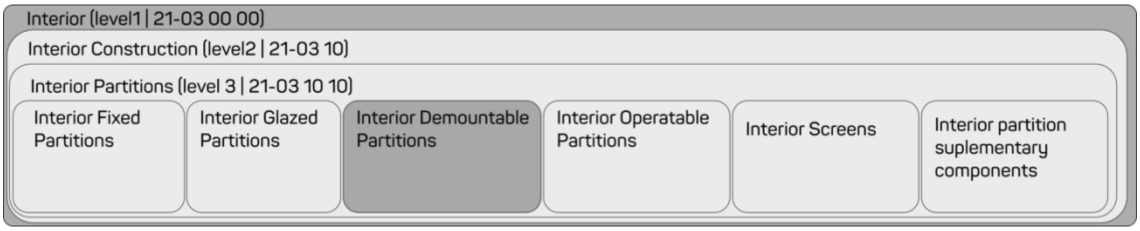

Figure 4-1: Partition wall functional element classification OmniClass 2012 table 21

Partition walls are part of the interior (level 1), interior construction sub-group (level 2), interiors partitions (level 3). The level 4 further disaggregates interior partitions into: interior fixed partitions, interior glazed partitions, interior demountable partitions, interior operatable partitions, interior screens, and interior partition supplementary components. The wall finishes are not included in the interior construction group (level 2) but on the interior finishes group, wall finishes (level3).

From the above classifications is possible to define in general terms the three main interfaces of a partition system: (1) the building structure, either on the floor, ceiling, or walls; (2) the external envelope; and (3) the internal finishes of the walls.

The above classification strictly positions the interior partition walls as non-loadbearing elements and identifies the locus of disassemble-able walls in its level 4, yet it does not clarify the basis for the functional distinction between the types of level 4. Faria (1996) provides a functional classification of non-loadbearing partitions considering the use of partitions (Figure 4-2).

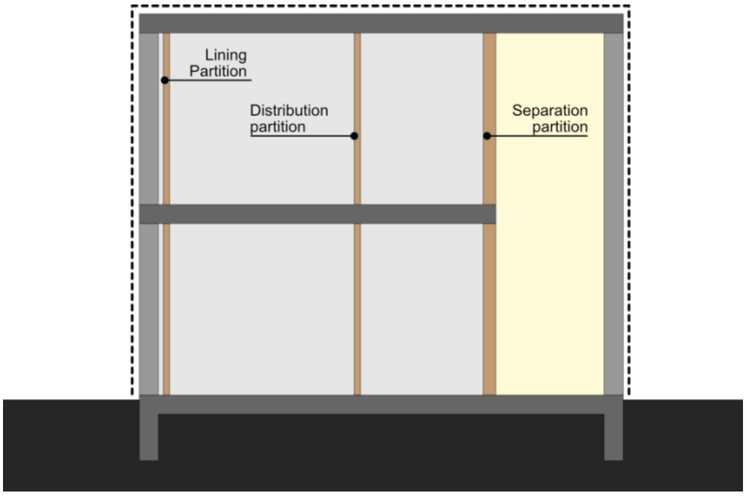

Figure 4-2: Functional classification of non-loadbearing interior partition wall systems

Separation partitions divide different building functional areas, e.g., different apartments or private and common areas. Distribution partitions divide a specific functional area into several rooms and lining partitions duplicate external walls. Separation partitions are less likely to change since they are the frontier between different owners or levels of control within a specific building and correlate with a legal property status. Conversely, lining and distribution partitions are only subject to the control of the unit owner and thus more likely to change. Hence, disassemble-able partition systems are particularly suitable for these types of functions.

Although lining partitions can be considered part of the group of non-loadbearing partition systems, it is important to note that these walls have implications on the performance of the exterior envelope and are thus frequently studied in conjunction with external enclosure walls.

A functional classification is useful to characterize the scope of application but does not provide information on the tectonic logic of the partition walls systems. To this end, Faria (1996) proposed a classification based on groups of solutions by tectonic processes divided into 3 main groups: Traditional wood frame partitions; Masonry partitions, light prefabricated partitions (Figure 4-3).

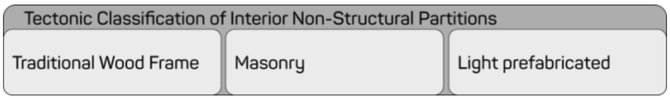

Figure 4-3: Tectonic classification of non-loadbearing interior partition wall systems. Adapted from Faria (1996)

The first group contains all traditional types of on-site assembled partitions such as those traditionally used in 19th century Porto townhouse or the light-wood frame partitions common in North American countries. The second group contains all wall systems composed of unit masonry elements whatever the material type. This class contains hollow ceramic brick walls which are still the most prevalent partition wall system in Portugal. Lastly, the light prefabricated category includes all other types of industrialized partition systems, independently of their disassemble-ability, including those that are digitally fabricated.

For each of these groups, Faria proposes a specific classification based on tectonic criteria mapped to specific solutions. Hence there is a loose relation between the criteria used to classify each group, but the classification is useful for designers to evaluate the range of available solutions in a design process. Considering the scope of the present work, only the latter group is presented (Figure 4-4).

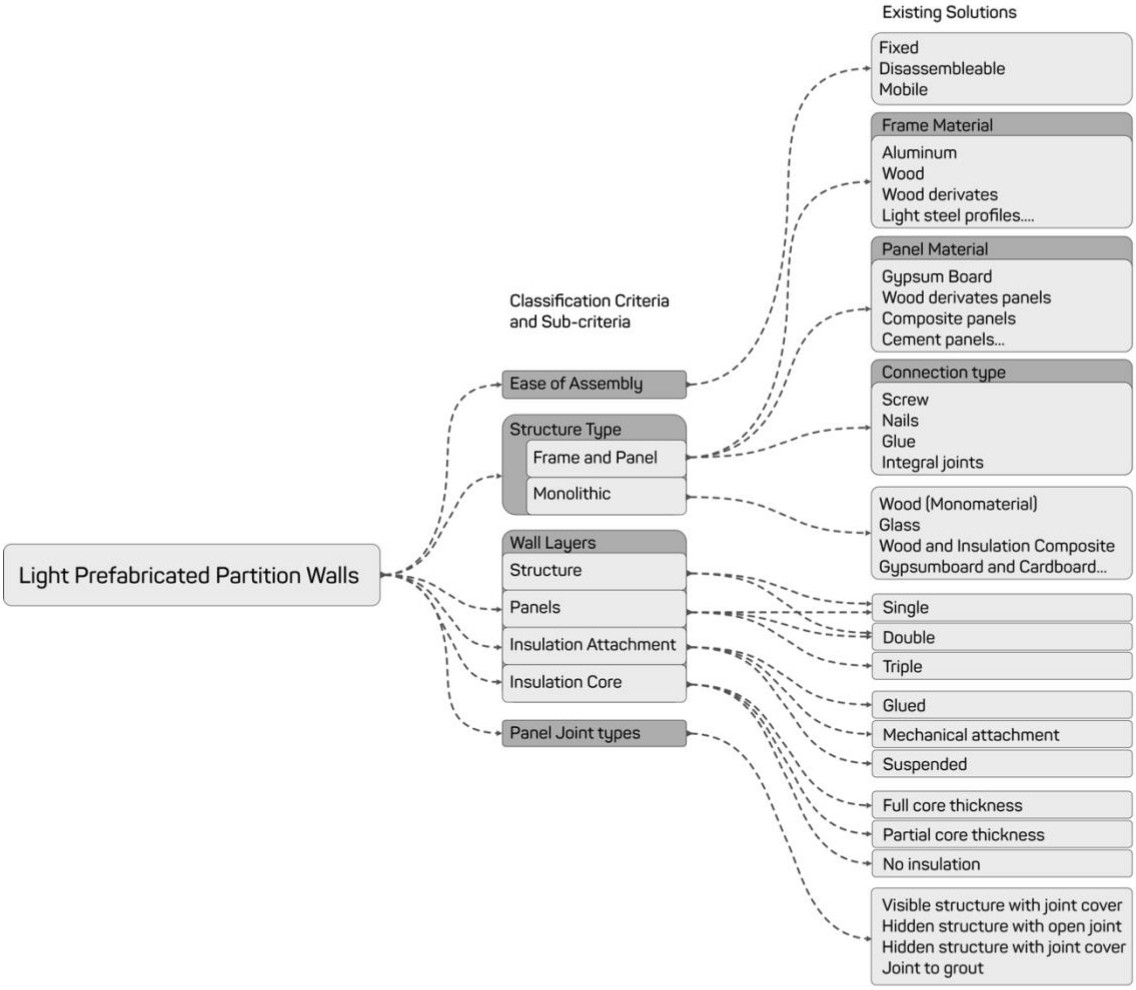

Figure 4-4: Classification of non-loadbearing interior partition light prefabricated wall systems. Adapted from Faria (1996)

Faria selects four main criteria to classify partition walls: Ease of assembly and disassembly, types of joints between panels, structure type, and wall layer. The latter two categories are subdivided into sub-categories related with the tectonic decomposition of the solutions into layers for each specific function and the type of structural solution.

The ease of assembly category is the critical aspect for disassemble-able systems. The partition systems are subdivided according to the degree they are demountable without damage to the interfaces[22]. The fixed category includes solutions that cannot be disassembled without significant damage to the partition materials or the supporting structure. Conventional light steel frame solutions are included in this group.

The disassemble-able category includes all solutions that are demountable with negligible damage[23] to the support and whose components can be reused in new configurations. The

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[22] Faria subdivides the solutions according to 4 categories, fixed, demountable, relocatable, and mobile, yet the difference between demountable and relocatable solutions is purely one of degree of reusability of constituent elements.

[23] Damage such as screw/nail holes is admissible as negligible.

degree of reusability is related with the durability of the constituent materials, connection types between the components and parts, and modularity. Lastly, the mobile category includes operatable partitions by means of rails or hinges. Both fixed and mobile partitions are outside the scope of the present research.

Disassemble able partitions may exist in any combination of the remaining criteria which constitutes a significantly large number of cases. The reader is directed to Faria (1996) which provides a sufficiently detailed collection of solutions for each criterion.

4.4.1.1 Regulatory Requirements and Guidelines

The performance requirements for building materials and products at the European level are defined by standards issued by the European Committee for Standardization (CEN) and guidelines defined by European Organization for Technical Approvals (EOTA). According to EU Regulation nº305/2011 (Construction Products Regulation, 2011), if a construction product is subject to European norms or tested according to a European technical guideline it must bear the CE marking, it is not required to be subject to further national approvals and can be marketed across the European single market.

EU countries are still responsible to establish their own standards and regulations regarding fire safety, mechanical resistance, stability, environmental, and energy performance applicable to construction works.

Products and materials that are covered by CEN standards, must be tested according to the relevant norm, which sets methods and criteria for assessing and describing the performance, to obtain a Declaration of Performance, and have compulsory CE marking.

Some construction products that are considered innovative, such as internal partition walls, have non-compulsory CE marking. These products can still obtain CE marking by testing if they are covered by an existing European assessment document.

ETAG003 (EOTA, 2012) is a guideline for European technical approval for internal partition non-loadbearing walls. It defines a set of requirements and the respective standard testing methodology and technical evaluation criteria to access the performance of partition walls. In March 2019, ETAG003 was replaced by EAD 210005-00-0505 (EOTA, 2019) which reorganized the classification of the requirements, merging the safety in use and durability and serviceability into a single category called Safety and Accessibility in Use. For briefness, Table 4-3 presents the requirements of the latest technical assessment guideline. These technical guidelines already are sound benchmarks for the structural, acoustic, thermal, hygrometric, and fire safety performance of partition walls. Yet, it is important to detail these aspects for an overall definition of criteria.

Table 4-3: Essential characteristics of the product's performance

Requirements	EAD 210005-00-0505		
Safety and Accessibility in Use	Resistance to damage and functional failure from horizontal loads		EAD -S1
	Safety agains personal injuries by contact		EAD -S2
	Resistance to damage and functional failure from eccentric vertical loads		EAD -S3
	Resistance to horizontal linear static loads		EAD -S4
	Resistance to functional failure from point loads parallel or perpendicular to the surface		EAD -S5
	Rigidity of partitions to be used as substrate for ceramic tiling		EAD -S6
	Resistance to deterioration	Physical agents	EAD -S7
		Chemical agents	EAD -S8
		Biological agents	EAD -S9
Fire safety	Reaction to fire		EAD -F1
	Fire resistance		EAD -F2
Hygiene, health and environment	Release of dangerous substances		EAD -H1
	Water vapour permeability		EAD -H2
Accoustic	Airborne sound insulation		EAD -A1
	Sound absorption		EAD -A2
Thermal	Thermal resistance		EAD -T1
	Thermal inertia		EAD -T2

The scope of the guidelines covers partitions walls of several types: frame and panel or composite panels walls, that are fully opaque, partially, or totally glazed. The function of the partition is the separation of interior spaces of a given functional unit, with or without fire safety, and/or acoustic insulation, and/or thermal capabilities. Included in the previous definition of the functions are the cases where a partition serves as a lining to interior or exterior walls or it separates spaces with different floor levels (EOTA, 2019, p. 4).

The guideline defines methods and criteria for testing and assessing the performance of the product for each of the identified characteristics. The compliance with safety against personal injuries by contact is verified by visual inspection of the geometry of the wall, the absence of sharp or cutting edges, and tactile inspection to determine the risk of abrasion. Water vapour permeability may be either tested, deduced from tabulated values, or taken from component specifications of the Declaration of Performance. Thermal inertia and reaction to fire performance are determined from the specific properties of the systems' materials. The remaining safety, fire safety, acoustic, release of dangerous substances, and thermal resistance requirements are tested using experimental methods.

It is the responsibility of the manufacturer of the partitions to define the scope of application of the partitions and promote the certification process. The testing may only be conducted by certified bodies, accredited by EOTA.

Since, thermal, acoustic, and fire safety characteristics are optional the critical design requirements are Safety in use and Hygiene. At the design stage the fulfillment of hygiene requirements may be foreseen if standard materials which have been subject to approval and normalized testing for application in construction, such as plywood, MDF or cork, are used.

On the other hand, the verification of compliance at the design stage for safety and static performance requirements must be done by simulating the behavior of the designed system according to the testing setup defined in the technical guidelines.

The partitions we are considering are, for the purposes of the guidelines, classified as non-loadbearing, relocatable, solid partitions. Non-loadbearing means that these walls do not transfer forces imposed by the structure and as such its contribution to the overall building stability is not considered. Relocatable means that they can be installed and reinstalled with minimal damage to the structure or itself. Lastly, the walls panels are opaque. These partitions are destined to use category A of Eurocode 1, which are areas for domestic or residential activities where users are expected to have a high incentive to exercise care.

4.4.2 Modularity vs Independence

Modularity means different things to different authors in three crucial aspects: function binding, i.e., each product function is mapped to a specific part or module in the system, material independence, and dimensional standardization.

For Salvador, a module may be an assembly of inseparable parts or materials as expressed by his definition of modularity. Yet, Salvador is merely concerned with the definition of the concept and makes no claims regarding the level of subdivision a product must contain. For Kieran and Timberlake modules are equivalent to "*fully assembled collections of parts*" (Kieran & Timberlake, 2003, p. 63) that are necessarily separable for assembly and disassembly purposes. Thus, Kieran and Timberlake (KT) parts are equivalent to Salvador's modules, or conversely KT modules are in fact bundles of smaller modules nested inside.

Similarly, the idea of 1:1 mapping of functions and modules, or parts, is not something that Salvador considers a necessary pre-condition for modularity (Salvador, 2007, p. 231). If we consider Kieran Timberlake "*nested modules*" and KT1 design criterium, then Kieran Timberlake agrees with Salvador. Likewise, KL11 and PC4 points to a similar understanding by Larson and Crowther. On the other hand, Durmisevic states that to increase the capacity for change, each material component must map to a specific function within the system. Furthermore, each material component must be separable. Thus, in Salvador's terms, Durmisevic understands that each material component must be a module, and this is a crucial pre-condition for decoupling systems and allowing for maintenance.

In Durmisevic terms, a module is a cluster of materials determined by the cluster functionality and hierarchically organized according to use and technical life cycles of each of its parts. Thus, another way to understand Durmisevic criteria is that material and functional independence of parts is an environmental requirement that must be extended into each module, such that all materials are fully recoverable (Durmisevic, 2006b, p. 169). Consequently, Durmisevic independence goes beyond a merely practical requirement of flexibility either in manufacturing, use or reuse.

Lastly, dimensional standardization is important for DfD proponents for similar reasons: the reduction of material waste in the production process that necessarily leads to a maximization of the use of standard materials sizes or integer subdivisions thereof (ED5, PC22), which is further reinforced by the recommendation of using compatible dimensional modular systems (ED12, PC10). Conversely, ED16 points to an acceptance of the need for flexibility in dimensional standardization to accommodate variation and irregularity while Crowther with PC23 suggests mass production and prefabrication should be used to reduce site work, improve component quality and conformity. While KT or KL would not necessarily disagree with the objective of PC23 design guideline, or the use of pre-fabrication, clearly, they disagree with the use of mass production in as much as it dictates a reduction of choice for the end-user.

All the previously presented divergencies relate in one way or another with the concept of modularity, the definition of what is a module and at what scale there should be modularity. Yet, module is a scaleless concept that may be applied to very complex assembled components of a larger system or its smallest parts, i.e., it is a property of that level and not the classification of a specific level within the technical arrangement of a building.

As an example, consider the layer decomposition of buildings proposed by Durmisevic presented in Figure 4-5. The building is divided into several levels, each nested in the previous one: Building (System)> Sub-system > Component > Materials. At each of the levels there may be one or more product systems that may exhibit modularity. Focusing on a specific product system at the sub-system level, such as partition walls, we may see that the system is decomposable into parts, e.g., studs, panels, and screws. Each of the parts of the wall system is a module if it is separable, including demountable after construction, and combinable with other modules of the wall product system to produce different versions of the wall.

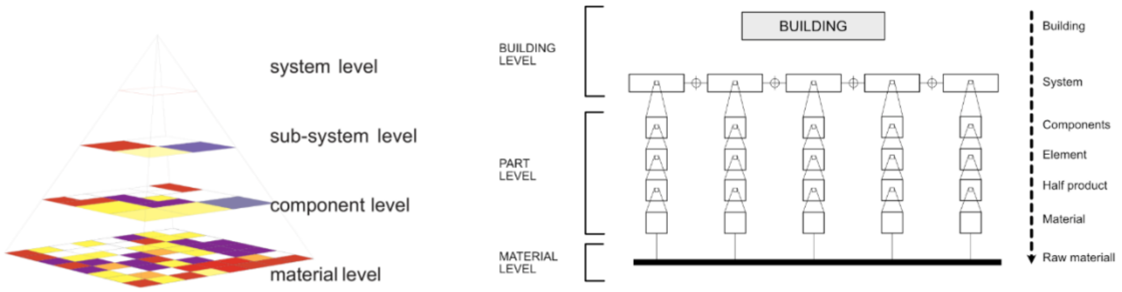

Figure 4-5: (Left) Hierarchy of material levels in building. Systems approach to the building (Right) Systematic integration of material levels in the building

If in the wall product system there is an electrical socket that meets the previous requirements for modularity, then the socket is a module, even if the module "electrical socket" may be separated into smaller constituent parts which may themselves be modules or not. In fact, from the point of view of the wall product system, if the module wall plug is only offered in one variant, it does not matter if the module wall plug is decomposable or not because it will be equally separable and combinable.

Thus, from the above follows that material and functional independence are different concepts than component combinability and separability and consequently modularity. Durmisevic's exchangeability is equivalent to modularity as defined by Salvador.

4.4.3 Limits of Independence

Since a building is an assembly of product systems which themselves may in turn embed components which are part of other product systems, it follows that there are necessarily modules that imbed several functions. Durmisevic proposed that all modules should be decomposable into independent parts which are made of a single material and perform a specific function. Figure 4-6 illustrates the concept of functional and material independence in external wall systems. Yet, it is important to note that functions are not easy to be defined unambiguously (Salvador, 2007). Functions may by defined with different levels of detail, may be time-dependent, and contextual.

Each of the functions presented in Figure 4-6 may be further decomposed into other functions and not all are necessarily technical, e.g., insulating may be divided into acoustic and thermal, or finishing can be divided into watertightness, impact protection, architectural character. Other functional requirements for walls, which are not considered in the example, may also be hard to apply to any of the material elements of the wall because they are the result of multiple layers or the whole solution, e.g., thermal mass.

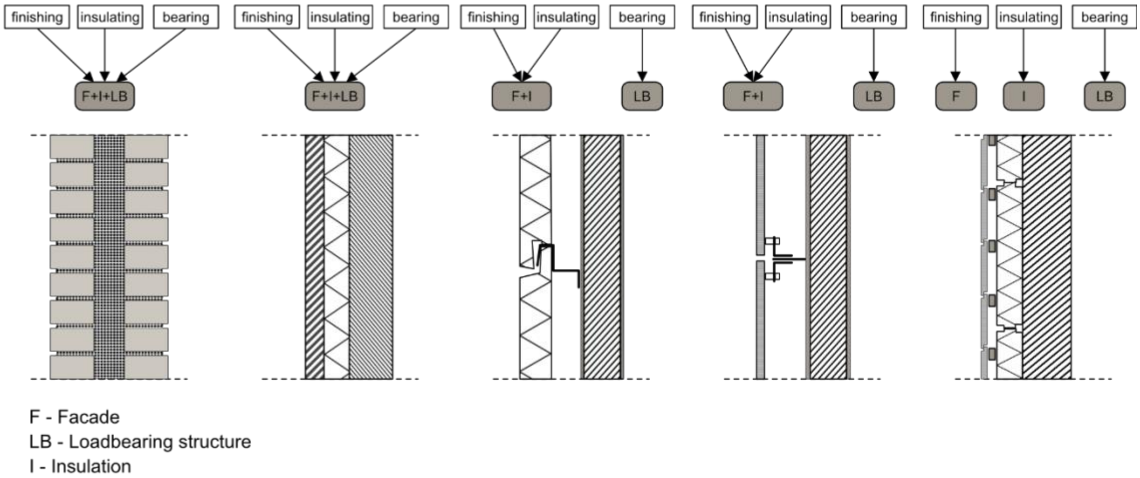

Figure 4-6: Integration of functions in external wall systems. Adapted from Durmisevic 2006, p 164

While most of the previous subfunctions could be mapped to specific layers of the wall, doing so could result in an excessively complex building system to be assembled onsite, making it impractical to build and maintain. Therefore, Durmisevic proposes that materials and functions should be clustered according to their use and technical life cycle. Thus, it is only reasonable to desegregate functions that cannot be performed by the same material in a co-variant way through its use and functional life cycle. Similarly functional independence is maintained by a cluster (or module) that aggregates functions iff all functions are co-variant.

The limits of material independence are related with the capacity of a given composite for reuse, recycling, or composting. Thus, composite materials like plywood, which can be processed with similar procedures as wood (McMahon et al., 2008; Sassi, 2008), meet the criteria for material independence although the material is made of several glued layers of natural wood. Yet, from an environmental standpoint is still arguable that using materials closer to their raw condition is preferable since it directly leads to less industrial transformations processes (Self, 2017). Nevertheless, is also true that engineered wood materials make use of a larger portion of the raw material. This results in materials that are mechanically more efficient which directly leads to less material use.

Nevertheless, the aim should always be to increase the number of materials that can be used in infinite loops (Sassi, 2008). Thus, this leads to two independent design challenges: (1) designing building systems that increase the reuse capacity; and (2) designing with reclaimed materials. In this thesis we focus on the first one.

Despite specific disagreements between the several areas presented there are large overlaps. A preliminary classification of design guidelines/criteria proposed in the literature into a framework organized into five groups is presented in Table 4-4. Each of the five categories, Environmental criteria, (Dis)Assembleability criteria, Flexibility criteria, Performance criteria, and Cost criteria, is further divided into subcategories of criteria.

Table 4-4: Mapping of literature design guidelines/ criteria to a Criteria Framework for Mass-customizable partition walls systems

Criteria		Subcriteria	Design Guidelines/Criteria
Environmental	ER	Renewable/recyclable materials	PC1, PC3, JT9, VF3
	EIM	Independence - material	PC4, PC5, ED24, ED25, ED29, ED31, KL1, JT7, VF4
	EIF	Independence - functional	ED7, ED8, ED9, KL1, KL6, KL7, KT3, JT7, VF4
	EEC	Low embedded carbon and energy	PC24, PC22, ED5
Assembleability	AS	Simplicity	PC2, PC17, PC18, PC23, ED10, ED14, KL8, KL10, KT4, KT5
	AP	Praticality	PC11, PC12, PC14, PC15, PC16, PC20, PC24, ED10, ED15, ED18, ED22, ED23, ED27, KT7
	AC	Comunication	PC6, PC21, PC27, ED6, ED30, JT1, JT12
Flexibility	FG	Geometric flexibility	ED16, ED19, JT3
	FS	Services integration	KL6, KL11, KT1, KT9
	FMS	Modularity - Separability	PC8, PC13, ED17, ED25, KL1, KL7, KL9, KT2, JT7, VF4
	FMC	Modularity - Combinability	PC7, PC9, PC10, PC18, PC22, ED9, ED11, ED12, ED21, KL3, KL4, KL9
	FP	Personalization	KL2, KL5, JT4, JT9, JT10, JT11, EAD-S6
Performance	PA	Acustic comfort	JT5, JT6, VF2, EAD-A1/2
	PS	Safety and Acessibility in use	JT5, EAD-S1-9
	PJ	Joint durability	PC19, ED20
	PT	Thermal confort	JT5, JT6, EAD-T1/2
	PH	Hygiene, health and environment	JT5, EAD-H1/2
	PF	Fire safety	JT5, JT6, EAD-F1/2
Cost	CI	Initial cost	
	CR	Reuse cost	

Environmental criteria are related with the potential environmental burdens of the system and used materials (ER and EEC), but also on specific system properties that foster and enable reuse or recycling of the system materials (EIM and EIF) but not its components. Using natural and renewable materials is only explicitly part of Crowther recommendations. Yet, using materials which can form infinite loops is considered a critical criteria towards sustainable construction and DfD (Sassi, 2008). Teixeira indirectly suggests the same in JT9, since most traditional construction systems are built with renewable materials, such as wood, and thus are compatible. Similarly, design criteria that map to reducing embedded carbon and energy are few and indirect as a cause of reducing fabrication waste and using lightweight materials (Mateus et al., 2013).

Most of the guidelines that map to the environmental criteria are about material independence either at a physical or functional level, which all authors relate to larger capacity for life-cycle adaptation or reversibility. Material independence (EIM) attempts to reply to the question: are all parts made of a single material or a composite of materials that is circular? While functional independence (EIF) answers the question: are the functions of each part co-variant?

Assembleability criteria are associated with the ease of assembly and disassembly of systems and components. The abundance of design guidelines that map to this group of criteria indicate that these are crucial aspects of DfD. In fact, Crowther (2009b) states that aspects such as communication, simplicity and practicality are as important to assembly as they are for disassembly.

Simplicity (AS) can be understood as minimization of the number and complexity of assembly operations onsite, to which aspects such as reducing the number of different materials, components, connectors, and types of connectors heavily contribute (PC2, PC17, PC18, KL8, KT4, KT5). Clustering parts into pre-assembled components (ED14), also mentioned by Kieran and Timberlake (KT10), also contributes to this aim. Indirectly contributing to the minimization of onsite operations are design guidelines that suggest the use of open hierarchical structures (ED10).

Simplicity achieved by proprietary means will make repairing, reusing and deconstruction harder in the long term (PC11). Also, walls with equal number of onsite assembly operations may have linear or non-linear assembly sequences. Clearly, a wall that can be non-linearly assembled can be locally deconstructed (PC12, PC20, ED23, ED27, KT7). Practicality (AP) measures operational aspects in assembly and disassembly process. It is the sub criteria with the largest set of design guidelines or criteria in the literature: (1) non-linear assembly (PC12, PC20, ED23, ED27, KT7) (2) simple tools (PC11) (3) weight and dimensions of components adjusted to one person handling (PC14, PC15, PC24, ED18) (4) tolerances (PC16, ED22)

Communication (AC) is related with the extant information about assembly, maintenance and crucially disassembly processes (ED6), about the materials used (PC6, ED30), and the component types (PC21). Only DfD and building renovation authors contribute with guidelines for this sub-criterium, with the largest concerns directed at keeping information in the long term (PC27, JT12). Keeping information of the intervention for the long term also facilitates information collection that is considered by building renovation authors as precondition for any intervention (JT1).

Flexibility criteria assess the capacity of a system to be applied to a larger set of applications. Geometric flexibility (FG) is the capacity of a system to produce a solution for a specific context with system standard components. One way to analyze it is the percentage of non-standard components that a given system requires to describe a solution for a specific context. Since this property is relative to the context, we can consider specific levels of geometric complexity of the product edge to generalize the analysis.

A possible description of the level of geometrically complexity can be found at component edge. Intuitively, components with orthogonal wall faces are less complex and easier to produce with 3-axis CNCs. As each of these angles becomes non-orthogonal the complexity of the geometrical relation between each of the component parts increases (Figure 4-7). Also, describing curved surfaces with flat panel materials may require compromises in the design of the components.

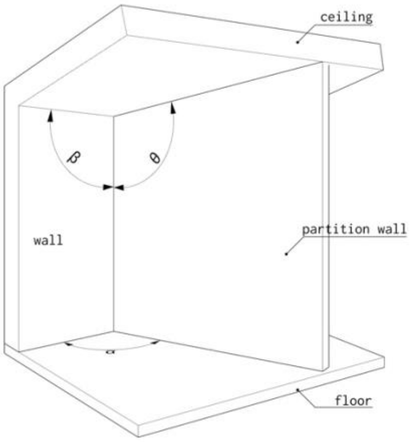

Figure 4-7: Component edge complexity in partition *walls*

Based on the previous assertions five levels of geometrical complexity can be considered regarding increasing angular complexity and one or two curvatures in the wall plane. Level I is buildable with components with orthogonal edge faces, Level II requires at least one non-orthogonal angle, in Level III there is at most curvature in one direction, Level IV there are two or three non-orthogonal component faces and lastly in Level V the wall plane has a double curvature or there are two different curvatures in different faces.

The prevalence of and the requirements for more complex geometries in partition walls is likely small yet the need to adapt the wall to pre-existing conditions in building renovation frequently dictates using more complex geometries, as will be discussed in As-Is Survey section of Chapter 5. This need is recognized by criteria ED16, JT3 and ED19, although the latter one proposes a different approach to solve the problem of adaptability, by minimizing the size of the components.

Services integration (FS) is an aspect that is discussed by MC authors and enounced in criteria KL6, KL11, KT1 and KT9, the latter three of which can be considered contradictory with functional independence. Yet, some level of services integration is unavoidable in partition walls. Durmisevic (2019) identifies five types of integration with decreasing level of spatial flexibility for rearrangement of services, ranging from reversible to irreversible (Figure 4-8): (1) No dependency between services and other functions; (2) Modular zoning; (3) Planned integration, services and structural elements intersect at predefined holes; (4) unplanned integration, services have ad-hoc voids integrated in the structure; and (5) total dependency.

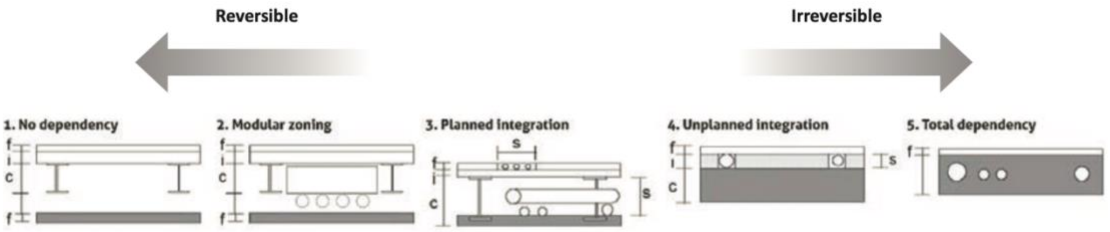

Figure 4-8: Five types of service integration: (f) finish, (i) insulation, (c) structure, (s) servicing (Durmisevic 2019)

Component Separability (FMS) is one of the conditions for modularity and is identified by all authors as an important criterium. It measures how easy it is to separate two modules of an assembly. Generally speaking, mechanical connections are preferable to chemical ones (PC8, ED25), and easy access should be provided to all parts and connections for disassembly (PC13, ED17) which implies assembly and disassembly should be totally symmetrical. Building renovation authors call this aspect reversibility (JT7 and VF4) and this is what MC authors mean when they discuss exchangeability (KT2) or modularity (KL9) and correlate it with the possibility to upgrade (KL7).

Durmisevic (2019) proposes a ranking of connection types, from Type I to X, with increasing degree of reversibility (Figure 4-9). The first three types are chemical connections ranging from no separability to mild separability: direct chemical connection, indirect connection with irreversible chemical connection, direct connection with reversible chemical connection. Type IV and Type V have direct and unidirectional connections with fasteners, with or without damage to assembly parts respectively. All higher types cause no damage to assembled parts. Type VI and VII are unidirectional interlock connections with or without assembly dependencies. Type VIII is a third element connection which is bidirectionally reversible, i.e., elements can be disassembled independently. Lastly, types IX and X are connections that are sustained by gravity.

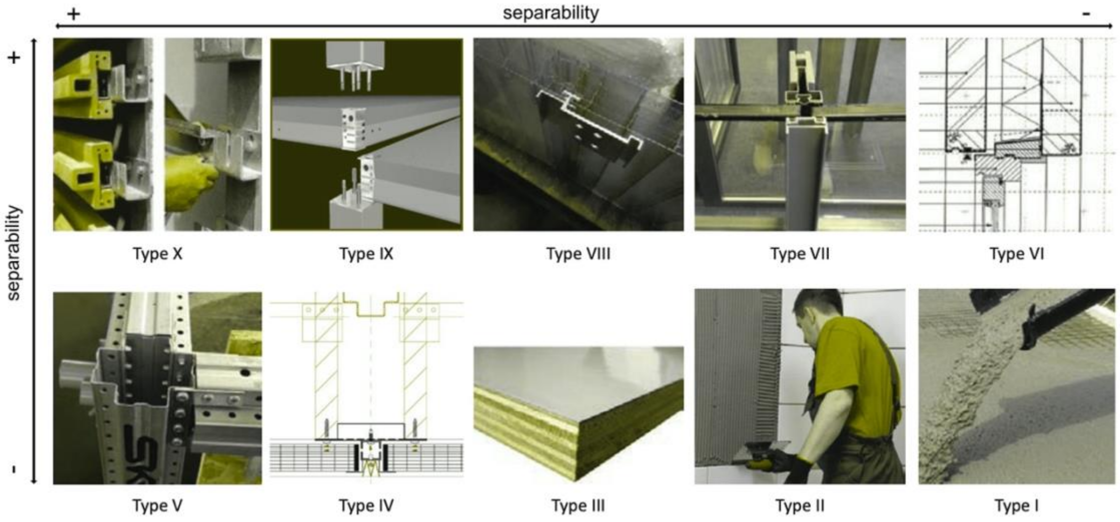

Figure 4-9: Separability of connection types (Durmisevic 2019)

Component Combinability (FMC) is the second largely discussed sub criteria and it measures the number of possible combinations with the system modules. Many of the reviewed authors' criteria, directly or indirectly contribute to increase the component combinability, such as minimizing component types (PC7) or connection types (PC18, ED21), using modular and open design (PC9, PC10, ED11, KL9), or standardizing connection types between building systems (KL4) or even across manufacturers (KL3). Open-source design (KL5) of connectors or joints are an indirect contributor to combinability as these increase the likelihood interface standards are adopted across a large group of manufacturers, which may lead to increasing the offer of modules with different designs. Similarly, adopting module dimensions that are compatible with other systems (ED12) can also contribute to increased combinability. Yet, both KL5 and ED12 also increase personalization potential.

Personalization (FP) is an important aspect of flexibility, although we cannot identify a specific criterion for personalization in KT, the authors dedicate a whole chapter of the book to it. This is perhaps not surprising since maximizing modularity necessarily increases the potential for variation in the product system and thus personalization. Yet, personalization is not variety but meeting the exact needs of the users or building owners (Kolarevic & Duarte, 2019a), and which in the case of building renovation also implies considering integration with context (JT4), the possibility of selecting compatible materials and construction systems (JT9), and visibility of the intervention (JT10). Another way to provide personalization is by ensuring population participation (JT11) which open-source may enable or even be considered a form of.

Performance criteria are related with how well the system responds to the technical demands it is expected to fulfill. These subcriteria are mostly established in the regulatory and technical guidelines, except for joint durability which is a concern of DfD authors (PC19, PC20). Although, technical evaluation guidelines define objective values for all aspects under consideration, these aspects should also consider proportionality criteria (JT5, JT6, VF2). In that regard, technical guidelines for partition walls are flexible, allowing for instance foregoing acoustic or thermal considerations when these are not reasonable requirements.

Lastly, cost criteria evaluate the system economic cost through its life cycle. None of the reviewed authors explicitly proposes criteria for this aspect, yet most of the above criteria that increase assembleability and flexibility, directly or indirectly reduce complexity and cost of assembly and disassembly by removing barriers, simplifying processes, reducing interdependencies and interferences between different technical systems. The above costs can be directly measured and disaggregated from production and assembly costs factors such as material cost, machine, and labor times. Yet it is important to note that production and assembly costs may vary with time and thus are always going to be an imperfect forecast of future disassembly cost (Sassi, 2008).

Criteria JT2, JT8 and VF1 do not evidently belong to one of our criteria and sub criteria proposed above because these criteria are intervention specific and not characteristics of a specific construction system.

4.4.4 Interviews

The 8 interviews were conducted during 2018 with AEC industry experts from different areas of the industry, architecture, engineering, construction and building material manufacturers, with the aim of including a wide scope of different views from different stakeholders (Table 4-5). Similarly, the selected experts include members of academia, some with experience in developing demountable partition walls systems, such as Professors José Amorim Faria (JAF) and Paulo Mendonça (PM), others focused on research in building renovation, such as Professors Vasco Freitas (VF) and Joaquim Teixeira (JT).

The practicing professionals group included architect Brimet Silva (BS), partner at Digitalab with experience in developing mass customizable products with generative design, João Miranda Guedes and Tiago Ilharco, two of NCREP partners, an engineering consultancy that provides services in structural rehabilitation of common building stock and built heritage. From the industry side we interviewed Antonio Rodrigues (AR), the CEO of Grupo Casais, a large construction group present in several countries, and José Moreira (JM), engineer, and director of LAMINAR, a plywood manufacturer of in Gaia, Portugal.

Table 4-5: Interview panel

Interviewee	Antonio Rodrigues	Brimet Silva	Joaquim Teixeira	José Amorim Faria	José Moreira	Paulo Mendonça	Tiago Ilharco, João Miranda Guedes	Vasco Freitas
	AR	BS	JT	JAF	JM	PM	NCREP	VF
Date	02/02/18	16/05/18	18/01/18	19/01/18	15/01/18	16/01/18	22/01/18	20/11/18
Main Area	Construction	Practice	Academia	Academia	Industry	Academia	Practice	Academia
Profession	Engineer	Architect	Architect	Engineer	Engineer	Architect	Engineer	Engineer

The interviews were exploratory with 10 open questions around some of the aspects discussed in this analysis:

1. What are major difficulties engineers, architects, builders, or the industry have in moving towards an industry adapted to building renovation?
2. Do you agree that the tendency towards increasing relevance of building renovation in Portugal will continue in the future?
3. How can automation and pre-fabrication be reconciled with building renovation?

4. What are the obstacles to the adoption of demountable and reusable construction systems?
5. Is independence between components and constructions systems with different life cycles, and particularly partition walls from the rest of the building, an important criterion to consider?
6. Is the integration of digital design and fabrication, with its instantaneous and flexible links between design and production an adequate fit to the challenges of building renovation?
7. Considering that the partition wall to be developed is meant to be assembled and disassembled by users without previous construction experience, which criteria should be included?
8. Which criteria make a demountable partition wall system more flexible?
9. Which performance criteria should be met by the partition wall system in development?
10. Beyond production and building cost which other costs should be considered?

All authors agreed that building renovation will tendentially increase in relevance in the medium term. In terms of difficulties in adaptation to building renovation, interviewees highlight:

1. Need for site adjustments not compatible with rigid contractual and AEC procurement process, i.e., the drawings are contractually binding (AR).
2. A model that includes builder and designers in the same team is more sensible (AR).
3. Lack of room for design experimentation (BS)
4. Low budgets make digital fabrication uncompetitive (BS)
5. Construction companies and sub-contractors were not prepared, lack technical know-how and builders use construction methodologies for new buildings in the rehabilitation of old ones (JAF, NCREP, VF)
6. The mindset to maximize the reuse of the pre-existence is not there (JAF, NCREP)
7. Speed in the process is not compatible with careful studies (VF)
8. Lack of sector specific regulation (VF)

In terms of reconciling automation and pre-fabrication with building renovation, VF, JAF and BS agree that there should be separate solutions for the pre-existing building and the new system. NCREP suggests that this prefabrication will be less standard and JM that lack of standardization in existing buildings is an important obstacle. JT and PM discussed the need for social, and environmentally balanced solutions. Lastly, AR stated that context-aware design-to-fabrication models are the key.

Regarding question 4, most of the authors consider reusing building components is not something society is yet ready to pursue, either because there is a lack of habits, are not informed of the need, or construction tradition prevents it (AR, JM, JAF, PM, NCREP, VF). BS points to some issues that are not specific to DfD but are a general problem of circular economy solutions, e.g., lack of supply chain information, resistance to the use of recycled materials in new products because of reduced technical performance and know-how. JT calls for taxation on construction waste sent to landfill and argues for a mix of Design for Durability with high quality design. PM further adds higher cost and barriers to the adoption of self-renovation in social housing as obstacles of DfD solutions.

All but BS agree that independence of partition walls from the support is an important aspect. JT extends the requirement to materials. Yet, JAF cautions that the aim of independence is not to reuse components since these systems are hardly reusable in different contexts because there is a lack of standardization. PM disagrees with JAF and argues that walls should be more like furniture, further stating that even if users or building owners do not take advantage of the extra flexibility it is always preferable to have it. While BS did not explicitly disagree, he exposed a similar view as JT in the question 4, that good design can increase the product lifetime.

All interviewees agreed that the integration of digital design and fabrication is an adequate fit to the challenges of building renovation. AR stated that the advantage would be to shorten the design to production cycle. BS talked of the capacity to respond to shorter production runs. PM, BS, and JM discussed the capacity to respond to context specific variations. VF cautioned that integration is easier in new construction and JT that digital fabricated solutions must integrate with the pre-existing. Lastly, JAF stated the transition will have to start at universities and progress to design stakeholders before it reaches contractors and subcontractors.

Table 4-6 summarizes the issues discussed with each interviewee and maps those issues to the proposed criteria in the previous section.

Table 4-6: Mapping of discussed issues during the interviews to the proposed criteria

Criteria		Subcriteria	AR	BS	JT	JAF	JM	PM	NCREP	VF
Environmental	ER	Renewable/recyclable materials	X	X	X	X		X		X
	EIM	Independence - material		X	X	X				
	EIF	Independence - functional								
	EEC	Low embedded carbon and energy				X			X	
Assembleability	AS	Simplicity		X			X	X	X	
	AP	Praticality						X		
	AC	Comunication	X					X		
Flexibility	FG	Geometric flexibility							X	
	FS	Services integration						X		
	FMS	Modularity - Separability	X	X	X	X	X	X	X	X
	FMC	Modularity - Combinability	X			X	X	X		X
	FP	Personalization			X	X		X	X	
Performance	PA	Acustic comfort	X				X	X		X
	PS	Safety and Acessibility in use	X			X	X		X	X
	PJ	Joint durability		X						
	PT	Thermal confort								X
	PH	Hygiene, health and environment								X
	PF	Fire safety					X			
Cost	CI	Initial cost	X	X		X	X	X		X
	CR	Reuse cost				X				X

Regarding criteria for assembly / disassembly by users without experience the interviewees highlighted the following criteria: Simplicity (NCREP, JM, PM, BS), Practicality (PM), Symmetry in assembly/disassembly - Separability (JAF), Communication (PM, AR), and Combinability (AR).

Replying to question 8, interviewees discussed Modularity - Combinability (AR, JAF, JM, PM), Modularity - Separability (BS, JAF, JM, PM), Independence - Material (BS), Personalization (JAF, PM, NCREP), Simplicity (NCREP), Practicality (NCREP), and Geometric Flexibility (NCREP)

Regarding performance issues AR, JAF, JM, PM, and VF place safety requirements first as a sine qua non condition. AR, JM identify acoustic as important, NCREP considers it is a differentiation factor. VF considers acoustic, thermal, and hygrometric demands should be characterized to allow a performative selection and not be criteria.

Lastly, replying to question 10, AR considers that automating production will reduce costs, BS mentions all the product development (design, prototyping, optimization, certification) and marketing costs. JAF and VF mentions LCA cost should consider initial cost, cleaning and disassembly and further propose that the evaluation of reuse cost should consider a percentage of global cost reduction. JM focuses on production and distribution costs. PM proposes the user could be informed of the estimated assembly times even if those are not costs of the product but only if providing this information is obligatory can it then be considered criteria.

Some interviewees observations which are not answers to any specific question are also worth highlighting. AR stated that lack of labor is a current concern and a driver their efforts of increasing pre-fabrication and automation. BS considers that architectural offices currently are in position to offer architectural products ranging from building components to houses. He further stated that the difficulty in adoption is related with education but also with the maturation of computational design knowledge by designers which must span from conception to materialization of design.

4.5 Assessing and setting design goals

From the previous analysis and the literature review we could identify evaluation methods for all the performance, cost, and environmental subcriteria (Table 4-7). Only PS performance criteria is mandatory, which at the system design stage may be verified using simulation, codes, or precedent. Regarding EEC is important to note that since the impact of digital fabrication has been found to be negligible (Agustí-Juan & Habert, 2017), the crucial aspect in designing an MCC partition wall system seems to be minimizing waste by maximizing input material usage. To this end, tools like nesting can be helpful also at the design stage.

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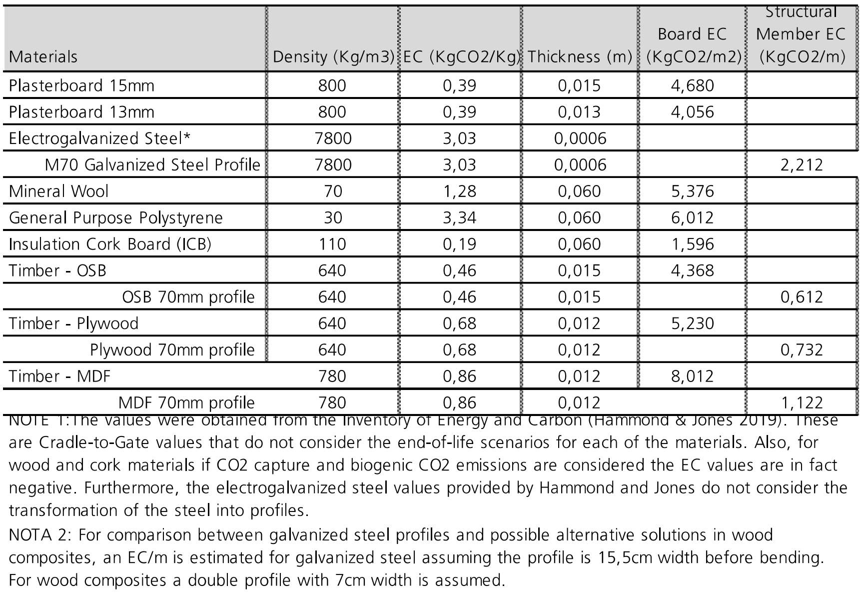
Table 4-7: Criteria Framework for Mass-customizable partition walls systems and specific evaluation methods

Criteria		**Subcriteria**	**Method of evaluation**	**Subfactors**
Environmental	ER	Renewable/recyclable materials	Sassi 2008	
	EIM	Independence - material	percentage of independent parts per system (Durmisevic 2006)	
	EIF	Independence - functional	percentage of parts with co-variant functions (Durmisevic 2006 | Salvador 2007)	
	EEC	Low embedded carbon and energy	EN 15804+A2 (2019)	material waste (ED5)
Assembleability	AS	Simplicity	Number of operations | number of different operations	
	AP	Praticality	Assembly sequence type (Type I - V)	
			Weight per component | Size of component to fit door	
			no tools | common tools | specialized tools | proprietary tools	simple tools
			_	tolerances
	AC	Comunication		Part identification
			_	long term information about materials and system assembly
Flexibility	FG	Geometric flexibility	percentage of non-standard parts per Type (Type I - V)	
	FS	Services integration	Levels (Type I - V) (Durmisevic 2019)	
	FMS	Modularity - Separability	Levels (Type I to X) (Durmisevic 2019)	
	FMC	Modularity - Combinability	Salvador 2007	number of connection types
				number of component types
	FP	Personalization	_	Design solutions (joints, etc) are applicable to a wide range of materials
				The system is customizable to meet typical renovation requirements (non-standard heights of doors, different baseboards heights…)
Performance	PA	Acustic comfort	EAD	
	PS	Safety and Acessibility in use	EAD	
	PJ	Joint durability	Number of cycles	
	PT	Thermal confort	EAD	
	PH	Hygiene, health and environment	EAD	
	PF	Fire safety	EAD	
Cost	CI	Initial cost	cost of materials + production + assembly time	
	CR	Reuse potential savings	Percentage of reusable parts	

ER and EEC are dominated by material choices yet since the purpose in this research is to determine design principles for open systems with digital fabrication, we focus on wood and cork composites of standard sizes commonly available in the Portuguese market: plywood, oriented strand-board (OSB) and insulation cork board (ICB). In all instances there are national manufacturers of these products, which in the case of eucalyptus plywood and ICB are known to depend on local raw material sources.

The choice of these materials is mostly determined by their capacity and precedent in cost-effective digital fabrication processes, yet their choice is favorable when compared with materials commonly used light prefabricated systems both in terms of their capacity for circularity and carbon emissions (Table 4-8).

Table 4-8: Comparison of material properties and Cradle to Gate Embedded Carbon values obtained from the Inventory of Carbon and Energy v3 (Hammond & Jones 2019)

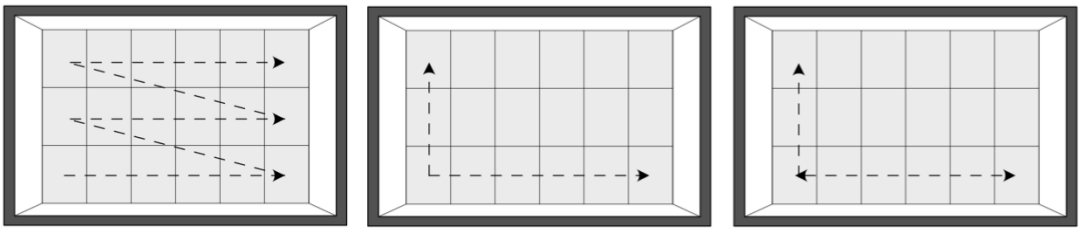


Materials	Density (Kg/m3)	EC (KgCO2/Kg)	Thickness (m)	Board EC (KgCO2/m2)	Structural Member EC (KgCO2/m)
Plasterboard 15mm	800	0,39	0,015	4,680	
Plasterboard 13mm	800	0,39	0,013	4,056	
Electrogalvanized Steel*	7800	3,03	0,0006		
M70 Galvanized Steel Profile	7800	3,03	0,0006		2,212
Mineral Wool	70	1,28	0,060	5,376	
General Purpose Polystyrene	30	3,34	0,060	6,012	
Insulation Cork Board (ICB)	110	0,19	0,060	1,596	
Timber - OSB	640	0,46	0,015	4,368	
OSB 70mm profile	640	0,46	0,015		0,612
Timber - Plywood	640	0,68	0,012	5,230	
Plywood 70mm profile	640	0,68	0,012		0,732
Timber - MDF	780	0,86	0,012	8,012	
MDF 70mm profile	780	0,86	0,012		1,122

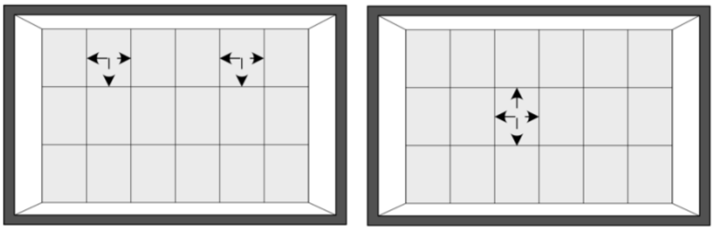
NOTE 1:The values were obtained from the Inventory of Energy and Carbon (Hammond & Jones 2019). These are Cradle-to-Gate values that do not consider the end-of-life scenarios for each of the materials. Also, for wood and cork materials if CO2 capture and biogenic CO2 emissions are considered the EC values are in fact negative. Furthermore, the electrogalvanized steel values provided by Hammond and Jones do not consider the transformation of the steel into profiles.

NOTA 2: For comparison between galvanized steel profiles and possible alternative solutions in wood composites, an EC/m is estimated for galvanized steel assuming the profile is 15,5cm width before bending. For wood composites a double profile with 7cm width is assumed.

Assembleability criteria have the highest number of design guidelines. The AS sub-criterium can be optimized by minimizing the number of different assembly operations. Practicality (AP) issues are too diverse and as such need different evaluation methods. The first issue relates to assembly sequences for constrained partition walls, these can be classified into types with increasing non-linearity of assembly and disassembly: Type I – Each layer of components must be assembled linearly; Type II – assembly/disassembly is sequential in both dimensions; Type III – assembly/disassembly is bidirectional horizontally and vertically unidirectional; Type IV – Columns can be disassembled independently; Type V – Any component can be locally disassembled (Figure 4-10).



Type I - Undimensional sequencial Type II - Bidimensional sequencial Type III - Bidimensional symmetric



Type IV - Column Local Type V - Local

Figure 4-10: Assembly sequence types

The second aspect, related with the size and weight of the components can be evaluated quantitatively, and the aim is to minimize total component weight and ensure its dimensions are adequate to enter the assembly site by a standard door. According to Faria (1996), component weight should not exceed 30kg. For the third issue, related with the type of needed tools, we propose a classification in 4 levels: no tools; simple or common tools – such as a hammer or a Philips screwdriver; specialized tools – tools that are used by experts; to proprietary tools – which are specific to a manufacturer. The last dimension of AP – tolerances - has no specific method for evaluation suggested in the literature we reviewed. In fact, Faria (1996) reports that this evaluation was done through prototyping. Sass (2006, 2007) details methods of testing and prototyping friction-fit joints in digitally fabricated constructions systems and embedding these as a parameter in the generative CAD model.

An important contribution to the evaluation of Communication (AC) criteria came from PM, who stated that the need for assembly instructions should be minimized by making product assembly as easy and failsafe as possible. To this end, traditional integral joining methods seem more fitting since these have self-explanatory assembly methods. Yet, this aspect is already evaluated by the simplicity criteria. Naturally, there are other levels to communication concerns such as accessibility and long-term preservation of information about material, component types, assembly/disassembly procedures and maintenance which cannot be addressed by this type of design strategy. Engraving parts and components with an identification code is an approach that has been widely used, alternatives range from an alphanumeric code (Sass 2006) to a QR-code (Peng et al., 2019). Another approach is to address those issues at a different level by introducing material passports. Yet, those issues are outside the scope of the present research.

Flexibility subcriteria FS, FMS and FMC can be deducted from the literature and for FG we have proposed an evaluation method on the previous section. Yet, FMC cannot be evaluated with Salvador method in a preliminary design stage since it is a system property. An alternative approach would be to set a design goal of minimizing connection and component types.

The FP criterium is also a system property and we have not found a specific metric in the literature. Yet personalization could be evaluated by considering several aspects that define the scope of possible application for different functional requirements, e.g., the range of different possible finishes, the possibility of transparency or translucency. Another dimension of personalization is adaptation to typical requirements in building renovation, e.g., non-standard door heights.

4.5.1 Cost-effective digitally fabricated systems

In this section, we assess the most relevant cost-effective digitally fabricated systems, identified in Part I, in relation to the proposed criteria. Most of the systems found in the literature and practice have been developed for small housing. Hence, they commonly focus on the outer shell and structure of the building. This focus on the longer lasting layers of the building implies that the dimensioning and design of these systems is optimized for these types of functions. Which precludes a direct application of these systems to partition walls, which are frequently thinner, have different types of assembly constraints, and structural requirements. Most systems have a direct lineage with frame and panel and Wood Frame Grammar (WFG) friction-fit joint design, with detail variation mostly aligned with the specific local vernacular traditions from the contexts were these emerge (Table 4-9). Larry Sass systems (Sass, 2006; Sass & Botha, 2006), perhaps because these are much better documented than the remaining cases, are cited by almost all other cases as a reference.

Table 4-9: Cost-effective digitally fabricated systems

Authors	System Name	Date	Country	Type	Precedent	Joint Types
Sass	WFG	2005	US	Frame	Frame/Panel	Friction fit
Sass and Botha	Instant House	2006	US	Frame	Frame/Panel	Friction fit
Sass	Shotgun House MoMa	2008	US	Frame	Frame/Panel	Friction fit
Parvin and Ierodiaconou	WikiHouse	2011	UK	Frame	Frame/Panel | WFG	Friction fit
Hiroto Kobayashi	Maeamihama Veneer House	2013	JP	Frame	WFG	Friction fit
Stoutjesdijk	ECOnnect Haiti	2013	NL	Frame	WFG	Friction fit
Parvin (Architecture 00)	WikiHouse (Wren)	2014	UK	Beam and Post	WH | Frame/Panel	Friction fit
Elsayed et al	Low Cost Housing	2017	IT / EG	Hybrid	WFG | Monolithic	Friction fit / snap-fit
Finch and Mariage	X-Frame	2019	NZ	Frame	Frame/Panel | WFG	Friction fit
Vincent and Backheuser	Digital Housing	2019	BR	Frame	WFG | WH	Friction fit
Brasil and Franco		2019	BR	Beam and Post	WFG | WH	Friction fit

Elsayed approach is the one that is most distant from Sass both in terms of overall system design and joining detail. He adopts a "*modular parametric*" approach to system components instead of the frame and panel approach that is common to all other cases. Modular parametric for Elsayed means defining modular components that are dimensionally flexible, yet no design strategies are defined of how this should be achieved. WikiHouse several iterations have been diverging towards a modular and dimensionally standard component approach; hence these are encapsulated in the range of possibilities defined by the two previous systems. Thus, the selected systems for analysis are Sass's Wood Frame Grammar (Sass, 2006; Sass & Botha, 2006) and Elsayed Low-cost Housing (LCH) (Elsayed 2017).

The analysis is limited by the available published information regarding the systems and focuses on aspects that are divergent between systems. As such, performance criteria and EEC subcriteria cannot be evaluated rigorously and ER subcriteria can be considered similar in all cases since all systems are made of similar materials. Likewise, since all systems are composed of a single material and joined strictly by mechanical means any combination that results in an irreversible subassembly can be considered equal in terms of material independence to any other reversible subassembly.

4.5.1.1 Sass Wood Frame Grammar

In WFG, and all frame and panel-based systems, all assembly operations are performed onsite, which from the point of view of Assembly Simplicity (AS) is a negative aspect. The number of operations will scale linearly with the number of parts, yet the number of different types of assembly sequences is related with the number of connection types and different part types. According to its authors the number of connection types is 8 (Figure 4-11)(Botha & Sass, 2006). Regarding the number of different part types, we consider that geometric variation can also introduce assembly entropy. So, although we identify at least 12 component types: panels, t-braces, shim plates, 2 types of dogbones, 2 types of wall studs, 2 types of corner studs, 3 types of corner braces; we estimate that the case-study presented in the original paper contains 260 different instances of different parts.

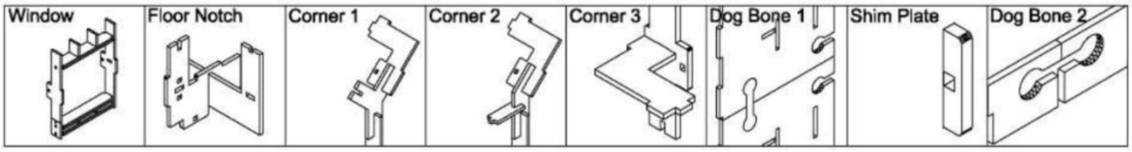


Figure 4-11: Joint types in Instant House (Sass and Botha 2006)

Sass systems are vertically unidirectional and horizontally bidirectional in terms of assembly and disassembly (Figure 4-12). The system only requires a rubber mallet for assembly and disassembly, which is a common feature to all WFG-based systems. According to Sass, the largest part weights 20,67kg, which can be caried by a single person, although the component dimensions make the transportation difficult in more constrained environments such as interiors.

Figure 4-12: Assembly and Disassembly sequences in the WFG (Botha and Sass 2006)

WFG uses a labelling system that is physically marked on the parts. This represents both an assembly time and a long-term solution to part identification within a specific design solution. Yet, the label is not related with the shape of the part, hence knowledge of the system and access to the digital model are always needed, both for assembly and disassembly. Furthermore, formal variation affects all system levels with implication on communication complexity and reduction of reusability of disassembled parts. The exposed joints contribute provide self-explanatory disassembly points.

In WFG, structural functions are distributed between the panel and the frame. If the frame is also considered finishing, then functional independence is low since finishing functions and its' use life-cycle are not co-variant with those of the structure.

Geometric flexibility of type II is possible. Although services integration is not accounted for in the grammar, the system can be classified as Type III in terms of services integration, since it provides voids between the inner and outer sheets. The system parts are Type VII separable with unidirectional interlock connections without assembly dependencies.

Although Sass system is based on a subdivision grammar that identifies three generic component types (wall, corner, end-wall) the system assembly logic and the panels subdivision does not follow the subdivision grammar. This implies that from the point of view of combinability, only the dogbones, t-braces and shims can be considered modules. Also, these parts are not affected by variations in the building dimensions and thus have a high combinability. The remaining part types are cut-to-fit and since frame and panel subdivisions are not aligned, variations in one of the parts has implications in many other parts in non-obvious ways. Although there might be some combinability of parts between different solutions, this must be analysed on a case-by-case basis, which makes reusing specific parts unlikely.

From the point of view of Personalization, the examples that have been published (Sass 2006, p 67) and built indicate that a high level of personalization of the shape of the building is possible. The types of joints are applicable to several classes of sheet material, not only wood-based, but cannot be used for connections with other building subsystems. The personalization is mostly concentrated on the design phase. The system would require separate finishing systems. For the reasons discussed above regarding combinability, personalization after construction can hardly leverage the design-to-production methods used to originate the building.

4.5.1.2 Elsayed Low-Cost Housing

Elsayed's LCH system is composed of parametric elements, wall, ceiling, and floor, which combine structural and skin functions, and a prefabricated core for wet spaces. Only the wall system is detailed in the paper (Elsayed 2017). The authors consider the system to be "*modular parametric*" meaning that the wall system components may be dimensionally adapted to context specific circumstances.

A thorough analysis of the proposed wall system reveals that there are in fact two types of straight wall components – male and female (Figure 4-13). We identify 5 different types of connections: 2 structure-to-panel connections, 1 spacer-to-panel connector, stud-to-stud connections, component-to-component connections; and 11 component types, assuming there is axial symmetry: 2 straight wall components, 3 L-components and 4 T-components. If the identified components are to be assembled onsite, as the authors propose, the system complexity increases. Each L and T component has 8 panel and 2 stud variants, with two panel and stud types for each straight wall section.

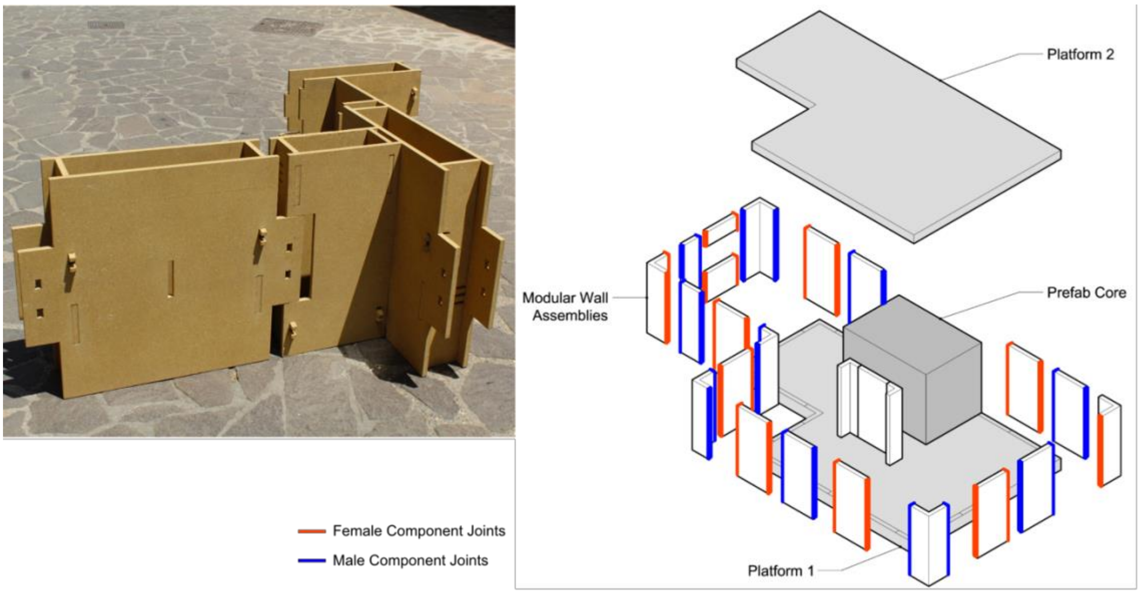


Figure 4-13: (Left) Assembled components with male straight wall, Male/Female T-Wall and female L-Wall, (Right) Application of Female-Male logic to original diagram (Adapted from Elsayed 2017)

The authors suggest the wall components are completely assembled onsite, which reduces simplicity of onsite assembly. Nevertheless, the system has a smaller number of part types, when compared to WFG, and there is potential for the components to be pre-assembled offsite.

Elsayed system assembly sequences can be classified as horizontally bidirectional for component assembly, it requires simple tools for friction-fit joints and no tools for snap-fit ones. The full heigh wall section is 700x2800mm. The selected material has a reported specific weight of 720kg/m3. It is not clear how the assembly process is conducted but assuming the wall section component is assembled on the floor, each fully assembled component weights 63,87kg and requires two people to erect it and connect the wall sections together.

No information is provided regarding how assembly/disassembly sequences are communicated to onsite assemblers nor if a specific part labeling scheme is used. Considering the low number of component types, instructions would be significantly reduced as compared to WFG.

The system provides level I geometric flexibility due to the selected connection types. It can be considered a type III in terms of services integration. Obtaining access to the wall voids is theoretically possible with local panel disassembly. In practice this should be difficult to achieve since there is no points to grab and pull the panel apart from the structure, also it is unclear if the system remains stable after the disassembly of the panels. Regarding separability, it is a type VII system, meaning that the disassembly sequences are still unidirectional. Removing a specific wall section does not seem to be possible.

Assuming that the height is constant from house to house the system would have a high combinability. But with changing heights only the connectors and the lower sections of the external sheathing are reusable between system instances. The vertical runners would have to be produced specifically for each system instance. Components can be combined in different arrangements but are limited by the male-female component-to-component connection logic.

Elsayed system suffers from the same issues as WFG regarding both functional independence and personalization. Although a more modular approach is adopted, the panels still perform structural functions. Also, regarding personalization, the protruding joint complicates adding different finishes to the system and the snap-fit joint is not as widely applicable as the friction-fit joints.

We use the case-study reported by Sass, a room with 7,3 sqm surface area, and the diagram presented in Figure of the LCH system, with 16,19 sqm building footprint, to analyze the systems. Table 4-10 summarizes the analysis regarding the specified criteria with all scores normalized. For simplicity and combinability, we chose to assume a theoretical optimal value of 1, which follows Salvador approach. LCH case is double the area of WFG case but only the number of operations is proportionally affected by this change, all the other metrics are system specific.

Table 4-10: Evaluation of WFG and Low-Cost Housing according to the defined criteria

Criteria	Subcriteria		Method of evaluation	WFG	LCH
Environmental	**EIM**	**Independence - material**	% of independent parts per system	**1**	**1**
	EIF	**Independence - functional**	% of parts with covariant functions per system	**0,84**	**0,59**
Assembleability	**AS**	**Simplicity**		**0,002**	**0,02**
			Number of operations (1/n)	0,00102	0,0019
			Number of different operations (1/n)	0,004	0,033
	AP	**Praticality**		**0,69**	**0,45**
			Assembly/Dissassembly Sequences (Type I to V)	0,4	0,4
			Tools	0,75	0,75
			Weight per component (Range 15-75kg)	0,91667	0,1855
	AC	**Comunication**		**0,6**	**0,4**
Flexibility	**FG**	**Geometric flexibility**	Levels (Type I, Type II, Type III, Type IV, Type V)	**0,4**	**0,2**
	FS	**Services integration**	Levels (Type I (embeded services), Type II (Services on tracks), Type III (Planned integration), Type IV (Modular zonning), Type V (independent)	**0,6**	**0,6**
	FMS	**Modularity - Separability**	Levels (Durmisevic 2019) - Type I to Type X	**0,7**	**0,7**
	FMC	**Modularity - Combinability**		**0,0669**	**0,11725**
			Connection types	0,13	0,2
			Component types	0,0038	0,0345
	FP	**Personalization**		**0,65**	**0,45**
			Applicability of joining solutions	0,8	0,5
			Applicability of solution to renovation	0,5	0,4

Thus, although the number of site operations in WFG is similar to that of LCH, the more modular approach reduces the number of different operations by one order of magnitude. Similar effects are seen in Combinability component types and in a smaller degree in connection types, which contributes to a significantly increased overall combinability score for LCH. The increased modularity in LCH comes at the cost of geometric flexibility, the joining solutions can only be applied to orthogonal geometries, which might be an issue at the system boundaries in building renovation. Regarding Practicality, there is no improvement regarding assembly and disassembly sequences between both cases.

The analysis revealed that there are opportunities: (1) to explore the interrelations between different criteria in practice, particularly those of Modularity (FMS, FMC), Simplicity (AS), Practicality (AP) and Functional Independence (EIF); (2) to determine how specific system design choices impact each of the criteria and ultimately influence the reuse potential; (3) to determine which design patterns may exist in systems which are more open and reusable; and (4) to determine how digital fabrication may meet the complex and diverging challenges of open system partition walls.

Lastly, some aspects of the analysis beyond the framework of criteria should be highlighted. Surveys are sine qua non first steps for adequate building renovation (JT1). Delivering context specific solutions, as required by JT3, JT4 and JT9, on a global scale demands multiple building systems. This requirement is also a corollary of EE criteria, it is not realistic to expect the scope of a single partition wall system to include all possible variations of material combinations. Hence, multiple customisable and disassemble-able partition wall systems of smaller scopes are needed, which underscores the need for criteria and design principles but also demands MCC systems capable of addressing the design level.

CHAPTER 5 Towards survey-to-production for an open system for customizable and disassemble-able partition systems

Contrary to most other industries, the supply chains for design and production in the AEC industry are frequently project specific, i.e., both the building and the process are prototypes[24]. Different design teams, e.g., engineers and architects, work with different software, often incompatible, hindering information flows or even forcing remodeling. If teams change from project to project, there are little opportunities for increasing process efficiency from experience.

Kieran and Timberlake argue that a *"new vision of process, not just product"* including all stakeholders, from architects to users and builders, in the building process is needed (Kieran & Timberlake, 2003, p. 107). The dissemination of this collective integrated process, replacing the authorial individual vision of the architect is a precondition for industrialization of architecture. The solution seems to be an integrated process, yet how should this process be? Vertically integrated or a flexible web of workflows?

Computational designers have been making do by developing customized workflows to assist in the delivery of large and complex projects with ad-hoc teams, bridging technological and cultural gaps. Miller considers *"inventing customized workflows are a necessary part of the design process and have a profound impact on the delivery of the architecture."* (Miller, 2010, p. 144). These workflows can then be abstracted and generalized into open-source or commercial plugins (Poinet et al., 2021, p. 4). In this process a large pool of computational design tools and designers skilled in their workings has emerged. Making conditions ripe for similar logics to be applied to smaller yet recurring problems like building renovation.

The possibility of continuous workflows from design to production is discussed by Fabian Scheurer (2014), who say that barriers still remain at the transition from design to production. Furthermore, the differing requirements of precision and accuracy of surveys dictates current building practice that each actor during the construction process does its own survey. Scheurer and Stehing (2020) state that this is the main obstacle to the adoption of lean, just-in-time and prefabrication in the construction industry.

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[24] In fact, in a recent and first ever interview, Bob McNeel details how this very observation was at the origin of the development of Grasshopper.

5.1 Design for a generic end-user and stakeholder roles in mass customization construction systems

As discussed in the second chapter, the growing adoption of computational design in architectural practice has made alternate modes of production, such as MC (S. Davis, 1987), increasingly viable models for AEC industry (Kolarevic & Duarte, 2019b). The MCC paradigm reconciles apparently contradictory goals of personalization and mass production, thus reviving the century old idea of industrialized architecture (Kieran & Timberlake, 2003).

Sustaining these efforts is the idea that building owners want to buy houses customized to their needs (Larson et al., 2004). As we have seen, MCC can offer building owners some design and production control over industrial construction, which some authors claim will democratize architectural design (Kolarevic & Duarte, 2019b). However, that democratization will be restricted to the latitude of customization producers and designers of said systems choose to provide (Vardouli, 2012).

OSArc (Ratti & Claudel, 2015) aim to achieve increased user control by integrating elements of the community driven open-source movement into the MCC paradigm. Its proponents claim that the notion of authorship in architecture has been challenged by the evolution of digital technologies, thus opening a new prospect for including the user in the design process. OSArc embraces N.J. Habraken ideas of incremental socially driven innovation in construction (Habraken, 2003) amplified by a digital vernacular process of evolution of building solutions. That digital framework would be a stage for the interaction, evolution, and delivery of design solutions in the AEC process.

However, two central questions emerge: who might be the users of these MCC systems? And what would the AEC stakeholder roles be under these paradigms?

To address these questions, we critically review four cases of MC in housing and building components: (1) Malagueira Grammar by José Pinto Duarte (2001); (2) FABModular by John L. Brown (2016); and (3) Chassis + Infill by the House_n research group at MIT led by Kent Larson; and (4) one example of a OSArc framework, the Wikihouse by Architecture 00. The analysis presents an insight of what should be the roles and actors under these paradigms.

It is important to note that although the main goal of architectural production is building, architects are mainly providers of services who must lean on other professionals to achieve the end product. Figure 5-1 depicts the typical relations in the most common modes of interaction between stakeholders in the AEC industry, Design-Bid-Build and Design-Build.

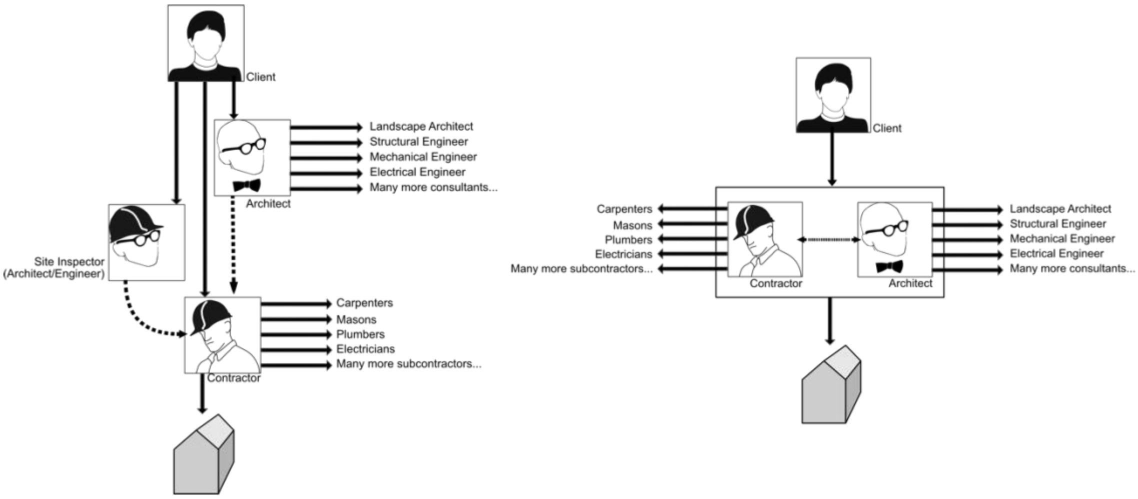

Figure 5-1: Common workflows and relations in the AEC industry, Design-Bid-Build (left) and Design-Build (right)

This section presents a comparative analysis of some of the major contributions to the advancement MCC systems. The aim is to clarify if there are substantial differences in the roles of the AEC stakeholders between MCC systems and OSArc systems. The methodology used is a critical analysis of the proposed construction systems, design interfaces and theoretical discourse of each author. The analysis is based on published journal and conference articles, thesis, websites, magazine, and journal interviews, and on the Wikihouse online repositories at GitHub. The Wikihouse plugin for Sketchup 8 and 2013 and the Leafcutter plugin for Grasshopper were also collected from GitHub as these are no longer available from their canonical sources.

5.1.1 Duarte's Malagueira Discursive Grammar

Duarte's discursive grammar follows the idea of Conversational AI by Negroponte and the ArcMac in the attempt to put the computer in the architect's shoes while having a dialogue with the client. The architect is granted the role of the grammar designer, and eventually the role of intermediary between the computer and the end-user.

The term MC was not present in Duarte's work until 2001, but the intention of creating an MCC framework to provide customization in mass housing using digital design was already elaborated, at least as far back as, his 1993 MsC thesis at the MIT under William Mitchell. In that thesis, Siza's work at Malagueira and Habraken theory of supports are studied as examples of the use of the module and type as strategies for the quest of variation in mass-housing. The idea of automating the design process as a solution to the obstacles of providing diversity in modular systems is already explored and shape grammars are the mechanism by which the design is generated (Duarte, 1993).

In 2000, during the development of his doctoral thesis, he presented a framework composed of shape grammars, an interpreter, and a website[25] (Figure 5-2), that allowed the exploration of Malagueira discursive grammar design universe (Duarte, 2000a, 2000b; Duarte et al., 2000). The framework was meant to enhance an architect/user ability to find a suitable solution to the client requirements in a predefined design universe.

Figure 5-2: Malagueira website (Duarte 1999)

Between 2000 and 2003, Duarte collaborates in a research project at MIT, with Kent Larson and Jarno Suominem. The goal of the project was to develop an integrated system for designing and producing prefabricated housing, which may have had some influence on the work developed by Duarte from 2000 on. In fact, in his PhD thesis he starts referring to his framework as a mass-customization system, which could be directly operated by a non-expert user to generate his own designs. A production system, first proposed in the joint article with Larson and Tapia, is identified as a future development, which should *"include computer aided manufacturing and assembly process"* (Duarte, 2001, p. 31).

Consequently, Malagueira Grammar only features a partial set of an MCC system components, namely an interface and a design system, and as previously discussed the user interaction with the design is limited to a form. Based on the previous analysis, Figure 5-3 exposes the effective stakeholder roles and workflow by Duarte's Malagueira Grammar.

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[25] http://home.fa.utl.pt/~jduarte/malag/

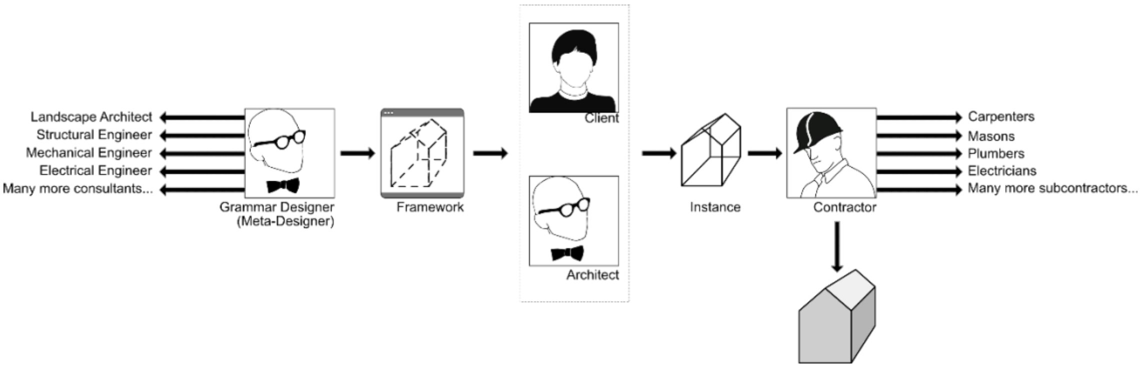

Figure 5-3: Malagueira Discursive Grammar stakeholder roles

The framework changes the traditional procurement process in mass housing by effectively pre-designing the design universe, a role that is attributed to Grammar Designers and which will likely involve all the designer stakeholders. This change enables the possibility of a more informed decision by the client/user but does not necessarily imply a change to the construction process.

5.1.2 Chassis + Infill: Open-Source Building Alliance

Kent Larson set out his vision for a mass-customized house of the future in a series of two articles published in A+U between 2000 and 2001. Larson calls for universal open standards for components interfaces, infrastructure, and protocols, drawing parallels from the PC hardware and automotive industries. The second article, co-written with Mark Tapia and José Pinto Duarte, establishes the basic components of a MCC system: the preference, the design, and the production engines. The examples of components in the article are an assortment of previous research: Jarmo Suominen Virtual Apartment System, a preference engine; Duarte's Malagueira grammar and Larry Sass's PhD thesis, both design engines (Larson, 2000; Larson et al., 2001).

The preference and design engines follow the template of Duarte's framework: the preference engine is an exhaustive online query replicating a client-architect interview; the design engine is Duarte discursive grammar. In later articles the preference engine is only used to initiate the design process and co-design environment, involving virtual reality and smart tables, is used for design development with prospective clients. To assist this process computational design critics were included in the system to provide feedback to users on the evolving design.

A "chassis-infill" system construction system is presented and detailed later in the MsC theses of Thomas McLeish (2003) and Tyson Lawrence (2003). It closely follows the open building philosophy, considering building life-cycle adaptation by disassembly of infill components. The "chassis" is built of mass-produced glass fiber polymer pultruded profiles, beams, and posts with mixed structural and infrastructural functions (Figure 5-4). The structural system can be used for buildings with up to 3 floors but is limited to orthogonal structures with a maximum beam span of 4,57m and with a fixed ceiling height of 2,74m. The structure had connection points for infill panels, window frames, ceiling and floor panels and integrated raceways for power, data, and HVAC ducts. The infill is divided into chassis structural infill, chassis façade and infill storage components., which double as interior partition walls, mixing partition, storage, infrastructural functions.

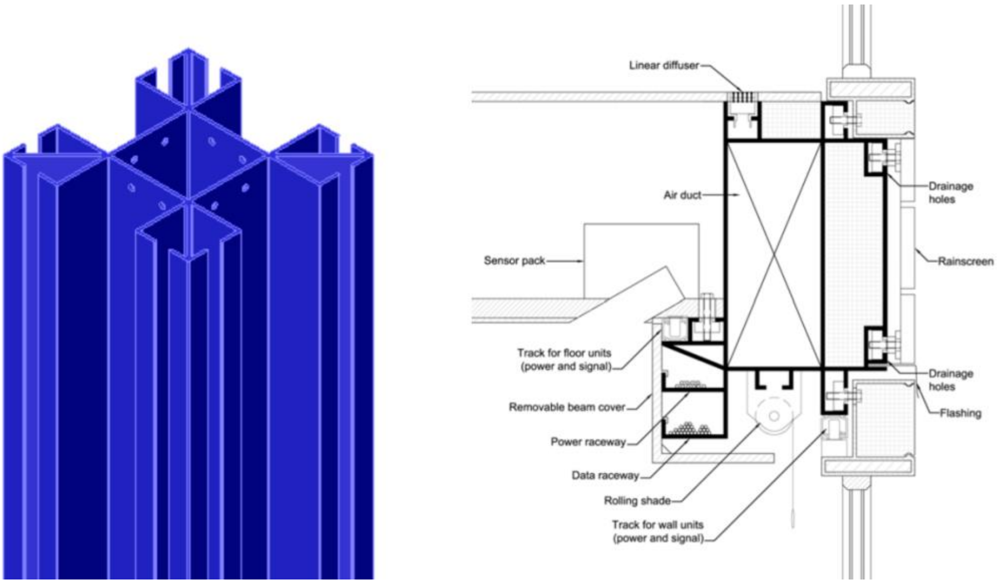

Figure 5-4: (Left) The chassis column. (Right) The beam has connection points for panels above and below, floor infill, and an optional rainscreen. When assembled the beams create an HVAC distribution system, power and data cabling raceways, and a system to connect power and signal to infill (Lawrence 2003).

The Chassis + Infill system and the design interfaces were meant to serve as templates upon which the industry was expected to build, and with that in mind the House_n research group created the Open-Source Building Alliance (OSBA). Its success hinged on the notion that all the roles in AEC industry had to change: developers to integrators, architects to meta-designers, builders become assemblers, and customers instance designers (Larson et al., 2004) (Figure 5-5).

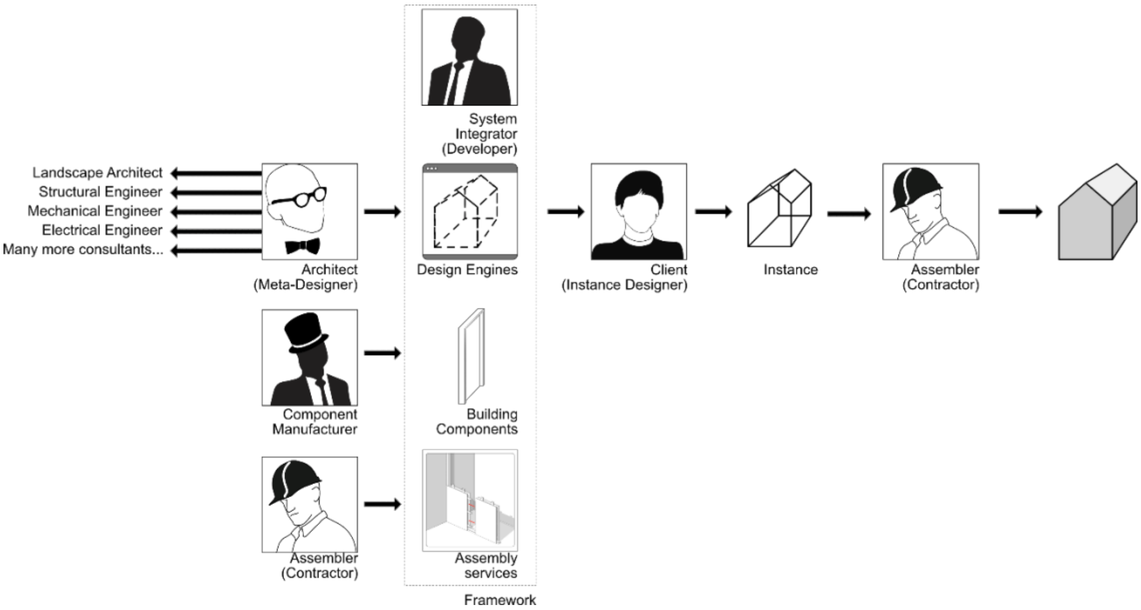

Figure 5-5: House_n Chassis + Infill envisioned stakeholder roles

The System integrators would be the key figure in a framework that included an array of design engines, building components and assembly services supplied respectively by meta-designers, component manufacturers and builders. The framework and the system integrator would be the actual frontend for the client, which would bear the responsibility for the design of the instance.

5.1.3 Brown’s Future Adaptive Building

Future Adaptive Building (FAB) is a reconfigurable infill system for an ageing population, developed by John L. Brown during his PhD dissertation (Brown, 2016), and is largely based on his professional experience. The system is composed by FABmodular, a system of prefabricated modular cabinetry, FABstudio, a web platform for interior design, social interaction, house management and health monitoring and FAB+, a set of medical addons that can be integrated into the FABmodular system (Figure 5-6).

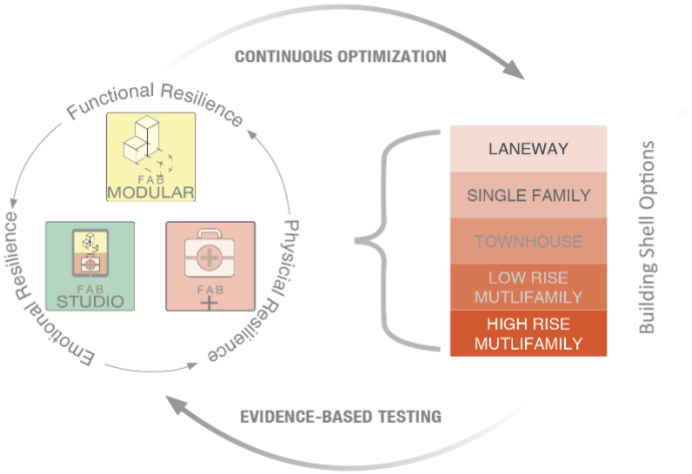

Figure 5-6: (Left) The components of the FAB system (Right) the contexts to which may be applied. (Brown, 2016)

It follows the open building tradition of separation of support and infill (Figure 5-7) and shares many of the traits of Habraken's Matura Infill System, with some important exceptions. In the Matura system, the infill includes all the interior partitions, floors, services (water, electricity, and sewer), doors, kitchens, and bathrooms. In the FAB system, there are two "time layers" of infill, one that is fixed: bathroom, kitchen, floors and ceilings, and another that is reconfigurable, the FABmodular cabinetry that defines all the remaining interior spaces.

Brown claims his system can be adapted to either existing houses or new ones of any type: apartments, townhouses, or single-family houses. Yet, it is likely that the system generality is limited to the Canadian context composed largely of prefabricated buildings. To renovate a unit, like the Matura precedent, it is necessary to strip the interior of the preexistent infill and to prepare it to receive the new adaptive system. In the Netherlands, this step proved difficult to implement in practice, requiring a perfect leveling of the support to receive the new fit-out (Kendall, 2015a). Also, the system does not resolve the issue of non-orthogonality of the spaces. While in the north American context these issues might prove not to be a problem, the applicability of the solution to other contexts becomes questionable.

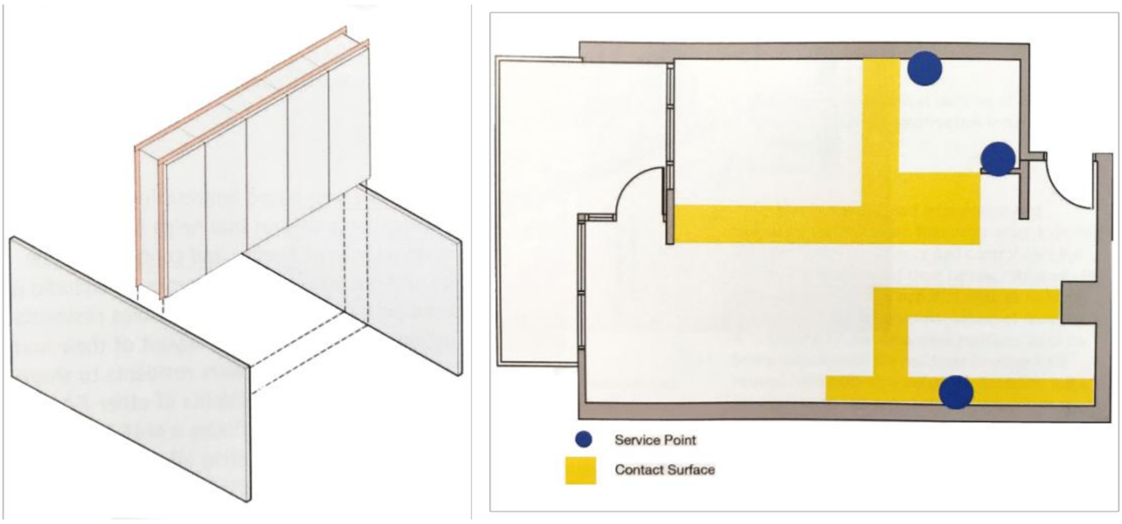

Figure 5-7: (Left) Concept of the infill system (Right) Plan of a possible apartment layout showing the placement of the infill cabinetry and the service points (Brown, 2016)

The FAB system by itself, as an infill system, only partially changes the traditional stakeholder roles. The typical design-bid-build procurement process of the AEC industry may be kept or not for the support: the structure, façade, roof, infrastructure, and bathrooms; but introduces a reversed system in the infill. This is a logical option since the system is meant for interior renovation (Figure 5-8).

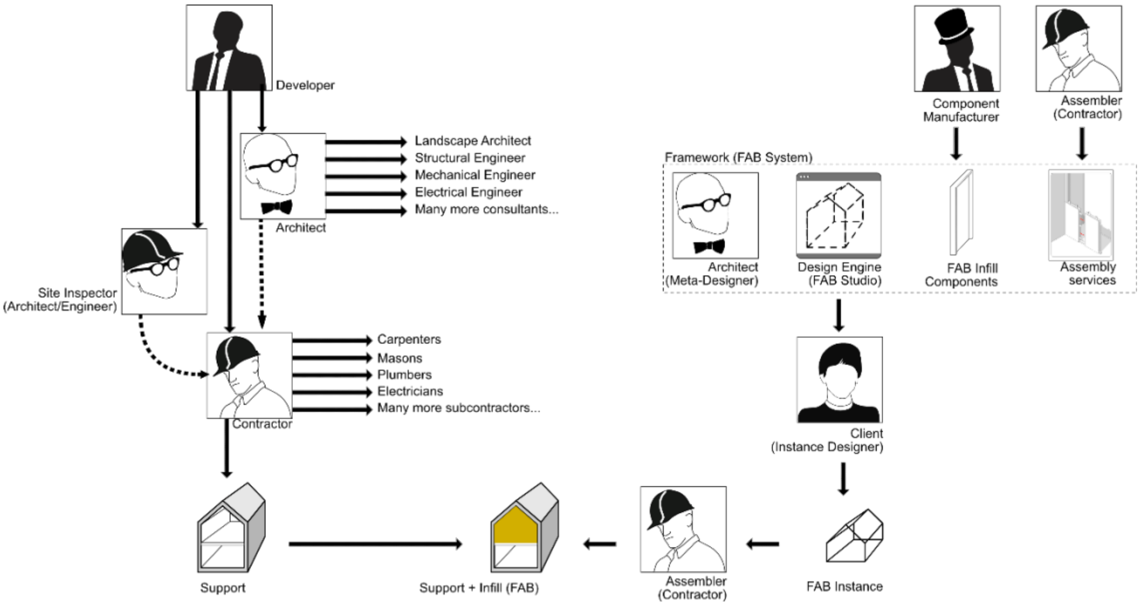

Figure 5-8: FAB system envisioned stakeholder roles

Evidently the end-users of the framework, i.e., the instance designers, are the inhabitants of the house whether they are their owners or not, which will ultimately become the elderly living in-place. What is unclear is who changes the layout? Does the elderly move the cabinetry around? Or is it a service that is provided? Brown does not explicitly define this but since the instance designers will eventually become elderly, one could assume that future renovations will be provided as a service.

5.1.4 WikiHouse

The Wikihouse project was created in September 2011 by Alastair Parvin and Nick Ierodiaconou, of Architecture 00[26], as a 3-axis CNC router cut construction system. The aim was to disrupt *"architecture's economic equation"* (Parvin, 2013, p. 94) that prevents a large chunk of the world's population from accessing architectural services.

The original system had many resemblances with Larry Sass Instant House and Wood Frame Grammar, with the structure reduced to repeated interlocking sections of plywood, interior and sheathing panels. As such, it suffered the same limitations as Sass's system. Firstly, components can be disassembled and reassembled but reuse in other contexts is hard and only partly possible due to dimensional customization. Furthermore, it shifts the complexity from the fabrication to the assembly stage, requiring a good knowledge of the system to be able to assemble it. In countries like Portugal, where conventional construction is cheap, labor costs are lower than the EU or USA average, and plywood is expensive, the system is only cost-effective if it is partially or totally self-built. Parvin acknowledged this limitation and stated that different vernaculars might be needed for different contexts (Cicero, 2013).

Wren or Wikihouse 4.0 was introduced in 2014 and is the currently available version of the system (Figure 5-9)[27]. It increases modularity compared to previous versions, which is a step forward to solve some of the previously stated issues and uses a stronger structural system suitable for 2-storey buildings. In May 2019, Blackbird beta or WikiHouse 5.0 was publicly announced by the Open Systems Lab Foundation, the system was made more modular, moving away from the previous section raising strategy to a more traditional post-and-beam approach. Yet, development eventually stopped on the beta stage and was abandoned in favor of a new design codenamed Skylark still in alpha stage.

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[26] Initial contributors were Momentum Engineering, Espians and Beatrice Galilee.

[27] Although it is the latest "stable" version with publicly available files it is no longer being actively developed.

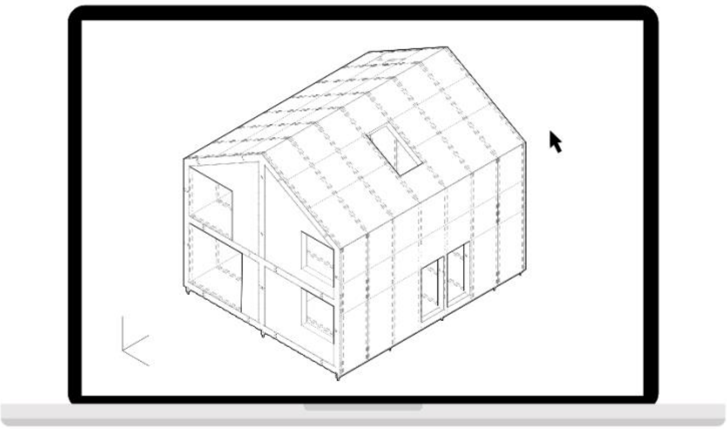

Figure 5-9: Model of Wikihouse 4.0 or Wren by Clayton Preston 2017

The first attempt to provide an interface for users to customize the system was a Sketchup plugin. This would allow an end-user to download a model from WikiHouse repository and perform some dimensional customizations. Eventually, this workflow was replaced by Grasshopper parametric model which is still available on GitHub.

Around 2017, there were some developments in the direction of creating an online customization interface, Buildx. A simple interface that could provide dimensional customization directly on a browser, foregoing the need of knowledge and access to software required to run computational models. Some of these files have been made available at GitHub but have not been updated since and a simplified version is still accessible[28].

WikiHouse platform (Figure 5-10) compared to the goals set by Ratti is still rudimentary. The designs, the CAD files and grasshopper parametric model are available online, but they still require technical know-how on CAD and parametric modelling. The Buildx website is still a prototype and cannot be used to generate a real solution. Furthermore, it can be challenging and confusing for a generic user, or even an architect, to customize a design or even access the information of previously built prototypes.

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[28] https://demo.buildx.cc

Library

Types

Ready-designed standard building layouts, combining a number of technologies into a whole building design which can be adapted to fit different users and sites.

Technologies

Open technologies and systems that can make up sub-components of an overall building.

Tools

Open source tools for the manufacture or assembly of homes.

Project Folders

A repository of known projects by WikiHouse Contributors shared under the WikiHouse Terms of Use. If you have completed a project and would like to share your files, contact us.

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Figure 5-10: wikihouse.cc online platform as of February 2019.

Since the end of 2018, the WikiHouse Foundation was replaced by Open Systems Lab Foundation, with a business model that is closer to Opendesk. Open Systems Lab became the open-source R&D team responsible for developing Wikihouse construction system, parametric model, and online configurator. The stated ambition is to reverse the building procurement process by predesigning the construction system. In the process, it is creating a new category of designers/engineers, the meta-designers, that in effect develop a customizable product for other architects/customizers, the instance-designers, to customize together with their clients (Figure 5-11).

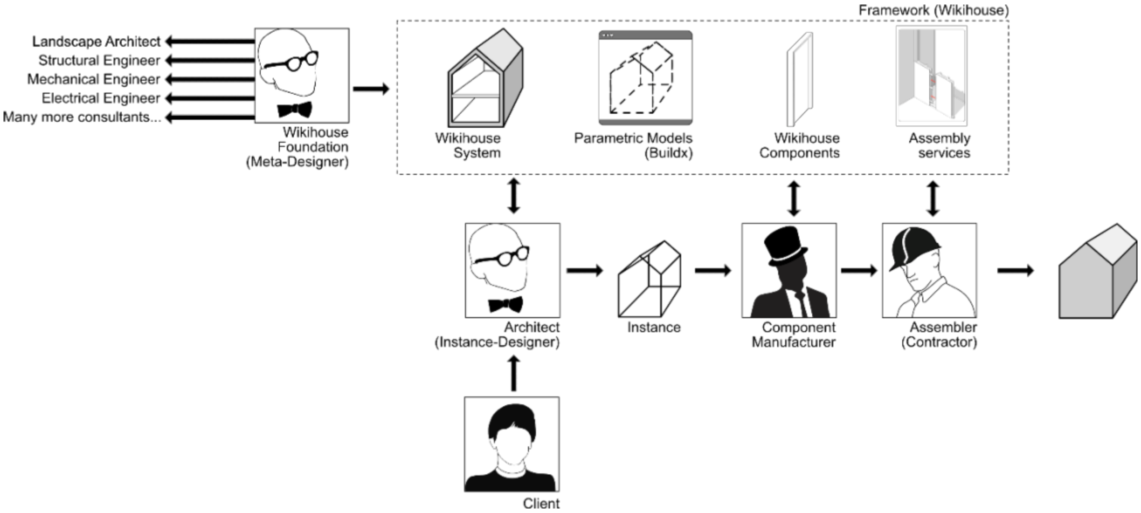

Figure 5-11: Wikihouse envisioned stakeholder roles

Wikihouse is being developed like the kernel of Linux: the templates are freely distributed; improvement suggestions can be submitted by anyone but are ultimately included in the canonical version by the foundation. This is still not an MCC system in the original sense but a digital model that can be customized and locally produced. The advantages are that the system success is not tied to its industrial scalability and may be improved by anyone, conversely it will likely be more difficult and expensive to procure by a client than an industrially produced mass-customized alternative.

5.1.5 Designer roles: Instance and Meta-Designers

To understand how MCC and OSArc shift the AEC roles it is necessary to analyze who are their ultimate users. Except for Wikihouse's Grasshopper model, none of the other cases interfaces, design engines or production systems are available. Malagueira website is still online but the design interface is nonfunctional. Brown's FABstudio is not available as website or application and none of the House_n software or website is publicly available. Therefore, it was not possible to perform usability testing or any other method of evaluating the capability of non-expert users to use these systems interfaces. However, it was possible to establish how each case aims to rearrange AEC roles based on the literature.

In all the reviewed cases there is always a clear separation between the work and role of designing the design and/or production system and that of using it to design the specific solution. The role of designing the system, the meta-designer, is generally reserved for designers with computational knowledge, which would eventually subsume different sources of knowledge into a computational model. The meta-designer level of control over the whole MCC system differs between the authors. For Brown and Duarte this role appears to encompass all aspects of the systems, while in the other two cases the control is distributed to different stakeholders. In House_n Chassis+Infill the control is centralized on the developer or system integrator, while in the Wikihouse the control is more distributed, yet the canonical source is ultimately the Foundation. Also, both cases foresee multiple meta-designers may possibly exist and contribute to the development of the system.

For Duarte and Brown, the instance designer can either be an architect working for a client or the client itself. Yet, since Brown system caters for lifelong adaptation, the inhabitants will be a second set of users of the system. These users may not be involved in the initial instance design step and may learn about the possibilities of the system collaboratively by experimenting with the design interface or by exchanging ideas with other users.

In House_n the instance designer is the building owner. The major shift in all three systems is that the client no longer invests in the development of the instance anything other than his/her time. However, Wikihouse still sees the need for the mediation of an architect in the design of the instance. One could argue that what sets Wikihouse apart is the lack of a proper design system. Which inevitably leads to the dependence on traditional CAD software environments for the customization of the design.

Based on the respective authors claims, House_n Chassis + Infill is the only case that implements a complete MCC system, including a preference and design engine, and a production system. It would cause the most radical shift in AEC stakeholder roles.

Brown system is a partial MCC system focusing only on the infill, consequently it would still require a traditional procurement process for building the support or at least striping the existing structure off its infill. On the other hand, since it focuses on a specific part of the building, it requires a more open-ended integration with other building systems.

Although Duarte announced the intention of developing a production system for Malagueira, it never came to fruition. In fact, the grammar encapsulates the design rules used by Siza, which could be argued, are adapted to conventional construction processes. Consequently, Malagueira Grammar as it was proposed generates designs which could then be used to build the house following the traditional AEC procurement process. Thus, the client must find contractors to bid for the project.

Wikihouse, in its current incarnation, is a construction system that could be used in a MC context. If coupled with the current parametric model, it could enable to automate the detailing and production of architectural designs, removing some uncertainties in the construction process, but it will not scale to mass production without a design system. With the currently available models and visual programming skills, some formal customization of the Wikihouse model, to adapt it to specific projects, is possible. Consequently, an architect will always be needed at the beginning of the procurement to design the instance. Essentially, the Wikihouse is an automated building vernacular, which would cause a smaller disruption to the traditional stakeholder roles in the procurement process that the other cases.

5.1.6 Outlook

Architects have long sought to provide their services to generic and less affluent clients. Throughout the last century this has commonly been achieved by providing standard mass-housing where customization, if possible, is limited to market segmentation or after-market customization. Digital design and fabrication combined with the development of IT and online collaboration tools have set the stage for the development of frameworks, designed by architects, for generic clients to design their spaces. These frameworks seek to address user's needs for customization of their homes by providing design systems that allow the controlled generation of solutions within specific bounds.

In doing this, the authors of all studied cases introduce the role of the meta-designer, separating the development of the system from its application. This entails some risks which are more acute in cases such as House_n, which seek to provide a holistic closed system, namely, the lack of capacity by the system or users to avoid unintended outcomes when applied to unforeseen circumstances or cases. If a system like the Malagueira grammar is deployed without a production system, ultimately providing a massification of service, there is the added risk of de-contextualization.

More generally, complete, and closed MCC systems like House_n require that a large group of companies adheres to the system for it to become economical and environmentally sustainable. Arguably, the possibility of vertical integration is extremely risky due to the complexity of the AEC industry[29]. Furthermore, the requirement of a complete change in the stakeholder roles makes it unlikely to happen unless there is a disruption.

All the previously identified risks are less significant in partial MCC systems, such as in Brown's FAB, or in customizable construction systems like Wikihouse. Moreover, their approach is more apt to the challenges of building renovation, thus making these types of solutions more generic. Nevertheless, the general applicability of systems like the Wikihouse is questionable for cost, cultural and sustainability issues. This further reinforces the need for the development of workflows to be replicated and iterated upon.

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[29] Although a subject of strong debate, this appears to have been the cause of the recent demise of Katerra, which was precisely an attempt of vertical integration in the AEC industry.

5.2 Configurator Platforms: Survey-to-design in Mass Customization Construction

Concurrently with the growing use of computational design in architecture there have been several attempts to provide ways to increase the access and distribution of parametric and computational models to users with less skills (Duarte, 2005a; El-Zanfaly, 2009; Huang & Krawczyk, 2006; Kwieciński & Markusiewicz, 2018; Mcleish, 2003). Directly distributing these models to other designers faces several barriers, as it requires from end-users a great cognitive effort and access to specific software or a specific version of it. Also, traditionally if meta-designers were seeking to deploy their computational design models to generic users, they had to develop a specific web application that would be the interface of the model for end-users. Examples of this are the work of Duarte et al (2000) or Gramazio and Kohler (2002). As frequently, designers would lack the skills for web development, deploying web configurators was mostly relegated to large research groups or companies.

Several online platforms for meta-designers have recently emerged seeking to address these issues. Contrary to traditional deployments of parametric, algorithmic, or generative models on the web, where the web interface is developed specifically for a computational design model, these platforms provide a base implementation of an interface that is automatically customized for specific model's inputs. The model and the interface together are a configurator. A configurator is understood as a customization application that is comprised of an automated design model that takes a set of expected inputs and returns a given output.

These platforms are thus a fundamental tool for the implementation of MCC systems since they can provide the interface for a broader audience. So, it is critical to assess them to determine if they can be used to implement the envisioned workflow. An important criterion is the possibility of using existing tools for each of the components of an MCC system: survey, design, and production. In this section we first review existing platforms to select one that is adequate, then we briefly look at the necessary available tools and tentative workflows design and production. As argued in Survey Systems in Chapter 3, research on MCC has not, to our knowledge, dealt with the problem of collecting geometric information of the user context. Also, geometric configurators lack a specific solution for collecting geometrical surveys that could allow meta-designers to leverage them to deliver contextual solutions for building renovation. Thus, this section finishes with a field review of existing tools to determine a workable approach to this issue.

5.2.1 Configurator Platforms

These platforms are essentially SAAS (Software-as-a-Service) platforms that allow the transition between traditional CAD or BIM software packages and web browser contexts. In general, they deploy the CAD application and the parametric model on the cloud. End-users may access it via an interface either in a browser or directly inside another design application. They are a step forward from the original experiences with bespoke configurators, enabling rapid prototyping and deployment of web configurators for MC

Those platforms aim to provide solutions for designers seeking to offer their customizable parametric models online to colleagues or clients or simply to collaborate with peers. One example of such is DynaMaker, a complete cloud-based service for developing, publishing, and maintaining parametric configurators from design to production. DynaMaker is a standalone solution which requires the meta-designer to implement the model using DynaMaker own scripting language, based on TypeScript, on their platform.

A much larger group of platforms for MCC have been developed around Rhino3D and Grasshopper. ShapeDiver or Emarf by vuild offer the possibility to leverage Grasshopper models to power online product configurators. Similarly, Paramate by Trinckle 3D, even though it has its own CAD system - trCAD, has developed a workflow for importing grasshopper models to its platform. All three platforms provide an automated process for creating a web interface for a configurator.

Swarm by CORE Thornton Tomasetti, Speckle (Stefanescu, 2020) or GHShot (Cristie & Joyce, 2019) are in a different group that focuses on powering collaboration over parametric models. Swarm in particular aims to be an app store for designers, allowing meta-designers to distribute their parametric models to instance designers directly inside their design tools, such as Rhino, Revit, or Illustrator as design apps. Swarm essentially offers an alternative to the existing methods of packaging “definitions” as components for sharing and introduces a focus on specific design tasks. Consequently, a user of a “design app” by default does not have access to the specifics of its implementation, although the author may choose to provide access to the source code.

GHShot takes a more open route, allowing all users to not only see the implementation, but also its development process, the specific states of the parameters of the model and ultimately to vote on each of these versions. In a nutshell, GHShot is a sort of visual version control system for digital design.

Speckle takes the version control approach to different level providing a Common Data Environment for a range of AEC applications, not only to Grasshopper (Poinet et al., 2021). It offers an open infrastructure for design collaboration between actors that does not impose a specific workflow, allowing the exchange of data between multiple existing applications.

Lastly, while Rhino Compute is not a platform per se, it can be used to deploy a headless Rhino on a server that responds to HTTP calls. In fact, it is the basis upon which Swarm is being built. Naturally, this could be used to build the backend of a website. The advantage is that Grasshopper and all the necessary plugins may be run without any further layers of translation. But there are several downsides of this approach: it is more complex to implement; the learning curve even for meta-designers may be too high; to offer the same functionality as in existing platforms would require a good amount of programming effort. Table 5-1 summarizes the main characteristics of the mentioned platforms.

Table 5-1: Summary of existing platforms.

	Development tools	**End-users**	**Model**	**Services / Capabilities**
ShapeDiver	Grasshopper	Designers and Non-Designers	SaaS	Model hosting, compute, visualization
Paramate	Grasshopper / trCAD	Designers and Non-Designers	SaaS	Model hosting, compute, visualization
Emarf	Emarf plugin for GH	Designers and Non-Designers	SaaS	Model hosting, compute, visualization, fabrication
DynaMaker	TypeScript	Designers and Non-Designers	SaaS	Model hosting, compute, visualization
Swarm	Grasshopper	Designers	SaaS	Model hosting, sale, distribution and compute
Speckle	Grasshopper / Dynamo / Visual Studio	Developers and Designers	Open-source	Design Development / Software Interoperability
GHShot	Grasshopper	Designers	-	Design Development
Rhino Compute	Visual Studio	Developers	Open-source	Compute

Besides being a testament to the digital transition that is taking hold of the AEC industry, these platforms are critical to establish a complete workflow from survey to production and must be usable by meta-designers and instance designers alike. Naturally, these instance designers may be other designers, non-designer professionals of the AEC industry or generic users with no specific experience in the construction field. Thus, the platform must be:

1. Functional and ideally on production stage to avoid difficulties to users (meta-designers or instance-designers);
2. Accept the most commonly used tools to develop models, and in particular those that are required for our workflow;
3. Allow the implementation of the workflow and of the tools developed during the course of this thesis;

4. Allow easy integration with websites or Content Management Systems (CMS) such as WordPress.

The previous requirements can be summarized by the following criteria: Functionality, Interoperability, UI Interaction and Website Integration. The first criterium involves not only checking if the tool is in production stage but also the deployment of some model to the platform to test if there are any unexpected limitations. More interoperability is interesting because it increases the possibilities, but it must also be checked if the necessary tools for the workflow are available: e.g.: design, optimization, nesting, simulation.

In UI Interaction we must check if each platform allows the needed user interaction and visualization modes required by the workflow, such as 2D and 3D modes, navigation, selection, drawing, dragging objects to the scene.

From the previously identified platforms, Emarf was excluded since at the time this research was conducted its website was only available in Japanese. GHShot and Speckle were also excluded since these platforms do not provide solutions for workflows that start with non-expert users, as is frequently the case with mass-customization workflows. Even though it might be possible to develop a workflow where non-expert users are involved during the process this is not sufficient. Similarly, Swarm announces a more limited scope of end-users, even though it is possible to use the design apps on a browser. Since the research was conducted, ShapeDiver and Swarm have announced they will merge into a single entity, combining their different plugins and different scopes of deployment. While it is not entirely clear what the combined platform will look like, it is probable it will combine the current features of both platforms. Since the timeframe of the merge may coincide with the testing to be performed, we included Swarm in the analysis.

Table 5-2 summarizes our analysis of the identified platforms according to the five previously defined criteria.

Table 5-2: Summary of features of each platform according to the selected criteria

	Functionality	**Interoperability**	**UI interaction**	**Website Integration**	**Current version 2020/11/20**
ShapeDiver	stable	Rhino GH support, 24 plugins and scripts (C#, VB and Python)	navigation, selection	embedding / API	1.7
Paramate	stable	Rhino GH support + one plugin, trCAD	navigation	HTML REST API	unknown
DynaMaker	stable	no support for 3rd party CAD applications	navigation, selection, drawing, delete	Wordpress / embedding / API	unknown
Swarm	alpha	Rhino GH support, 17 plugins and scripts (C#, VB and Python)	navigation	no	0.23.8

All selected platforms follow a cloud-based model. The file containing the model and the configuration interface are hosted on the server, which deals with the computation on end-user demand. ShapeDiver is in production state and Swarm is in alpha stage. While it wasn't possible to determine the specific software versions of Paramate or DynaMaker, these seem to be in production stage with sufficient documentation. Amongst the identified platforms all either have plugins or methods to import grasshopper models except for DynaMaker which has no support for 3rd party development tools. Amid them ShapeDiver has the widest support of Grasshopper's plugin ecosystem, and the support of third-party plugins has been growing fast. All the analyzed platforms, except for Swarm, provide clear and documented processes for integrating the configurator on external websites. DynaMaker has the most complete set of User Interaction modes, on the other hand ShapeDiver has a wider range of options when it comes to input / output types and formats (Table 5-3).

Table 5-3: Inputs and outputs types and formats by platform

	input types	**data types**	**output types**	**file types output**	**file types input**
ShapeDiver	geometry, text, image, sliders, toogles, value lists, color	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text, image	3dm, stl, dxf, dwg, step, obj, txt, csv, g, gcode, json, xml, ifc, jpeg, png, bmp, tiff, gif, pdf	txt, csv, json, xml, jpeg, gif, png, bmp, tiff, dxf, obj
Paramate	sliders, value lists, boolean toogle, digit scroller, control knob	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text	stl, 3mf	not stated
DynaMaker	sliders, dropdowns, text boxes, color, binary dropdown	numbers, booleans, vectors, images, text, line, arc, plane, mesh	geometry, text	stl, ply, pdf, dxf, txt, xml	not stated
Swarm	geometry, image, sliders, toogles, value lists	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	not aplicable	not aplicable

Currently, only ShapeDiver and Rhino Compute provide clear paths to the integration of to-be developed tools. ShapeDiver, presently supports a good number of GH plugins and provides a guide on what needs to be done for a plugin to become supported.

Presently, Grasshopper VPL is the most widespread development platform for the design community, in terms of users, developers, and available plugins. Within Grasshopper ecosystem it is possible to gather most of the needed tools to implement the proposed workflow. Furthermore, while a subject of strong debate, is arguably less intimidating or more accessible to designers unfamiliar with programming.

The appraisal indicates that currently ShapeDiver provides the most straightforward path to implement our proposed workflow. Yet, it is important to note that none of the reviewed platforms are open-source, but at the time of writing there is no open-source alternative.

5.2.2 As-Is Survey

In this section we address the first question regarding the processes by which instance-designers may provide necessary information about their contexts. Relevant contextual information for design can be divided into user preferences and context information which can be collected independently. In this section we focus on the context information, which can be further divided into geometrical and semantical properties. Semantical properties relate to the nature of the building elements enclosing the space, e.g., wall, floor, door. While geometrical properties identify the geometrical relations between building elements and their specific dimensional properties.

The process of acquiring geometrical and semantical information of a given context and converting it CAD/BIM primitives is studied and described in the literature as As-Is Survey (Becker et al., 2019) or As-Built Survey (Pătrăucean et al., 2015). Becker et al proposed that the concept of As-Built be reserved for the process of updating existing design models, e.g., the As-Designed BIM, during or after the construction process. Thus, an As-Is Survey occurs when there is no pre-existing digital model, and all the information is inferred from a survey and/or documentation of an existing in-use building.

As-Is surveys have several objective limitations (Pătrăucean et al., 2015): (1) High level semantic information such as cost and product specifications are not inferable (e.g. type of paint used); (2) The achievable level of detail in an as-is survey is limited by practical considerations of data collection and can be cast as a tradeoff between cost and sufficient detail; (3) It is not possible to collect geometric data of occluded building elements.

There are several approaches to deal with the problem of producing As-Is Surveys and all of them depend to some extend on user intervention, i.e., the surveyor, at the very least to collect the data to be processed. Since there is a need of user intervention in the collection process, the limitations of minimum required user expertise and required tools must also be considered. We identify three main groups of workflows which can be distinguished by the methods that are used to collect the relevant geometrical data (Figure 5-12): capturing point-clouds, assisted plan generation, and sketching / measuring.

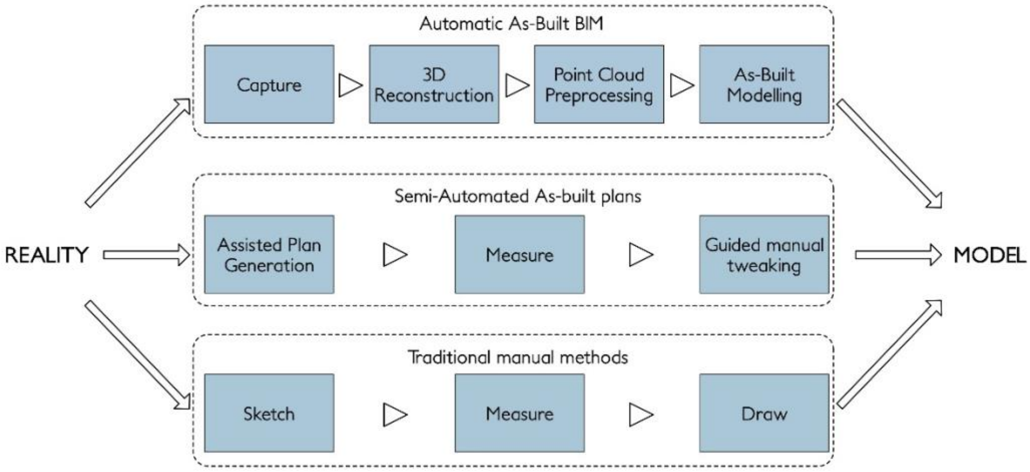


Figure 5-12: 3 commonly used workflows to generate as-is surveys

According to Tang et al (2010), the first group of workflows involves a data collection, data preprocessing and modelling stages. Pătrăucean et al (2015) further divides the data preprocessing stage into 3D Reconstruction and Point-cloud preprocessing. The most common methods for data acquisition are Terrestrial Laser Scanning (TLS), with time-of-flight or phase-shift laser scanners (Tang et al., 2010; Yue & Krishnamurti, 2007), or Photogrammetry (PHG), with digital cameras (Pollefeys et al., 1999, 2004b; Remondino et al., 2012; Yue & Krishnamurti, 2009), each requiring specific 3D reconstruction algorithms. The 3D reconstruction stage output is point-cloud and a preprocessing stage is generally deemed necessary to improve modelling accuracy, and may involve removal of outliers, reduction of noise, segmentation, or down sampling (Pătrăucean et al., 2015). The last stage is the process of converting the point-cloud into a model, either 2D or 3D, that is usable for design, maintenance, or documentation process.

The previously described workflow may be conducted in a semi-automated (Jung et al., 2014; Quattrini et al., 2015) our completely automated fashion (Brilakis et al., 2010; Tamke et al., 2016). Semi-automated workflows have gained popularity in the architecture, engineering and construction industry for BIM modelling (Jung et al., 2014; Xiao & Furukawa, 2012). Although extremely precise and rich in detail, these methods are computationally intensive, time consuming, mostly manual, require advanced modelling knowledge, and access to specific expensive equipment (Brilakis et al., 2010; Tzedaki & Kamara, 2013). Research on completely automatic processes to obtain As-is BIM models from point-clouds, Scan-to-BIM, is mostly ongoing (Becker et al., 2019; Pătrăucean et al., 2015).

Photogrammetry is a cost-effective alternative of generating point-clouds from existing buildings using off-self cameras (Pollefeys et al., 1999, 2004a) or mobile phones (Poiesi et al., 2017; Tanskanen et al., 2013). However, 3D reconstruction pipelines using smartphones still require cloud processing to generate dense 3D models (Kolev et al., 2014) or meshes (Muratov et al., 2016). Furthermore, the quality of the output of photogrammetry-based methods is highly susceptible to quality of the network, which can be adversely affected by user skills and a number of issues common in building interiors: homogeneous textured areas, room clutter, mirrors and reflective surfaces, repetitive patterns, windows, etc (Erickson et al., 2013; Kolev et al., 2014; Remondino et al., 2012). Most of these problems are only visible after the system builds the model.

The last workflow in Figure 5-12 is the traditional empiric methods used by architects and construction professionals. The first steps are to sketch the existing space and take the needed field measurements. Lastly, this information is used to geometrically reconstruct plans, sections, and elevations. In orthogonal spaces is enough to measure the length of each wall of the perimeter of the space and register the turn, left or right, at each corner to accurately reconstruct the space.

Smartphone applications, such as Magicplan (IOS 12.1, version 7.2.2) or RoomScan (IOS 12), leverage these empiric methods to provide semi-automated workflows for generating as-is models onsite involving user interaction, smartphone sensors and camera (Figure 5-12, middle). These methods are fast and cost-effective for as-is surveys of a few rooms or spaces. Furthermore, these methods are multiplatform since they do not depend on specific platform capabilities, such as cameras or smart-phone sensors, and can generate 2D plants and 3D models which might be integrated or exported to configurators, or vice-versa, the configurators might be delivered to these apps as services.

In this context, two questions emerge: Are these semi-automated methods of capturing or generating floor plans for non-expert users sufficiently accurate for MCC systems for customizable and disassemble-able partition systems? Are non-expert users able to use these methods reliably to produce sufficiently accurate plans?

5.2.2.1 Two As-Is Survey Experiments

To reply to the preceding questions, we conducted two experiments: a comparative test of the two applications with reference surveying methods used in practice, and a usability test (Molich & Dumas, 2008) with expert and non-expert users. In the context of this research, an expert user is a person with professional experience in doing building surveys (Brandao & Paio, 2019).

5.2.2.2 1st Experiment: Comparative Test

The first experiment was conducted by the researchers, using several surveying methods to produce as-built plans of three rooms. In the second experiment, a group of non-expert users and a group of expert users were asked to survey one of the rooms using phone application-based methods.

The objective of the first experiment is to collect insights on the accuracy, time, and usability of the different methods, and for researchers to become acquainted with the workflow of each app. The goal of the second experiment is to evaluate the usability of the applications by carrying out usability testing to ultimately determine if these users can produce sufficiently accurate plans.

Usability testing was selected since it will allow us to observe the users in action and specifically answer the following questions:

1. Is the user aware of the room's relevant geometrical properties such as the number of sides?
2. Was the user capable of using the app(s) to draw a polygon with the correct number of sides?
3. Is the user confident that the result faithfully represents the space and its dimensions?
4. How good are their tape / laser measurement procedures?

Two applications were selected to conduct the experiment: Magicplan (IOS 12.1, version 7.2.2) (APP 1) and RoomScan (IOS 12) (APP 2). The selection criteria were the user and download ranking, free availability at the time of selection (September 2018), and the possibility to survey rooms. At the time of testing, these were highest ranking free apps with a complete feature set for designing room plans on the App Store. Both applications were designed to be used by experts and non-experts alike, provide several different workflows and used a freemium model having all features available to use except for the ability to export the plans, which was subject to payment. The selected expert survey methods were Terrestrial Photogrammetry (PHG), Terrestrial Laser Scanning (TLS) and manual survey techniques (Manual).

TLS is used as primary reference to compare the performance of the remaining methods, since it has been found to be more accurate than PHG when compared to topographic surveying methods (Nuttens et al., 2011). Yet, it is important to note that TLS phase-shift scanners, accuracy can be influenced material properties, such as color and reflectivity, and angle of incidence (Alkan & Karsidag, 2012; Kersten et al., 2009).

Three rooms in a to-be renovated building, part of a larger group of four buildings, were chosen to conduct the experiments (Figure 5-13 and Figure 5-14). The selected rooms are in a 19th century building in the historical city centre of Braga in Portugal, which is representative of the common building typologies found in Portuguese city centres. Distinctive typological features are stone façades and party walls, wooden floors and roofs, a central staircase with a skylight, located in a narrow plot. The rooms were selected for the challenges they present to surveying, but also because they represent the usual situations which are found in building renovation in Portugal, particularly in 19th century buildings.

Figure 5-13: Case-study buildings street façades (drawing by PARQUR)

These challenges are higher geometric complexity, such as rooms with more than four sides, containing non-orthogonal corners, uneven walls, floors, or ceilings; (1) cluttered rooms with furniture or objects; and (2) challenging wall finishes, such as black painted or high reflective surfaces, and high contrast situations. Some of these characteristics can pose problems to the

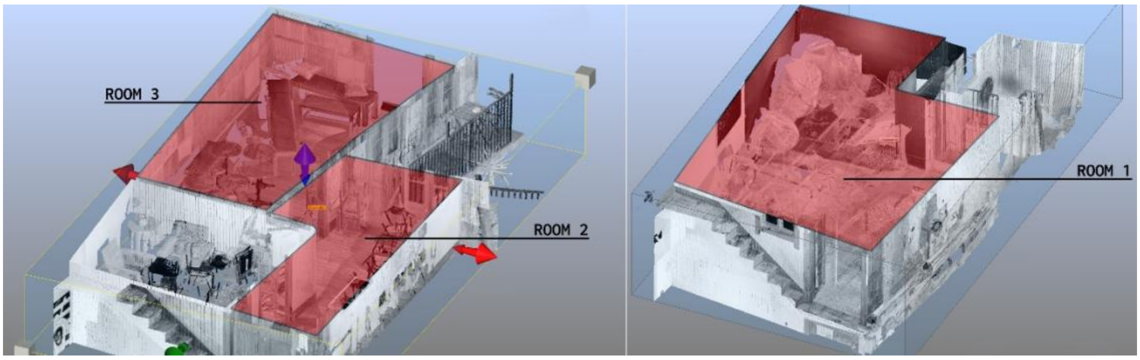


Figure 5-14: Case-study rooms in to-be renovated buildings

users' perception of the space, others can be challenging to some surveying methods (Alkan & Karsidag, 2012; Kersten et al., 2009).

Table 5-4 presents some of those characteristics of the selected buildings, such as the proportion of rooms with five or more sides and the proportion of rooms with one or more internal angle that deviates more than two degrees from orthogonality.

Table 5-4: Number of rooms per number of sides and angular threshold.

Rooms	**Sides**			**Angles**	
	4	**> 4**	**%**	**Bellow T**	**Above T**
Building 1 (Nº Rooms)	12	5	29,4%	3	14
Building 2 (Nº Rooms)	11	7	38,9%	5	13
Building 3 (Nº Rooms)	16	5	23,8%	5	16
Building 4 (Nº Rooms)	16	6	27,3%	2	20
Total	55	23		15	63
%	70,5%	29,5%		19,2%	80,8%

Angles Bellow T: All internal angles deviate from orthogonality less than the Threshold of 2 degrees
Angles Above T: At least one of the internal angles deviates more than 2 degrees from the orthogonal

5.2.2.3 Data Collection, Processing and Analysis

For the TLS survey a FARO FOCUS S120 phase-shift scanner, a Leica GPS 1200 GNSS station and a Leica 1203 TCRP total station were used. The survey encompassed the 4 buildings interiors, the street and backwards façades, and the backyards of each building. It took 3 days to complete and generated a point-cloud composed of 258 scans grouped in 23 clusters. The average interior scan took 2 minutes to finish, not including the machine setup time, and an exterior one 8 minutes. Scanning Room 1 required 3 stations, and Room 2 and 3 required two. The point clouds were aligned in SCENE with an average error of 2,36 mm. Lastly, horizontal sections of the rooms at 1,8m distance from the floor were then exported in DXF format to AutoCAD and the 2D plans drawn to compare the plans with the other methods. Since there were only three plans, we opted for a manual drawing process that mimics semi-automated workflows (Andriasyan et al., 2020): the points of each side of the room were selected and a best-fit line was found. Then these were extended to their respective intersections at the corners.

The photogrammetry survey followed a similar workflow. Photographs were taken inside the three selected rooms with a Nikon D700 camera equipped with a 25mm manual focus lens in RAW format. The images were post-processed in Lightroom and exported to JPEG. These images were then imported to PhotoScan to produce a point-cloud for each room, which was exported to Cloud Compare to create sections for drawing the 2D plan of the room.

The rooms were also surveyed using traditional empirical methods of survey. Starting with a sketch of the room plan, measurements are then taken 1.8m from the floor, with laser distance meter or tape measure and annotated on the plan (Figure 5-15). These measurements and sketches were later used to design the plan in a 2D CAD program.

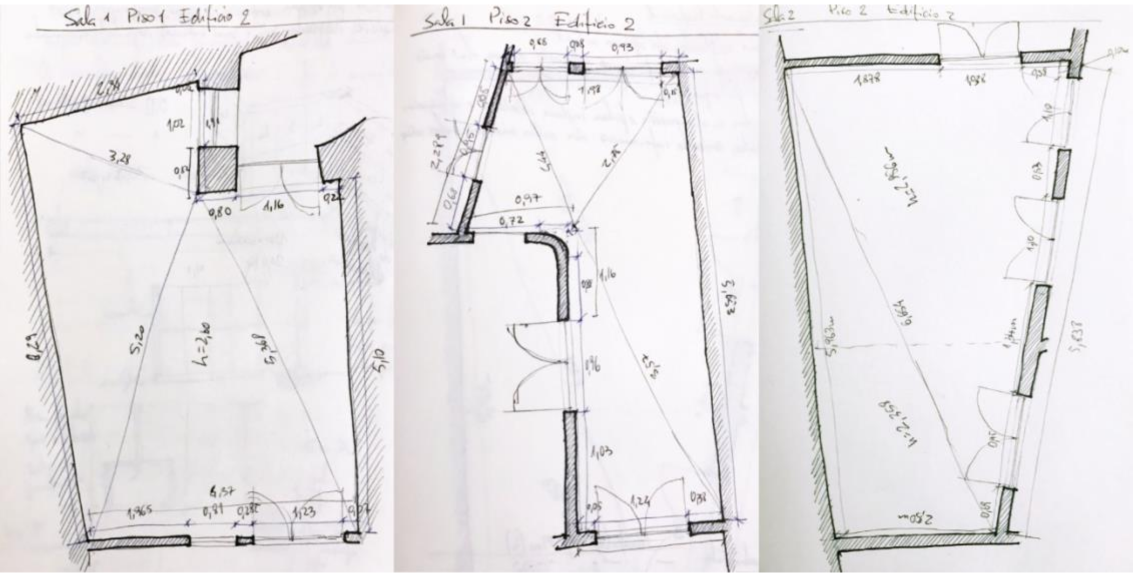


Figure 5-15: Sketches of the rooms and onsite measurements (Brandão & Paio, 2019)

Each app provides several workflows for surveying rooms. App 1 has four workflows: (1) survey by capturing the corners of the room using the phone's camera; (2) Draw a rectangle room using the editor; (3) sketch a free shape using the editor; and (4) draw the space plan using an underlayer plan. App 2 offers three workflows: (1) survey by touching walls; (2) survey with camera; and (3) draw manually. We selected two workflows that represent the most common types available across multiple applications.

The first method from both apps was selected. On APP 1, this first workflow uses Augmented Reality, orientation sensors and user input to map the room corners, which must be captured in a clockwise or anticlockwise order. On APP 2 the first workflow requests the user to place the phone against all the walls in clockwise or anti-clockwise sequence, the same method can be used to place doors or windows. The phone's accelerometer and orientation sensors are used in combination with user movement, to determine the shape and dimensions of the space. Both APP 1 and 2 allow the room plan to be edited after the survey process is completed, i.e., changing wall lengths, adding/subtracting walls, or corners. The generated plan and the manually edited plan, with the wall measurements obtained with a laser distance meter, were recorded, and reproduced in CAD for comparison purposes.

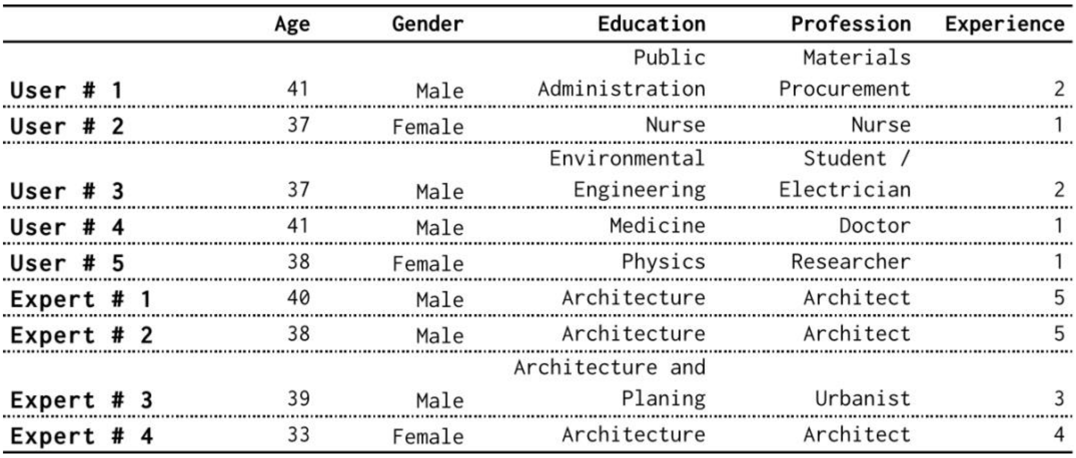
The plans were compared using two metrics: (1) the difference of side lengths; and (2) the angular difference. The time it took to complete each of the workflows was also registered at each step of the process. Since the TLS scan campaign was not conducted specifically for these

3 rooms only the last two tasks were measured specifically for each room: exporting a section and drawing the 2D plan. The remaining task were estimated as a percentage of the number of scans stations per each room.

5.2.2.4 2nd Experiment: User Testing

The second experiment was conducted in 3 separate sessions, between 10th and the 18th of November 2018 (Brandao & Paio, 2019). The experiment was completed with a group of 5 non-expert users and 4 expert users, in line with usability tests for an iterative development process (Molich and Dumas, 2008), of which were 33% female and 66% male with ages between 33 and 41 years old (Table 5-5), on one of the previously selected rooms.

Table 5-5: Participant's profile and results



	Age	Gender	Education	Profession	Experience
User # 1	41	Male	Public Administration	Materials Procurement	2
User # 2	37	Female	Nurse	Nurse	1
User # 3	37	Male	Environmental Engineering	Student / Electrician	2
User # 4	41	Male	Medicine	Doctor	1
User # 5	38	Female	Physics	Researcher	1
Expert # 1	40	Male	Architecture	Architect	5
Expert # 2	38	Male	Architecture	Architect	5
Expert # 3	39	Male	Architecture and Planing	Urbanist	3
Expert # 4	33	Female	Architecture	Architect	4

In the non-expert group, two participants worked in construction companies but do not have experience in surveys. One of them is an accountant and the other is a student of environmental engineering and an electrician who stated having experience using two CAD software packages. Thus, although they do not have specific experience in surveys, they should be considered more proficient than a generic user and be classified as a prosumer sub-group within the non-expert group. Similarly, although Expert # 3 has previous experience on surveying, he has worked mostly as an urban planner. While Expert # 4 only has 5 years of practice.

The participants were invited to survey Room 1 with the selected mobile phone applications to produce an as-built plan of the existing space. The aim of the survey was not explained and none of the users had previous experience with these applications or has acquainted with similar applications. The participants were free to use one or both applications, using any of the workflows available, consequently, they had at their disposal all 7 workflows to survey the room. We provided a laser distance meter and a tape measure, and the users were instructed on how to use these tools but no information regarding good measurement practices was provided.

The process was recorded in video by the researcher, and the participants were told to terminate the experience when a satisfactory result was achieved. To the determine the user perception of the room and results a few questions were asked at the end of the session.

To evaluate the user measurement procedures, i.e., the quality of measurements (QoM), we selected 3 evaluation criteria, whose assessment was done by observing the users in action: measurements taken at a constant height, distance of the laser from the corner, and number of walls measured. The first criterium was evaluated using the participant body as a frame of reference to determine a range of heights. The second criterium was evaluated by estimating the distance from the corner using visual cues of know objects, such as the laser distance meter. A classification was attributed to each of metrics following the levels in Table 5-6. The plans produced by each of the users was recorded and reproduced in 2D CAD.

Table 5-6: Levels of Quality of Measurement (QoM)

QoM value	Constant Height	Distance from Corner
5	+/-10cm	against the corner
4	+/-20cm	<10cm
3	+/-50cm	10<X<50cm
2	+/-80cm	50<X<100cm
1	+/-floor	more

5.2.2.5 Testing Results

This section presents the results both experiments starting with the first experiment workflow timings, then the geometric accuracy comparisons between plans, and an exemplification of the consequences of using one of the APP plans for designing partitions for digital fabrication. Lastly, we present the results of the user testing.

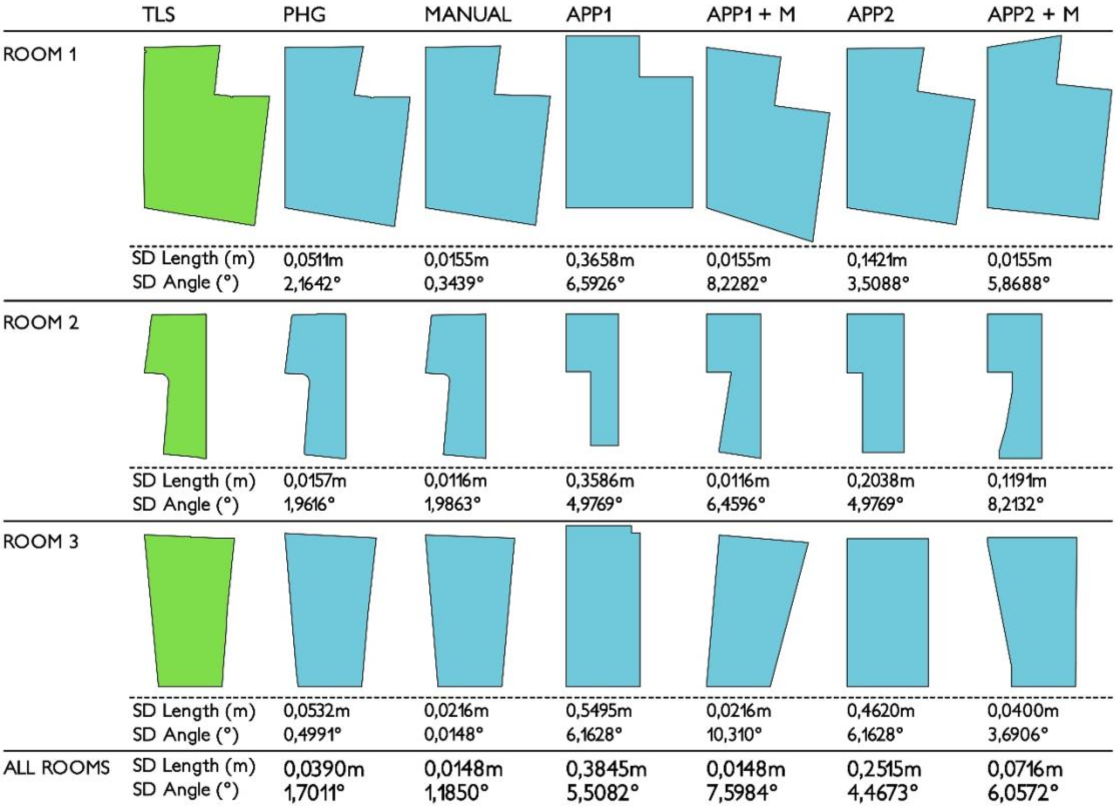
5.2.2.6 Comparison Tests

The time it took to complete each workflow is presented in Table 5-7. Clearly the App methods are the fastest, followed by the Manual method which takes slightly under twice the time. TLS and PHG take several orders of magnitude longer to complete and are both dominated by the data processing stage. This indicates that increasing computational power and improvements in algorithmic performance may significantly reduce the difference between these methods in the future. Also, automation in the drawing stage, i.e., automatic methods of extracting 2D and 3D geometry from point clouds, is also an important avenue for improvement. This is especially relevant since the Data Collection stage is similar between all methods, with TLS data collection time being related with the number of stations and PHG with the number of photographs.

Table 5-7: Workflow times per stage and room

		TLS time (s)	PHG time (s)	MANUAL time (s)	APP 1 time (s)	APP 2 time (s)
ROOM 1	Data Collection	900	703	435	395	406
	Data Processing	3284	8233	_	_	_
	Drawing	1139	1060	365	_	_
	TOTAL	5323	9996	800	395	406
ROOM 2	Data Collection	360	260	373	390	400
	Data Processing	2189	1581	_	_	_
	Drawing	650	990	241	_	_
	TOTAL	3199	2831	614	390	400
ROOM 3	Data Collection	360	304	365	263	262
	Data Processing	2189	5970	_	_	_
	Drawing	640	1000	117	_	_
	TOTAL	3189	7274	482	263	262

For length and angle comparisons between the workflow plans, the TLS and PHG output were simplified to a polygon of 4 or 6 sides, depending on the room. For clarity all the windows and doors have been removed, only the inner outline of the space is kept. This process demonstrated that important details that would have impact on fabrication are not captured, e.g., in Room 3 a bulge of 4 cm is eliminated. The plans produced in first experiment are compared in Figure 5-16, together with the Standard Deviation (SD) of angular dimensions of corners and length of walls. TLS is used as a reference for calculation of the standard deviation



		PHG	MANUAL	APP1	APP1 + M	APP2	APP2 + M
ROOM 1	SD Length (m)	0,0511m	0,0155m	0,3658m	0,0155m	0,1421m	0,0155m
	SD Angle (°)	2,1642°	0,3439°	6,5926°	8,2282°	3,5088°	5,8688°
ROOM 2	SD Length (m)	0,0157m	0,0116m	0,3586m	0,0116m	0,2038m	0,1191m
	SD Angle (°)	1,9616°	1,9863°	4,9769°	6,4596°	4,9769°	8,2132°
ROOM 3	SD Length (m)	0,0532m	0,0216m	0,5495m	0,0216m	0,4620m	0,0400m
	SD Angle (°)	0,4991°	0,0148°	6,1628°	10,310°	6,1628°	3,6906°
ALL ROOMS	SD Length (m)	0,0390m	0,0148m	0,3845m	0,0148m	0,2515m	0,0716m
	SD Angle (°)	1,7011°	1,1850°	5,5082°	7,5984°	4,4673°	6,0572°

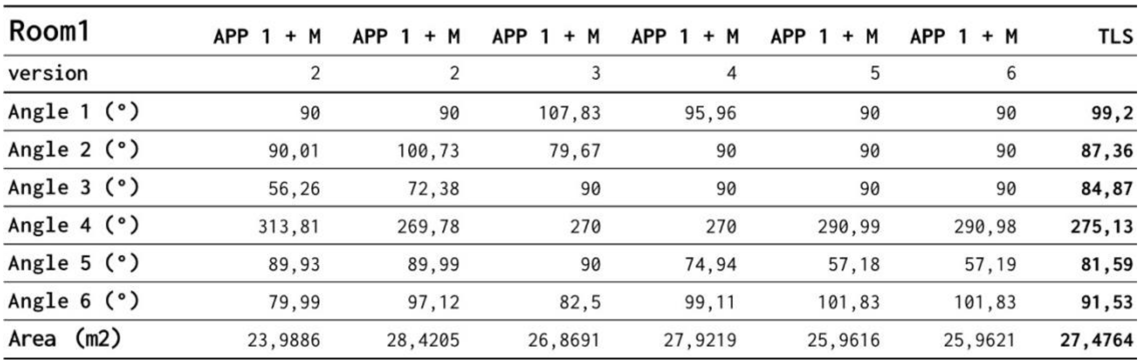
Figure 5-16: Matrix of plans by surveying method and room with Standard Deviation of angles and lengths per room.

(SD). APP 1 + M and APP 2 + M are the plans of each of the apps after the side lengths measurements are introduced.

TLS and PHG output plans have more detail than the remaining methods, particularly in Room1 where their respective polygons have more sides. Automated app-based methods are significantly less accurate than the expert methods. Introducing onsite measurement to correct the plans does increase the accuracy of the side's dimensions, as would be expected, but decreases the accuracy of the angles of the polygon (Figure 5-16).

The Manual workflow has a smaller SD than PHG. This can be attributed to the PHG sensitivity to bad lighting conditions, lack of detail, or reflective objects such as mirrors. In the experiment a full-frame DSLR was used which improves signal to noise ratio, but the low room lighting required the use of a large aperture, thus decreasing the depth of field. Room 1, which has the highest SD on angle and length measurements amongst the rooms surveyed with PHG, has half of its' walls painted in white and the other in black. The high contrast between white and black walls requires a compromise on exposure. Using high dynamic range images may possibly improve the quality of the results but this was not tested. However, all expert methods of survey presented significantly better results than app-based methods.

Table 5-8: Angle and Area variation of the plans from workflow APP 1 + M on Room 1 by varying the starting side



Room1	APP 1 + M	APP 1 + M	APP 1 + M	APP 1 + M	APP 1 + M	APP 1 + M	TLS
version	2	2	3	4	5	6	
Angle 1 (°)	90	90	107,83	95,96	90	90	**99,2**
Angle 2 (°)	90,01	100,73	79,67	90	90	90	**87,36**
Angle 3 (°)	56,26	72,38	90	90	90	90	**84,87**
Angle 4 (°)	313,81	269,78	270	270	290,99	290,98	**275,13**
Angle 5 (°)	89,93	89,99	90	74,94	57,18	57,19	**81,59**
Angle 6 (°)	79,99	97,12	82,5	99,11	101,83	101,83	**91,53**
Area (m2)	23,9886	28,4205	26,8691	27,9219	25,9616	25,9621	**27,4764**

It was also noted that the final plan of the Apps workflows (APP 1 + M and APP 2 + M) can vary significantly depending on the side where the introduction of the manual measurements starts (Figure 5-17). As an example, Figure 5-17 presents all the possible outcomes of APP 1 + M on Room 1 and Table 5-8 the respective internal angles and area. The onsite wall length measurements were inserted on the application clockwise, beginning on the side marked with the arrow for each of the plans. This workflow produced 5 significantly different plans of the same room.

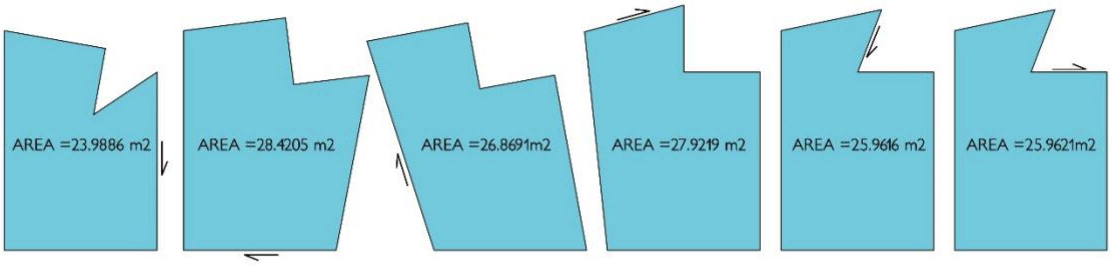


Figure 5-17: Outcomes of the workflow APP 1 + M on Room 1 by varying the starting side (Brandão & Paio, 2019).

The observed behaviour of the applications is: (1) the application automatically locks the user introduced dimensions and scales the remaining unlocked dimensions to maintain the angular properties of the space; (2) The shape of the space is kept constrained to an ortho-polygon until all the lengths of the "third side" are introduced; (3) When the total dimension of a wall where there is a door is changed, the dimension of the door is kept, and the wall's partial dimensions are changed; (4) The form of the room polygon is the result of the introduced dimensions; and (5) It is not possible to edit the angular dimensions or to add diagonal measurements. The issues outlined above and observed behaviour are present in both applications. App 2 introduces one further problem, when the second last side measurement is introduced, the last side can be split in multiple segments. This behaviour was observed in Room 2 and 3.

To determine the consequences of using each of the surveyed plans as a starting point for planning the subdivision of the space and the partition walls production with digital fabrication, several possible subdivisions of Room 1 were considered. Since the space area is below the minimum for a housing unit in Portugal, the space would have to be used as part of a larger whole. Figure 5-18 shows the position of the space on the first floor and the floor above it. Expanding towards the opposite façade is not possible since there would be no way to create a private connection while maintaining the current communal staircase. Clearly there are two more likely scenarios either the space is part of a larger whole that occupies the whole building or there must be some internal stair that connects it independently to the upper floor. Independently of the chosen scenario, since the space has a small façade and is below the backyard ground level a likely possible use would be a bedroom.

For briefness we present a subdivision solution for the first scenario, Sub 2. In Sub 2, the space is divided in three functional spaces: a double bedroom with a en suite bathroom and a corridor connecting both spaces, the entrance door, and the exit. This is a common trait of the renovation interventions in these building typologies, since many of these 19th century buildings do not have interior bathrooms as is expected in contemporary housing in Portugal.

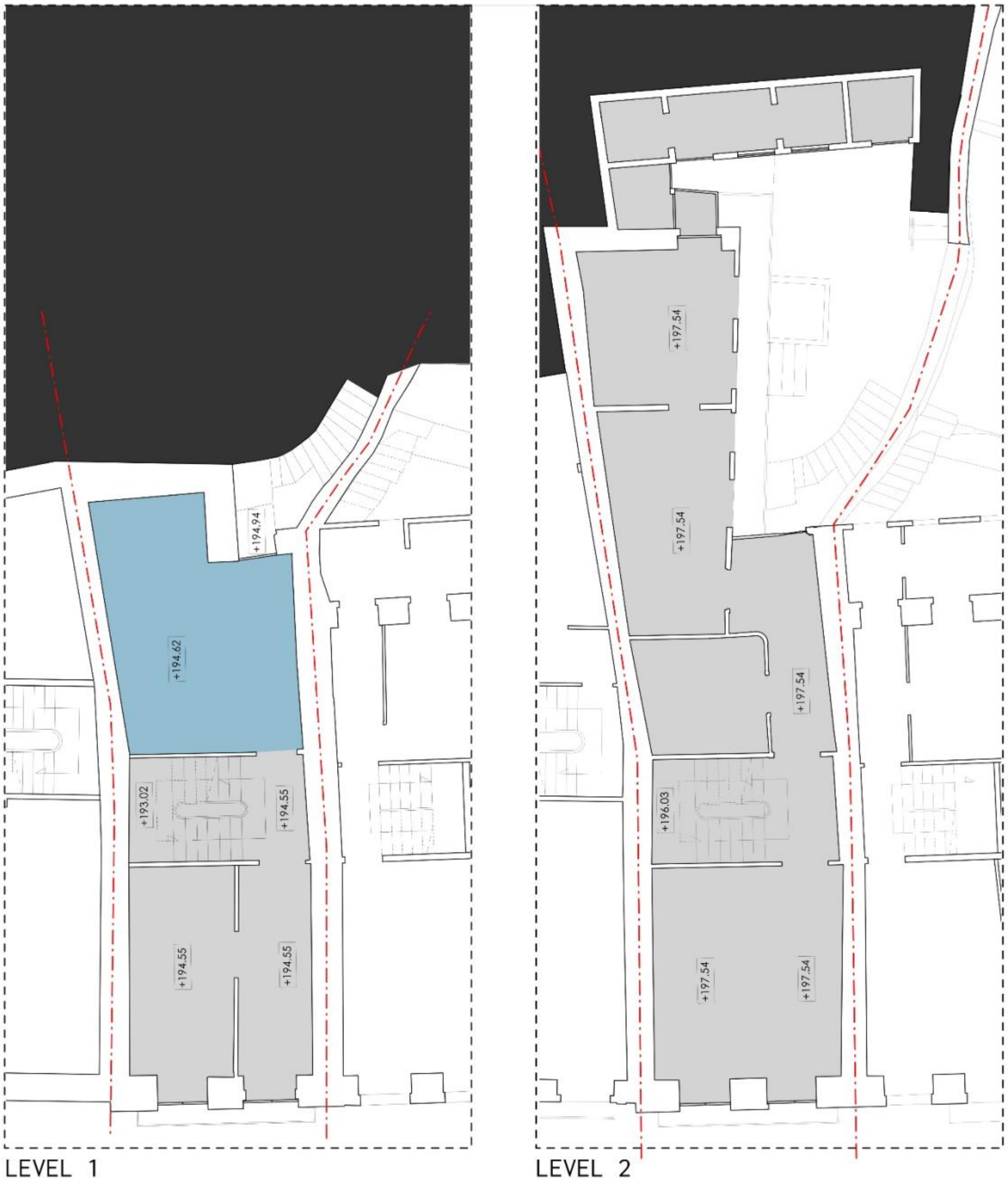


Figure 5-18: Plan of first and second levels of the studied building

To design the subdivision the TLS plan and following rules where used: (1) subdivide the space with a wall running parallel to the party wall with an offset of 1.42m; then (2) subdivide the larger space by creating a wall parallel to the stair partition wall with an offset of 1,8m.

The first rule places the wall between the interior window and the door on one side and next to the exterior door on the other. A minimum of 1,1m is required by law, but in this instance the corridor cannot be made thinner because of the existing doors. There are visible remnants of a wall in this position, both on the walls and ceiling, that was demolished at some point. This position is optimal but there is space on both sides to accommodate some rotation, while this is not desirable since it would imply a misalignment with the wall remnants.

The second rule is meant to create a bathroom with a bathtub, with 1,80x0,8m standard dimensions, a toilet, a wash basin, and a bidet. The parallelism of opposing walls should ideally be kept, particularly because of the bathtub, however that it is not mandatory, as it would still be possible to install the standard bathtub if the shortest distance between walls is larger than the length of the bathtub.

These rooms would naturally require doors but as these are generally within the partition walls, the impact of dimensioning errors of the walls would only affect the doors if these were at the extreme edges of the partitions. Thus, this is not considered relevant for the present purposes and the doors are not presented in the plans.

Figure 5-19 presents the outcomes of applying the proposed rules to each of the as-is plans. Hereafter, for briefness we will refer to the walls generated by applying the rules to each as-built plan by the name of the respective method used to survey it. PHG walls are shorter and have a 0,26 degrees larger internal angle than TLS walls. This indicates that the assembly of the walls onsite would not be constrained by the existing walls. The Manual walls have a smaller angular error, but the longer wall is 3 cm longer. This could cause fitting problems if the construction system has no length tolerance.

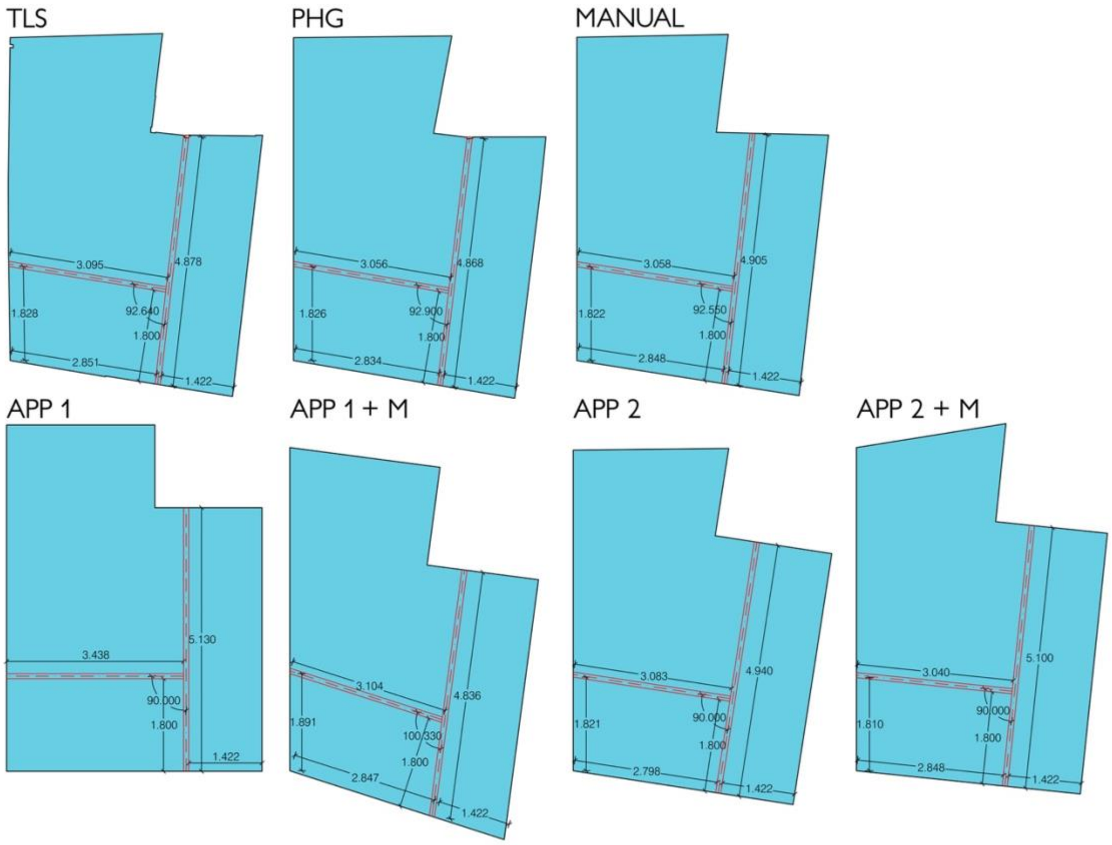


Figure 5-19: Outcomes of the application of rules of wall generation to each of the plans (Brandão & Paio, 2019).

In all the App cases the differences are larger both in wall lengths and internal angle. App1 plans are meaningfully different in terms of shape. App 1 +M plan might lead the user to change the design rules or select an altogether different design solution to avoid spaces with acute angles. App 2 and App 2 +M are the most similar to the walls generated in the TLS plan.

From the previous results, it is evident that using any of these as-is plans for designing a subdivision solution will have some onsite consequences in fitting the digitally fabricated solution. To test this, we used the TLS as-is plan as a ground truth to position the Manual, APP 2 and APP 2 + M generated walls (Figure 5-20).

To position the walls, we tried to follow the design rules, which was only possible with the Manual walls. In the other cases, if the parallelism of the bathroom wall to the stair wall is kept, the longer wall would overlap the interior window on one side and the exterior door on the other. Otherwise, if the parallelism of the longer wall to the party wall is kept, it would not be possible to install the bathtub. Yet, the most important issue in both cases is that the longer wall is 6,2 to 22,2 cm longer than the existing space.

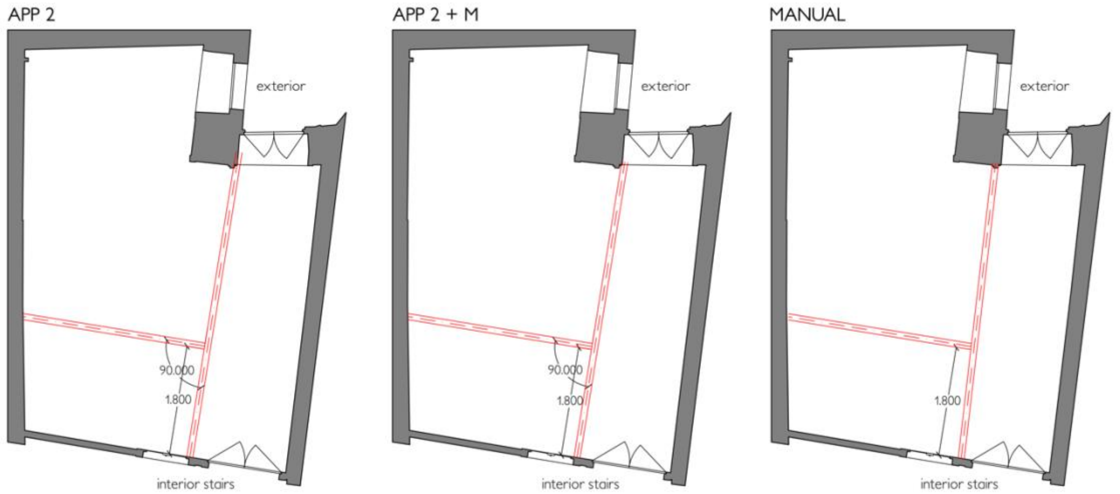


Figure 5-20: Application of walls generated in APP 2, APP 2 + M and Manual plans to TLS plan (Brandão & Paio, 2019).

5.2.2.7 User Testing

The results of the user testing experiment are summarized in Table 5-9 for each of the initial questions and evaluation criteria. 89% of the participants started with a Camera workflow and 78% of them used the Camera workflow of App1.

Table 5-9: Summary of results from user testing experiment on Room 1

		User #1	User #2	User #3	User #4	User # 5	Expert # 1	Expert # 2	Expert # 3	Expert # 4
	Experience	2	1	2	1	1	5	5	3	4
1.	Perception of Morphology	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2.	Produced a Plan	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
2.1	Number of Atempts	1	4	1	3	2	2	7	2	1
2.2	Number of Completed Plans	1	2	1	0	1	2	2	2	1
2.3	Morphological Similarity	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes
3.	User perception of results	High Confidence	No Confidence	High Confidence	NR	No Confidence	Low Confidence	Low Confidence	Medium Confidence	Low Confidence
4.	QoM: Average	3,3	2,0	3,7	2,7	2,3	4,7	5,0	3,3	3,3
4.1	QoM: Constant Height	3	1	2	4	4	3	4	4	3
4.2	QoM: Distance from Corner	1	1	3	2	1	5	5	5	1
4.3	QoM: Measured Walls	6	4	6	2	2	6	6	1	6
	Total Time	1053	1974	550	842	516	813	1990	567	691

All participants were aware of the geometrical shape of the room. Even if they could not use one of the Apps to complete the survey, at the end of the session, they were all able to express what were the limitations of the plan they had produced.

All users except User # 4 produced some plan using one of the available application workflows, independently of its' morphological similarity with the existing room. This participant, out of frustration, decided to draw a plan of the room with some measurements on the blackboard. The plan he drawn showed both a morphological and a strong geometrical similarity with the room (Figure 5-21).

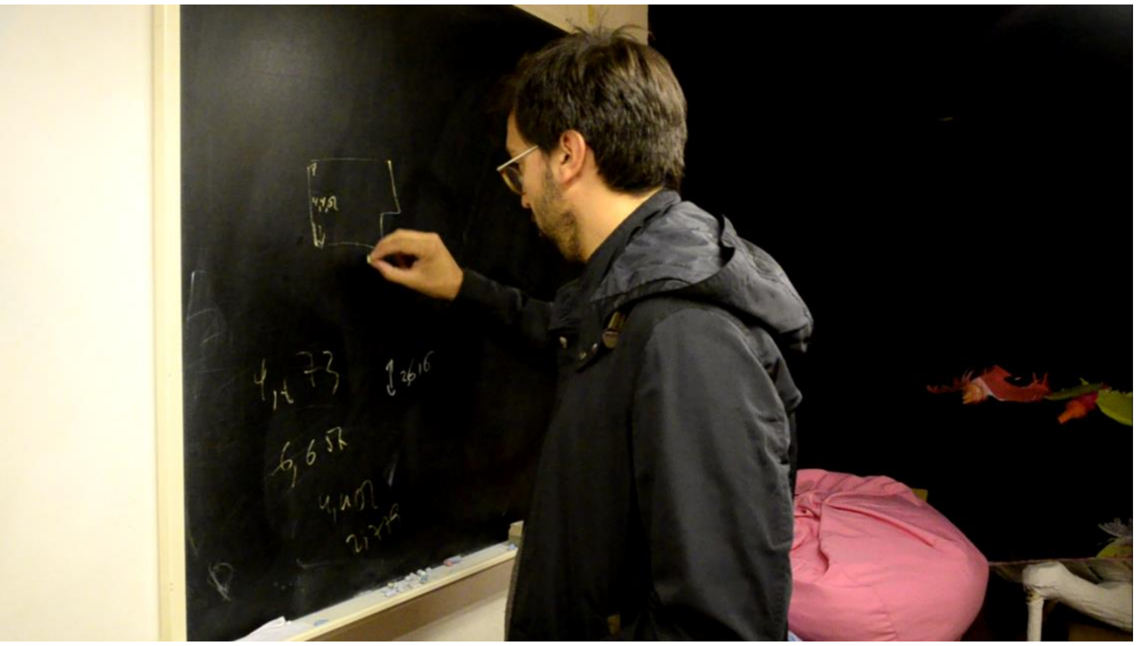


Figure 5-21: User 4 drawing room plan on the blackboard

In the expert group, all participants successfully completed the task and created a plan with morphological similarity. In this group the confidence was low, with Experts #1, #2 and #4 questioning the accuracy of the angles generated by the app. Expert 1 and 2 mentioned the need for triangulations to validate results. Despite only measuring two walls, Expert 3 understood that results were not accurate but felt these were sufficient for a preliminary assessment.

In the non-expert group only two participants, User #1 and User #3, were able to draw a morphologically similar plan to the surveyed room, i.e., a polygon with six sides. Both users completed the task using only the camera workflow in App 1. This sub-group had the highest confidence on the produced results. The other participants of this group faced several issues using the Apps, such as workflow and interface misunderstandings and had no confidence in the results.

User # 2 experimented with two workflows in App 1: sketch a shape and start with a square plan. With the first method the blocking difficulty was to close the polygon and with the second workflow the user could not find a way to add the two missing sides. Lastly, User # 2 also tried App 2 using first the square method, in which she found the same roadblock as in App1, then the camera method. In the Square method, the user designed two 4-sided rooms because she could not find a way of designing a six sided one. With the Camera method in App2, the user could not understand what the required inputs to capture the walls were.

User # 4 used the camera workflow of App 2 first but faced similar difficulties as User # 2 and switched to App 1 camera workflow but also gave up without drawing any plan. User # 5 made two attempts with App 1 Camera workflow. In the first try she did not understand there was a need to click to confirm the corners. On a second try, User # 5 realized it was required to point the camera at the intersection of the floor with two walls and to click a button to confirm. When going around the space in sequence User # 5 missed one corner.

The plans produced by the expert users and non-expert users were compared with the TLS plan. Figure 5-22 presents these results with the Standard Deviation of angle and length measurements. Expert #2 produced a second plan, but it was omitted since is very similar to the first.

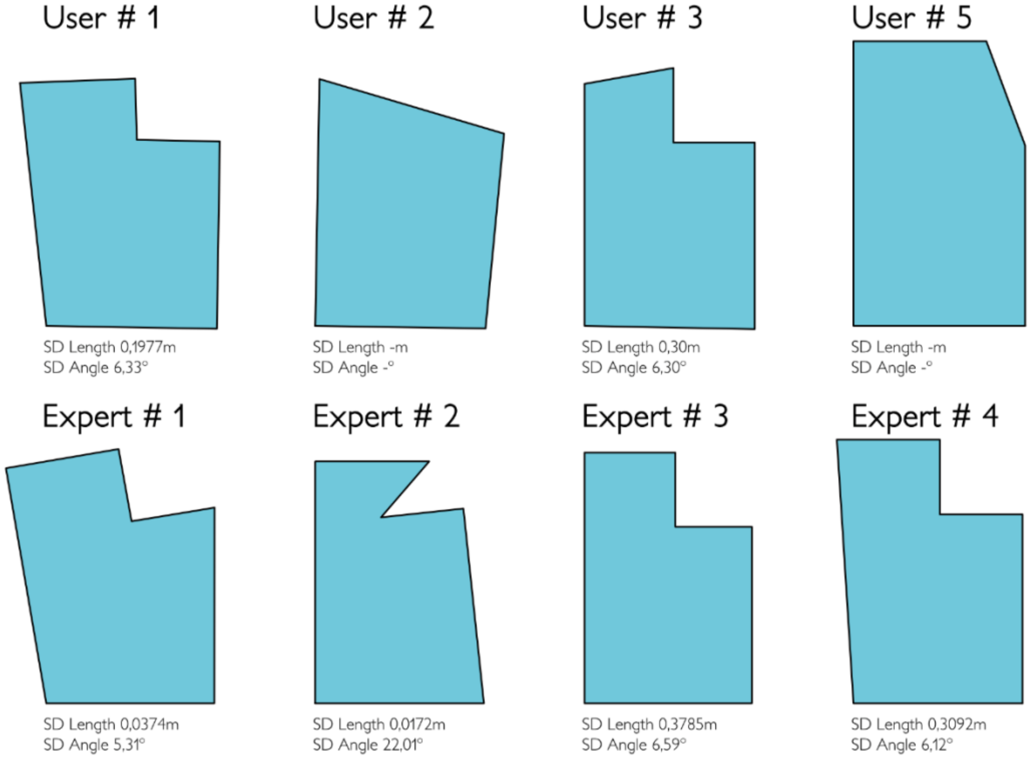


Figure 5-22: Participant generated plans with Standard Deviation of angle and length measurements to the TLS plan (Brandão & Paio, 2019).

Only experts #1 and #2 have shown sufficiently meticulous method on conducting the measurements of the space both with the tape measure or the laser distance meter. This is visible both in the SD of lengths (Figure 5-22) and the QoM results (Table 5-9). In fact, there appears to be a correlation between the standard deviation of lengths and participant average QoM, but as seen from the previous experiment there is no relation between the angular error and both being able to use the app workflow and measure properly.

Several users expressed frustration with the number of steps required before starting to measure the space, particularly with the requirement to add information about the space being measured.

5.2.2.8 Assessment

From the results of first experiment is safe to conclude that these App workflows do not produce accurate plans of non-orthogonal rooms. This limitation is not related with user experience or perception of the space morphological and geometrical properties, as the second experiment demonstrates. In fact, there is no relation between angular accuracy and higher experience and/or quality of measurement.

The sample size is not statistically significant to draw conclusions on average angular errors. Yet, this is irrelevant when these app-based workflows display the angle control problems the experiments uncovered. The polygon perimeter is not sufficient to accurately draw an irregular non-orthogonal polygon, more information is required such as angular dimensions or diagonal measurements. Also, as the wall planning exercise demonstrated, even small angular deviations have a high impact on the partition walls lengths.

These findings are generally applicable to any conventional construction workflow, but these are particularly taxing to design-to-production workflows that require higher precision and offsite fabrication.

The App workflows, when the user becomes proficient, seem to be significantly faster than any other method we compared mainly because of the automation of the drawing process. In fact, the Apps workflows data capturing stage does not include the time spent to measure the room sides. When this time is considered, there is no difference between the manual method and the app-based ones.

Furthermore, since the automated methods of data capturing, such as the Camera or Touch Wall methods, are not very precise, there is in fact a duplication of the measurement steps to obtain a precise plan which expert users where keen to point. But the camera data collection steps do not seem very intuitive to users with little to no experience, and expert users see them as a waste of time compared to simply sketching a plan.

Automation seems to be applied in the wrong place. While in theory it seems better to have a simple workflow to guide the user and simultaneously perform the measurements, thereby eliminating the need for experience and reducing the margin for error, the method is not sufficiently precise. Thus, experts don’t trust it. And since it is so different from the traditional process, non-expert users lack a frame of reference to allow them to easily understand what it is they must do.

Nonetheless, these methods require simple inputs from users which makes them an appealing option for MCC systems that run on the web. A new workflow must be developed that solves the problem of surveying any room using simple drawing metaphors. We believe this issue can be overcome with better polygon drawing algorithms that include diagonal measurements, which could be informed with architect's practical knowledge in surveying building interiors. Directly measuring angles on site is error prone and requires specialized tools. Surveyors circumvent this by measuring diagonals. The process is like subdividing a shape into triangles. By measuring all the sides an accurate position is obtained. In practice, it is hardly ever necessary or possible to measure all diagonals of a space, so a classical triangulation would be unwarranted, triangulations in this case are a means to define the polygon, i.e., close it.

Non-expert users experienced difficulties in using the workflows. While some of the usability issues are app design specific the recommendations can be generalized: introduce clear and concise stepwise workflow instructions, introduce ways of guiding the user, namely better initial tutorials, and contextual interface hints. Also, the interface and workflow should be unobtrusive to allow the user to focus on the room.

MCC requires a link between the product variation and the features of the user's context, physical and social. Thus, a MCC system in architecture should offer ways for users to provide the needed contextual information on the physical environment. Tested methods of generating floor plans for non-expert users are not adequate. We will focus on ways of improving the accuracy of these methods. In conclusion, better methods of capturing context by building owners are needed to allow the implementation of a MCC system of partition walls for building renovation.

5.3 Partition Walls: design–to-production of a customizable and disassemble-able construction system

Frame and panel partition systems require that all parts are assembled onsite. Partition systems made of composite elements address this issue, but the materials are not independent and frequently do not meet circularity standards. Our hypothesis is that a hybrid between composite and frame systems with integral digitally fabricated joints could address the issues of material and functional independence and modularity. These composite components would need to have reversible connections between each of its constituent parts and other components of the partition system. The interfaces of the partition system with the supports must be defined to address issues of safety, comfort, tolerance, and reversibility. Lastly, the materials and the functions they perform must be specified. The above goals must be negotiated with architectural and construction constraints, habits, and standards.

In a nutshell, the question is how to transform materials into parts that can be assembled into components which in turn must be assembled into a partition system.

The above question requires considering five different levels. In heed of a place to start we recognized that using a modular system requires thinking on how to subdivide the wall element into components and deciding which dimensions and functions these components can have. A simple subdivision grammar emerged upon which construction systems were designed. In turn, the reflection about the design experiments led us to hone it into generic principles that may assist meta-designers in developing and analyzing modular partition wall systems.

We name it a generic grammar, that is applicable to modular partition wall systems that separate spaces, although the principles might be applicable to other types of partitions. Although this grammar is a consequence of the design experiments, it is presented first to simplify the discussion of the systems' advantages and shortcomings.

We developed several partitions that attempt to address the matrix of criteria identified in Chapter 4 and further focused on the following specific goals and constraints:

1. Minimize the number of components to assemble onsite
2. Increase modularity by maximizing the number of standard components onsite and by minimizing the number of different connection types.
3. Minimize waste of input materials
4. All components must enter through a standard 200x90 cm door.
5. All components must be digitally fabricated from standard flat wood composite or cork panels.
6. Only single sided fabrication should be used
7. Reduce visible joints

The presentation of the partition walls systems is organized by the chronological order. ORW v1 was developed during the first half of 2015, in the context of the 2nd edition of Advanced Course in Digital Architecture (CEAAD) under the association of ISCTE-IUL and FAUP (Brandao et al., 2016), and was our first attempt to address the issues discussed in this thesis. The ensuing construction systems were developed between the end of 2017 and the middle of 2018. At a certain point in time, some cross fertilization of systems started happening as the experiments with less common router bits revealed a new class of digitally fabricated joints that could address some of the limitations of the more common friction-fit joints.

The process was necessarily messy, but the emergence of the systems mostly aligns with the introduction of divergent classes of joints. Hence, ORW v2 started with friction-fit joints, ORW v3 with snap-fit joints and lastly ORW v4 is built around T-slot joint, a new class of digitally fabricated joinery specifically developed during this thesis to address the issues of partition walls.

5.3.1 Generic Wall Grammar

The following simple subdivision grammar can be used in the development of the partition wall systems to identify typical dimensional and functional subdivision patterns. This grammar is not so much a new solution to an existing problem but the reinterpretation of our previous experiments and the cases in the literature. The aim is to subdivide the partition into prototypical components for further development. Thus, it is generic in the sense that it does not specify particular solutions to each of the identified types.

5.3.1.1 External Interfaces

The starting point is to recognize that any interior partition has interfaces with other building systems of different types and possibly different functions, we name them external interfaces (Figure 5-23). Those interfaces will enable or prevent the transmission of energy, e.g., the transmission of structural stresses or sound, and the flow of energy and matter by allowing or disallowing connection of services like electricity and plumbing.

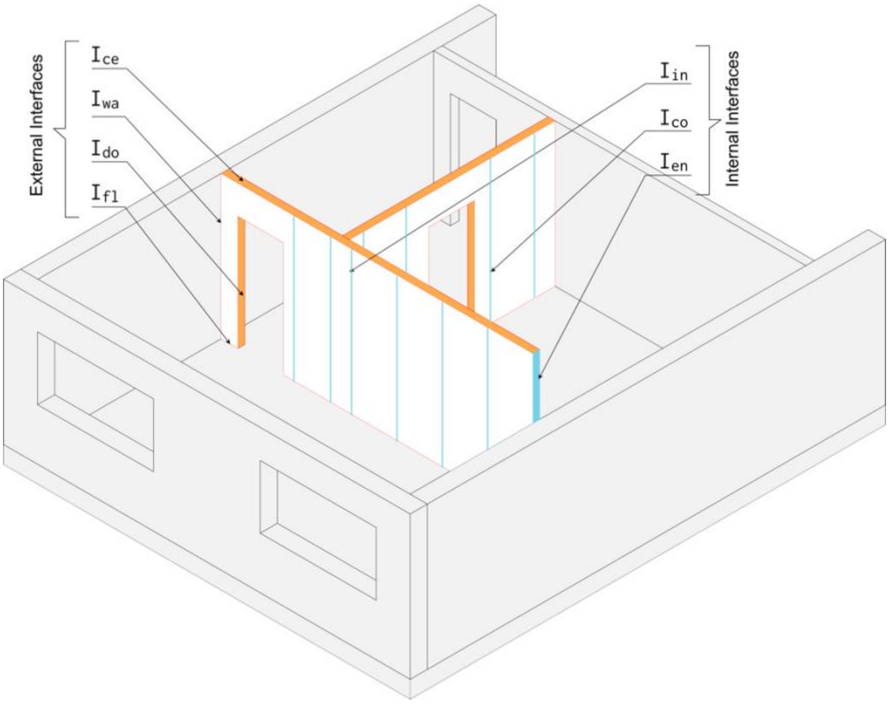


Figure 5-23: Interior partition wall external and internal interfaces

Other issues that frequently emerge at the interface is the joining of different materials. Hence, there is a continuity problem that must be resolved ideally considering the temporal order of assembly, the use-life cycle of the systems and their hierarchical order in the building. Another aspect of the discontinuity is that the differential behaviors of systems must be accounted for by providing tolerances. These tolerances are also important for assembly and disassembly purposes.

Figure 5-23 presents some of those interfaces and Table 5-10 some of the typical problems that may emerge. Some problems must necessarily be solved at all interfaces, such as tolerance and continuity, others are optional or may happen at only one of the interfaces, e.g., electrical services only connecting to floor or ceiling. Structural connections will at least happen on the floor and may also happen on other interfaces, while on doors and windows the structural and assembly dependency may be reversed.

Table 5-10: Typical problems at external interfaces

		External Interfaces				
		Floor	Wall	Ceiling	Door	Window
		I_{fl}	I_{wa}	I_{ce}	I_{do}	I_{wi}
Problems	Structural	◉	○	○	○	○
	Acoustic	○	○	○	○	○
	Infrastruture	○	○	○	○	○
	Continuity	◉	◉	◉	◉	◉
	Tolerance	◉	◉	◉	◉	◉

Level of : ◉ Required ○ Optional

The external interfaces may be with building systems with a longer use-life cycle, e.g., floor or ceiling slab, or shorter use-life cycle, e.g., a dropped ceiling, or a decorative baseboard. Doors and windows should be considered an external interface with components of shorter use-life cycle if they are embedded in the partition wall. Yet, if these are self-standing the use-life cycle of both systems can be independent.

The assembly and disassembly dependencies should be defined by the above hierarchy, since components with shorter use-life cycle will have to be disassembled first. Yet, in built heritage these hierarchical orders may be changed to abide to the reversibility criteria of newer interventions. In the types of interfaces where there is a clear hierarchical order of assembly and disassembly, and lack of control over one of the systems, a unidirectional connection from shorter to longer use-life cycle system is the only option.

5.3.1.2 Internal Interfaces

Since the aim is to develop a modular system, internal interfaces will emerge because of the subdivision of the system into components and parts. Unlike external interfaces, internal interfaces exist between components or parts of the same system, and hence are totally controllable by the designer. Thus, bidirectional connections are possible.

We first focus on modular subdivision of a planar wall. Since partition walls are necessarily higher and longer than what might enter a standard door, and heavier than what might be transported by a person, these will have to be subdivided into smaller components. The geometric subdivision may have any conceivable pattern, e.g., quadrilateral, triangular, hexagonal, etc. Yet we focus on regular quadrangular subdivisions, because we are aiming to minimize the number of different components onsite, increase the compatibility with existing systems, and we will be using standard rectangular materials.

There are three basic types of quadrilateral dimensional subdivision: parametric or integer subdivision and modular linear and modular symmetric subdivision. Integer subdivision essentially divides the plane into a given number of parts with equal dimensions in length and/or height (Figure 5-24). Modular linear subdivision divides the plane into parts of a given dimension and the remainder will be left to an off-standard component (Figure 5-25). The symmetric modular differs from the previous subdivision by symmetrically distributing the remainder of the subdivision by the two ends of the plane (Figure 5-26).

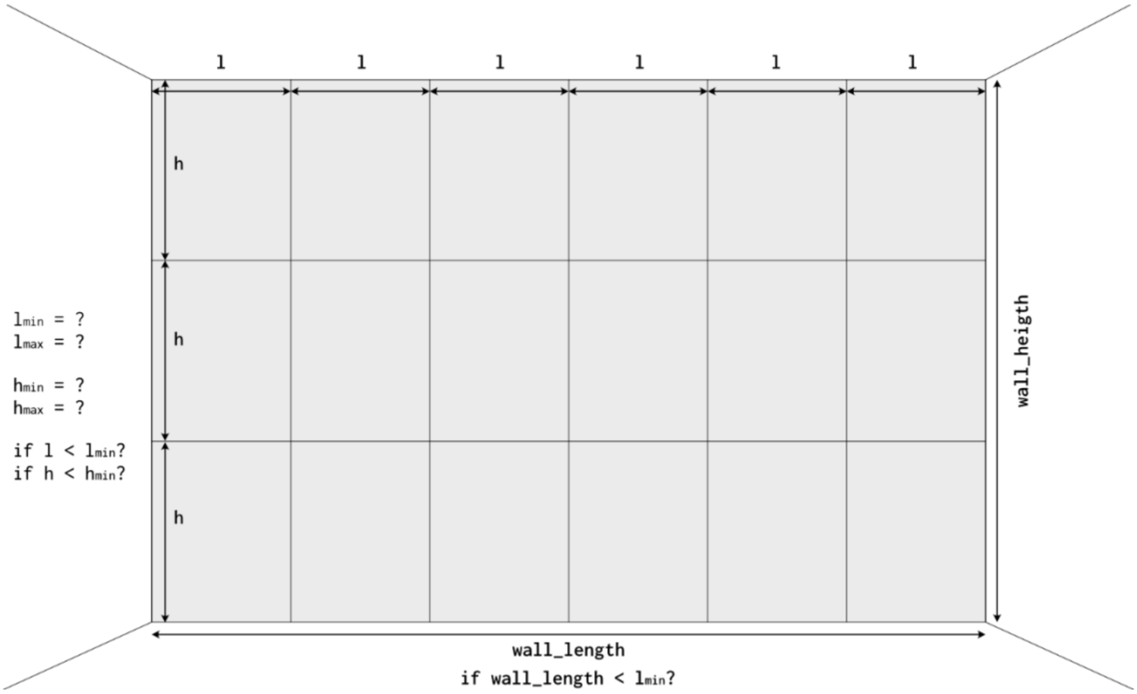


Figure 5-24: Integer or parametric subdivision of a wall into components

Whatever the chosen subdivision, since the modules are made from standard materials and must be transported by a person through a standard door, there will be an upper size limit on the component dimensions. Conversely, there will be limits to how small a component may be because of the material thicknesses, properties, fabrication method and assembly sequence. Within the previous domain, it is necessary to decide if the dimensions should be minimized, maximized or if there is one or more local optimum within the domain.

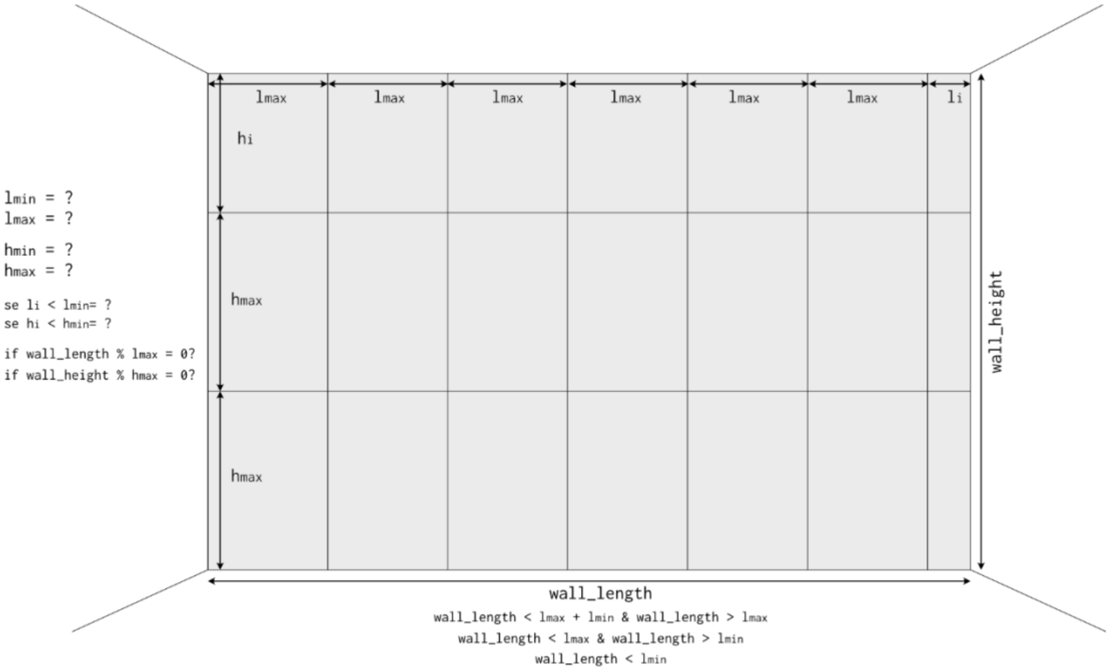


Figure 5-25: Modular linear subdivision of partition wall into components

For each subdivision type there will be edge cases that must be solved (Figure 5-24, Figure 5-25, Figure 5-26), and since there is a limit to the size of the components, even the integer subdivision is more complex than simply dividing the surface dimensions by a given number.

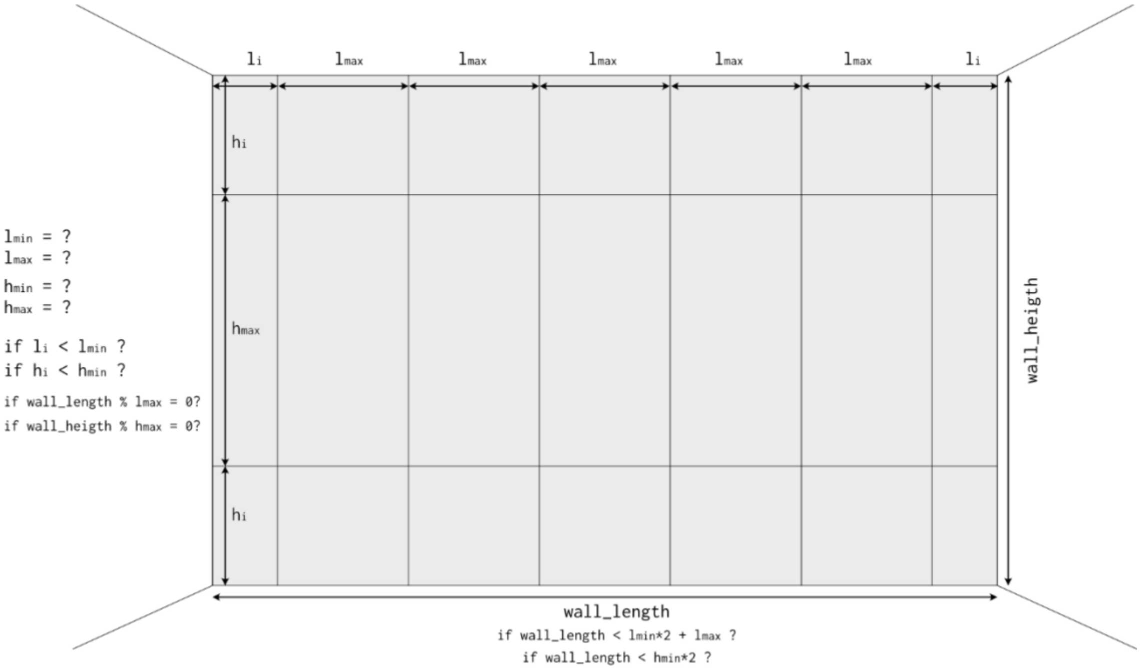


Figure 5-26: Symmetric modular subdivision of a partition wall into components

Whatever the selected geometric subdivision type, the components will have different functions depending on their position in the system. Clearly, components that are adjacent to the boundary of the plane have different assembly limitations and geometrical boundary complexity than components that only have internal interfaces. Within those components with boundaries with external interfaces there are corner cases, i.e., two adjacent edges, and edge cases, with only one edge (Figure 5-27).

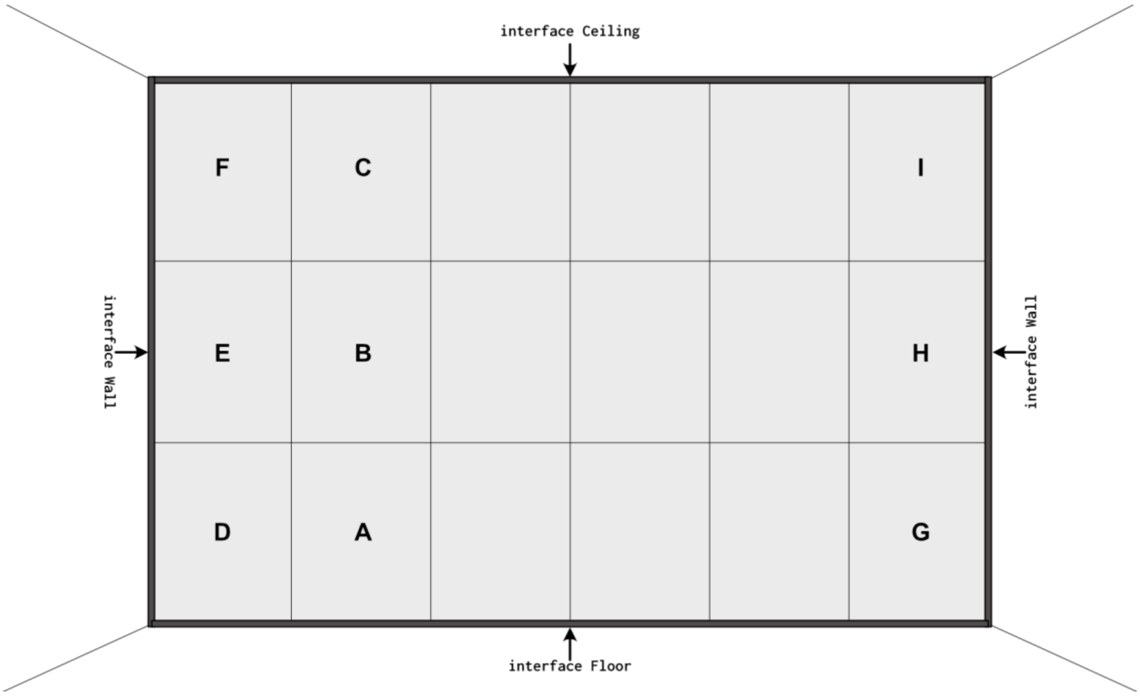


Figure 5-27: Functional subdivision of a planar partition wall

There is a functional symmetry between components, e.g., D and G. Similarly, it could be argued that in certain circumstances there might be double symmetry, e.g. A and C, or rotational symmetry, e.g., D and I. Yet, as implied in Table 5-10, assembly, structural, infrastructural constraints may force different solutions for each of the types shown. For instance, since ceiling components will necessarily be assembled last, they will have different and more complex assembly constraints, which might result in different solutions for the component.

5.3.1.3 Doors and Windows

As previously stated, embedded doors and windows are external interfaces with lower-level components which may have dependencies with the partition, i.e., structural stability or electrical wiring. We identify two patterns to deal with those elements: isolating the sub-plane containing the element with full partition wall height or isolating only the element. The first pattern typically introduces structural reinforcement members surrounding the element. The second will only rely on the wall capacity to distribute the loads over the hole and the impacts to the surrounding wall elements.

5.3.1.4 Wall intersections

Independently of their dimensions or whether they are visible, angular shifts and wall intersections are special internal interface cases within the overall system where two or more wall planes meet. In fact, both cases are really particular cases of the general problem of n walls meeting at a specific edge, yet there are architectural peculiarities of the L-shaped and T-shaped cases. A third special case is the end-wall where the wall plane finishes before meeting any other building element.

Any n-shaped intersection may be solved either by isolating the intersection as a specific module or by using a specific combination of external interfaces and system modules. Yet, converting the intersection into a module reduces the disassembly dependencies of walls that meet at the intersection. Consider Figure 5-28 left, all walls are independently demountable if the internal interfaces with the T-shape module are bidirectional. It follows that any possible reconfiguration of the 3 spaces into two can be done by only disassembling one wall and the T module. Yet in the case on the right, the interface of B with A is unidirectional from B to A, Hence, while disassembling B was no implication on A, disassembling any part of A can only be achieved by partial or total disassembly of B.

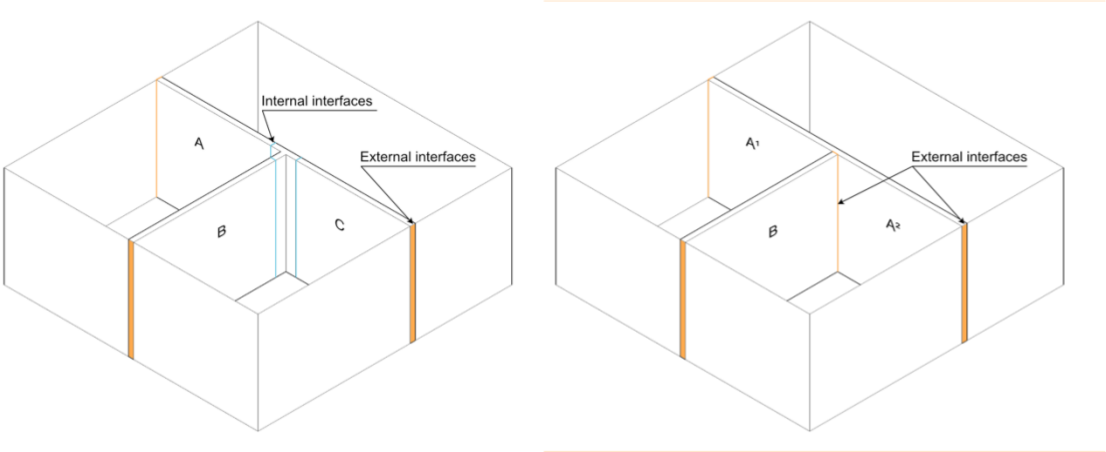


Figure 5-28: (left) T-shape intersection is a module with internal interfaces with walls A, B and C, (right) T-shaped intersection is an external interface of wall B against wall.

From the preceding example it is clear why it is desirable to have bidirectional internal interfaces between wall components. They can reduce the assembly interdependence between components, allowing the possibility of local disassembly.

Independently of the type of separability that wall intersection components may have with other internal components, solving the intersection may done in multiple different ways. We identify two main types: component intersection, the intersection is solved by morphing one or more standard wall components; third element intersection, a special component is used at the intersection to connect standard components together (Figure 5-29). Within these larger types there are subtypes with different rules to solve the intersection, e.g., in mitre joint all components that meet at the corner are customised to solve the intersection.

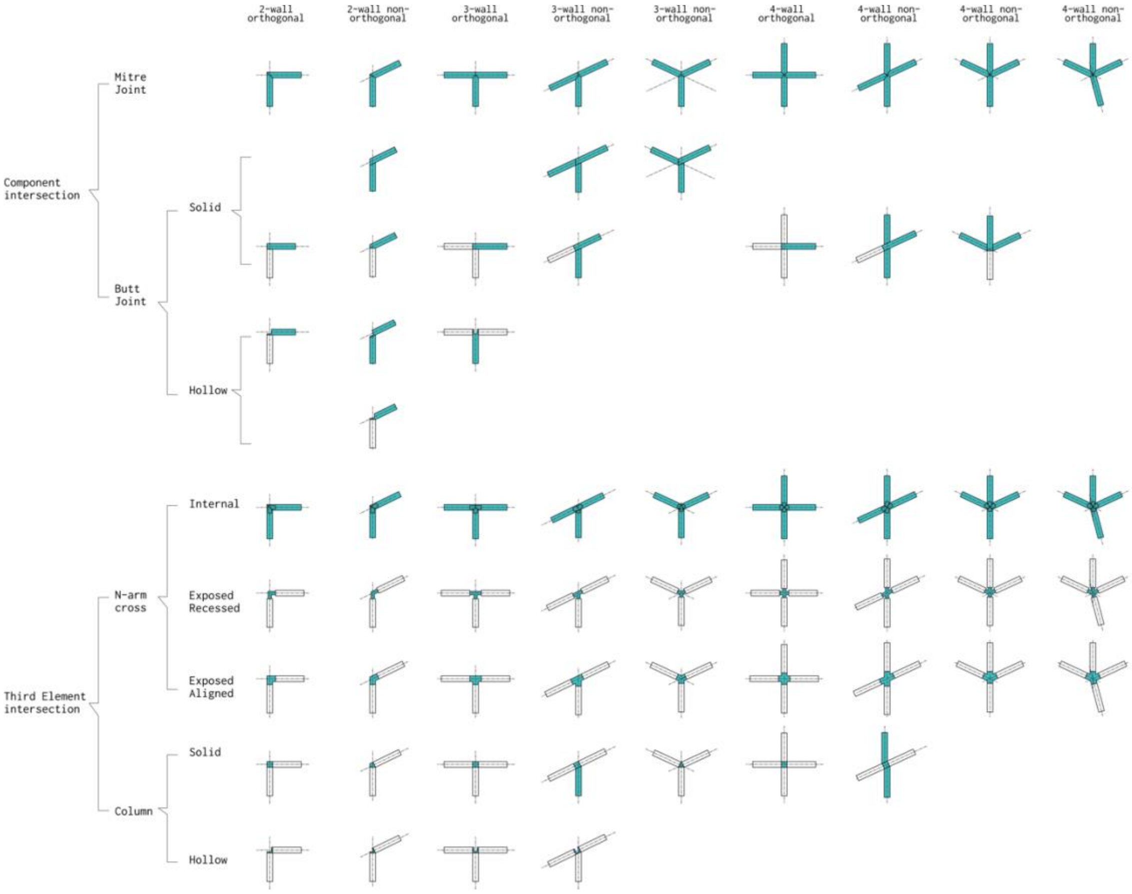


Figure 5-29: Different types of intersection component solutions that solve the continuity problem. Non-standard components are painted in blue.

Clearly, some types are better at decreasing the number of non-standard modules across all the geometrical intersection cases. Third-element n-arm cross exposed types can do so with only one component but there are geometrical conditions and architectural criteria that may lead meta-designers to select other solutions.

As previously stated, L-cases have some peculiarities. Evidently, L-cases will always have one reflex angle, and whatever the type of intersection used, since the components will be assembled from flat materials using 3-axis CNCs, miter joints between parts at the reflex angle will not be possible. In fact, for very large reflex non-ortho angles even butt joints may be undesirable either for aesthetic or safety reasons, since it will not be possible to cut the parts at non-orthogonal directions. Although less likely, any n-wall case can exhibit reflex angles and these considerations are equally applicable.

A peculiarity of modular partition systems is that both sides of the wall share the same subdivision. This can be problematic in 3-wall intersections with two directions, when the wall that terminates at the intersection is not aligned with the selected dimensional subdivision of the longest wall. Using component intersection butt joint types might solve this issue, another alternative is to have two parallel walls.

5.3.2 ORW v1.0

ORW v1 is a frame and panel digitally fabricated partition wall system developed during CEAAD. It aimed to reinstate the use or traditional materials in the renovation of 19th century townhouses, implementing generative design and digital fabrication to overcome the loss of traditional building techniques and craftsmen.

The system (Figure 5-30) uses similar assembly logic as Sass WFG (2006), yet with completely redesigned frame friction-fit joints due to the small wall thicknesses. The frame is cut from OSB and the panels are a composite of plywood and ICB with three customizable patterns: horizontal bars, Voronoi pattern and Ice-ray pattern. As with Sass system, the panels also perform structural functions bracing the studs, and hence have mixed structural and finishing functions.

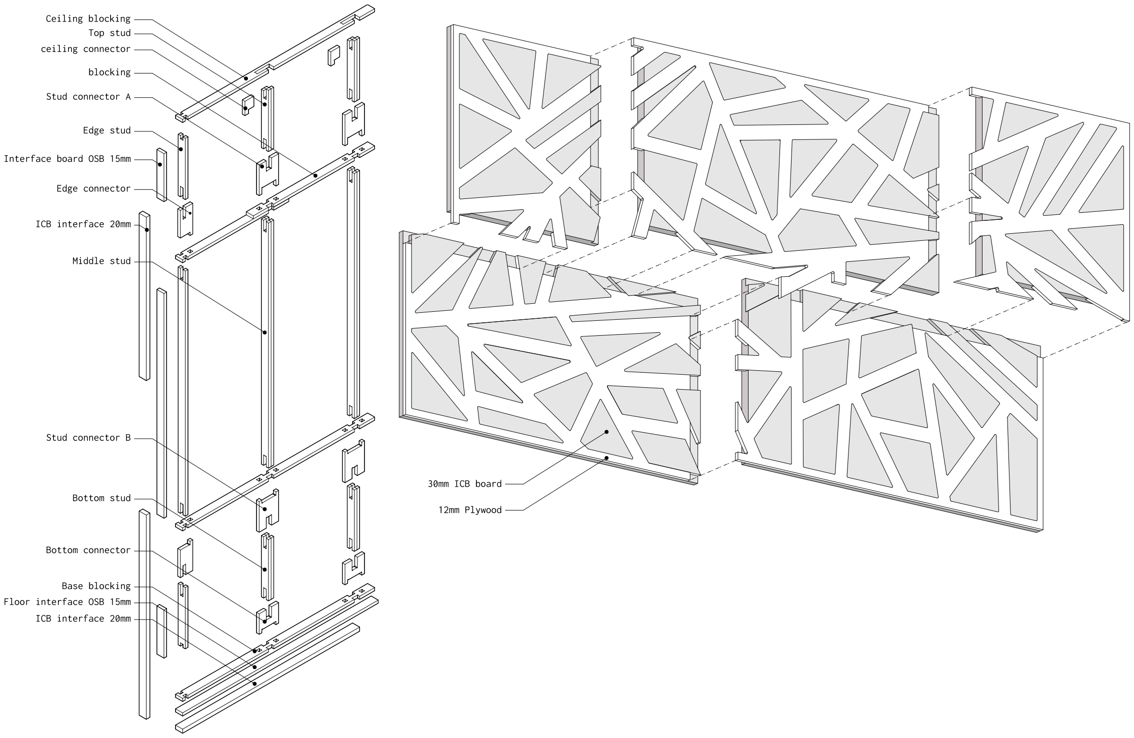


Figure 5-30: (Left) Exploded Axonometry of frame and interface components (Right) Assembly sequence of composite panels

The panels have a vertical and horizontal unidirectional assembly sequence (Type I) while the frame is slightly more flexible. Both the panels and the structure have 9 functional subdivision cases for a simple straight wall. The combinability of the panels is contingent on the selected pattern, with the horizontal line pattern being the only one with some level of intermutability. The panels are preassembled offsite, yet all the frame parts must be assembled onsite. Figure 5-31 shows the number of part types involved in a small wall section.

Figure 5-31: (Left) Frame Parts sorted by type before assembly (Right) Assembled frame at Vitruvius FabLab in 2017

5.3.3 ORW v2.0

The first iteration of the ORW v2.0 system was developed strictly with friction-fit joints. Important challenges were: (1) creating structural connections between pre-assembled components; (2) creating reversible yet sufficiently stable connections between panel and structure; (3) developing components that could be used for more than two functions, e.g., A and D; and (4) creating non-linear assembly / disassembly sequences.

Since the main goal was to create a hybrid composite system that avoided chemical connections, a secondary internal structure is necessary to connect the panels and hold the insulation in place inside the component. The connections between the parts must be sufficiently strong to withstand manipulation and transport, but sufficiently easy to disassemble for maintenance if necessary.

The effectiveness of friction-fit joints relies on the surface contact area between parts. Thus, attempting to hide the joint reduces its effectiveness which is further compounded by the requirement of easy disassembly. Since placing the joint at the edge of the panel could further reduce the contact surface of the joint, in ORW v2.0 the structure is offset by 4 cm of the component edge, a design feature that is common across all iterations of version 2 (Figure 5-32). Therefore, the ICB infill must be offset from the panel on all sides where the structure connects to the panel. For this reason, an asymmetric design was chosen to attempt to coordinate material dimensions to the minimum denominator, the ICB standard dimensions (Figure 5-32).

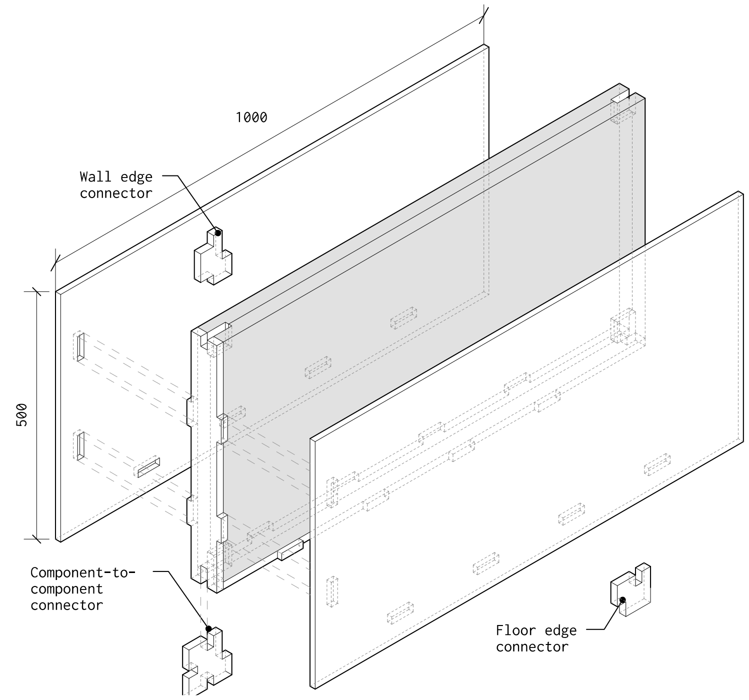


Figure 5-32: Exploded axonometry of ORW v2.0 type A component

Using only a vertical stud and a horizontal blocking has the added advantage of reducing the cost of the internal structure. The component is oriented with a horizontal aspect ratio following the observation that this aspect ratio reduces the ratio of non-standard parts to standard parts as the wall length increases.

ORW v2.0 asymmetric component design addresses the problem of structural connection between components but also implies a bidirectional assembly. The component-to-component connector design (Figure 5-32) further reduces the assembly directionality to unidirectional. This creates the need for a special edge floor and wall connectors and precludes the possibility of adding connectors to the ceiling.

The wall external interfaces with the existing wall, floor and ceiling are solved with a layer of 30mm ICB and a OSB 15mm slab screwed to the perimetral surfaces. ICB is used for sound insulation purposes, as a compression layer to absorb surface irregularities, and as tolerance buffer, leveraging ICB’s Poisson coefficient. The OSB slab is used to distribute the pressure evenly across the ICB and as an intermediate between the wall system and the existing structure, enabling friction-fit connections between the system components and the interface (Figure 5-33).

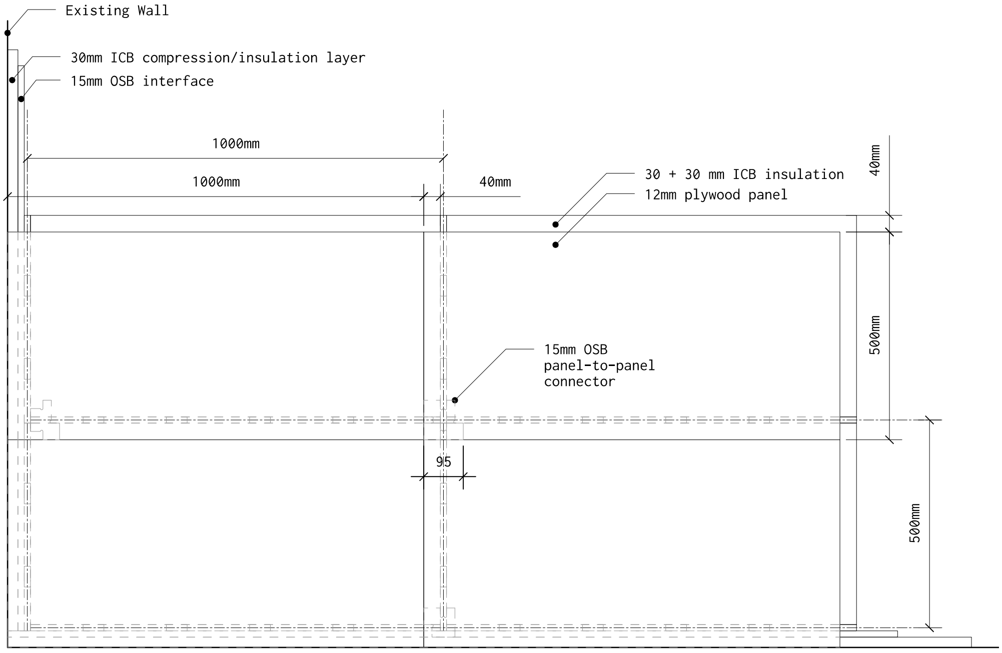
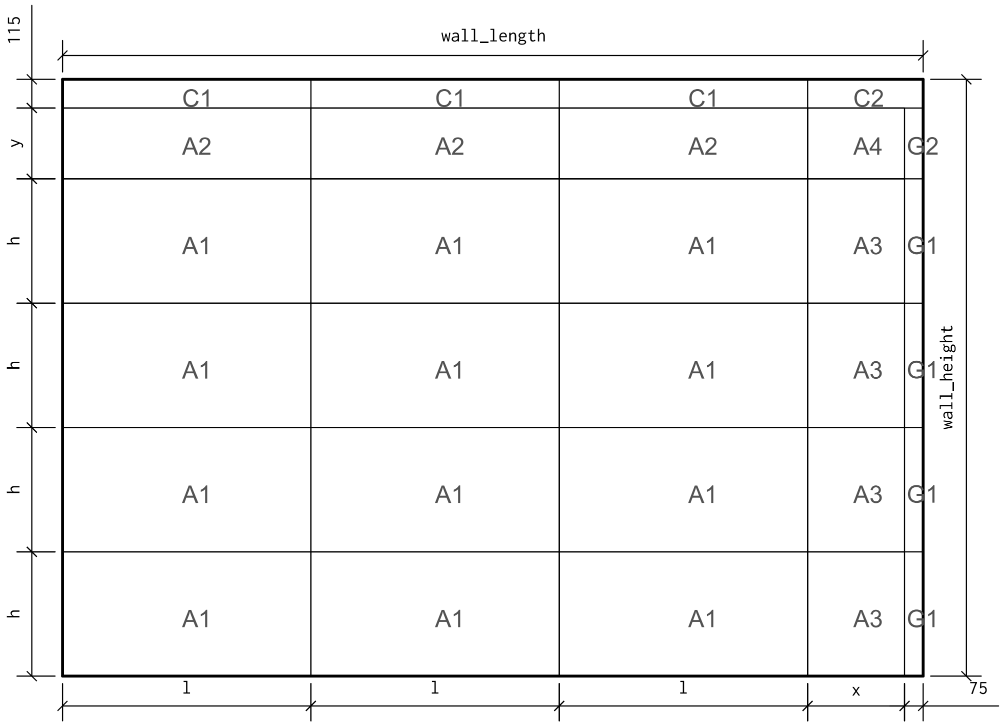


Figure 5-33: Elevation of an assembly of 4 ORW v2.0 components against a corner

Since assembling, and disassembling ORW v2.0 is a layer-by-layer unidirectional process (Type I), consequently ORW v2.0 must have special edge components at one wall and on the ceiling (Figure 5-34). Furthermore, it can only have integer or metric subdivisions and to remove a type A3 component all the layers above it and type G1 component must be removed.



y = wall_height - 115 / h - Floor(wall_height - 115 / h)
x = wall_length - 75 / l - Floor(wall_length - 75 / l)
l min = 165mm h min = 150mm

Figure 5-34: ORW v2.0 typical elevation with metric dimensional subdivision and functional subdivision

On a system level, introducing services inside the wall must be done at the factory, although ICB is easy to cut onsite with simple tools allowing for site adaptations. Yet, these adaptations cause material waste onsite where is harder to recycle it. Thus, in terms of service integration the system can be at best of Type 2.

On the maintenance level, removing the panel with the wall assembled is not too difficult but no visual cues are provided as to how this should be done. Placing the panel back in place is hard since there are no visual cues of tab alignment and force must be exerted in the normal direction to the wall plane. Making the panel reassembly easier with friction-fit joints can only be achieved by either increasing tolerances or exposing the joint, both undesirable features.

Safety concerns dictate that panels should not fall when the wall is subjected to a soft body impact. In ORW v2.0, this is can only be guaranteed by increasing the friction in the panel-to-structure joints. Thus, the performance in those impact safety tests is determined by the degree of ease of disassembly of these joints.

The component aspect ratio is a system design decision with implications on the wall structural performance, percentage of non-standard components and architectural design. The first two aspects are inversely related, i.e., the third is optimized allowing any component aspect ratio thus increasing the flexibility for the instance designer to adjust the component dimensions to the specific context of application.

5.3.4 Joints

The first iteration of ORW v2.0 demonstrated the limitations of friction-fit joints: they do not constrain the sheathing in the normal direction and joints are visible from the outside. The first aspect is desirable from the point of view of disassembly and assembly yet warping of the panels produced by variations of moisture and temperature might cause connection problems (Cardoso & Sass, 2008). The latter aspect might be considered a design feature, but it can be aesthetically undesirable, particularly in interior walls. Adding extra layers to the wall is a possibility that is unwelcome in interior walls because it increases costs, wall thickness and reduces the disassemble-ability of the system.

The above findings kickstarted a joint design process to attempt to find designs that could have more adequate properties for partition walls and specially to panel-to-structure connections. The process was divided in two stages, the first focused on experimenting with joints that have been reported in the literature and the second on experimenting with different inexpensive bits that could be used to develop new typologies of joints.

In panel-to-structure joints for partition walls it is desirable that there is the least number of visible joints, for aesthetic reasons, to reduce sound transmission, and tolerance problems. Conversely, these connections should be reversible for two sets of requirements: (1) to allow changes and maintenance during the system service life; and (2) to allow material reuse when the components are no longer useful for their original purpose. Regarding the first requirement, the needed changes should ideally only require local disassembly which means that panel-to-structure joints play a key role in providing access to the interior of the wall.

Hence it is useful to consider two types of reversible connections. Type I joints can be disassembled at any moment in the system service life while the latter type, Type II is only assembled at the fabrication site or disassembled during deconstruction stages. The latter has lower tolerances and better overall performance while the first type trades structural performance for ease of assembly on site.

Considering joint designs is critical because the types of joints attainable with a given fabrication or construction process dictate the possible material assemblies and consequently the form of a construction system and its expressiveness.

5.3.4.1 Snap-fit Joint

The first experiments focused on snap-fit joints, that have already been reported in the literature by Robeller et al (2014) for use in panel-to-panel edge connections in shell structures and structural members and Elsayed et al (2017) for cost-effective housing construction. The original snap-fit joint design by Jochen Gros (1999) in his digital wood joints catalogue (Figure 5-35) was used as a base to produce a joint design that would fit the requirements of partition walls, particularly by removing the protruding tab and reducing the cantilever to be able to use the joint on thin vertical studs (Figure 5-36).

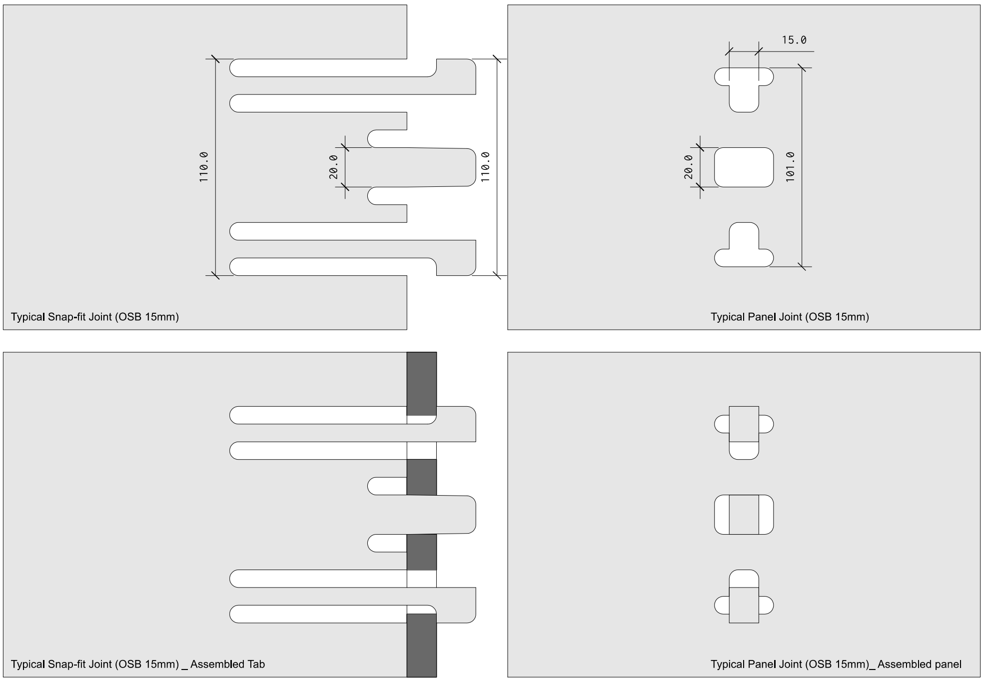


Figure 5-35: Typical Snap-fit joints appropriate for 3-axis CNC adapted from Jochen Gros (1999). Parts for cutting (top), assembled section (bottom left) and elevation (bottom right)

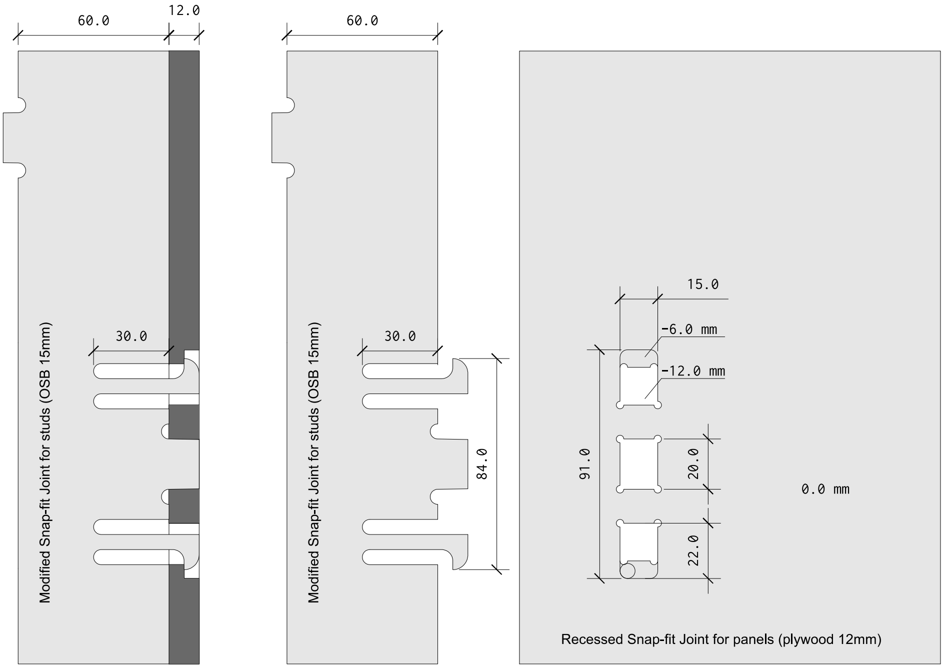


Figure 5-36: Modified Snap-fit design. Assembled wall section (left) and parts for cutting (right)

Even before testing functionality several problems were already visible in the design. The cantilevers significantly reduce the section of the stud, and their dimensions prevent a symmetrical design on both faces of the wall. Furthermore, holes in the surface are needed for the joint to be functional. Still, the modified design was fabricated and assembled for testing, yet the prongs of the OSB cantilevers could not resist the assembly process, which can partly be attributed to the material.

An alternative approach, where the snap-fit joint is applied in panel-to-panel connections, was used as a basis for ORW v3. To prevent previous issues of prong breakage, plywood was used for the cantilevers also. The joint design was tested with the system prototype, whose overall design is presented in next section (Figure 5-37). Despite using a stronger material, similar problems of prong breakage emerged. In this instance caused by sanding the parts during post-production.

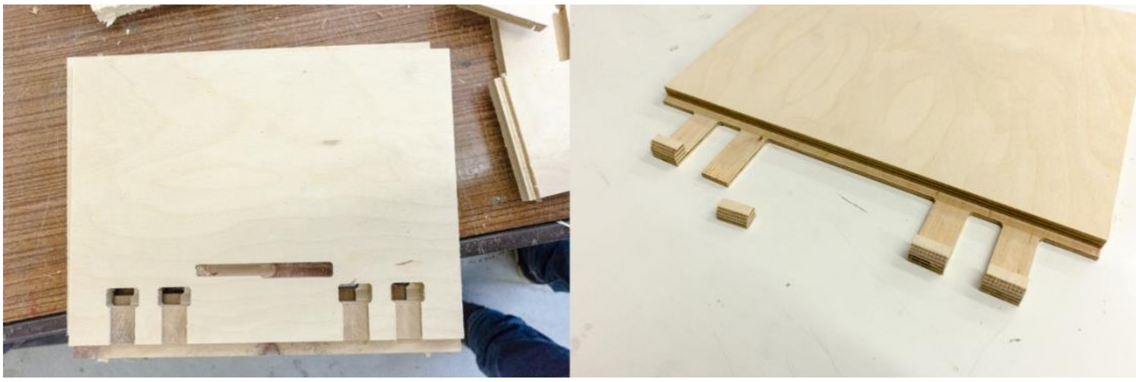


Figure 5-37: Panel-to-panel snap-fit joint prototypes

5.3.4.2 T-Slot Joints

Snap-fit joints solve the issue of constraining the sheathing in the normal direction, but the geometry of the joint can introduce safety issues (EAD-S2) and sound insulation issues by leaving gaps to the interior of the wall. Solving these issues with further layers of materials is even more problematic than friction-fit joints.

Thus, the second stage of the research into joint design considered the use of different types of router bits to overcome the limitations of 3-axis CNC regarding creating features that constrain parts normal to the surface of the material.

The T-slot router bits are inexpensive tools commonly used with 3-axis CNC routers to cut grooves in MDF panels for metal profiles or keyhole slots for screws (Figure 5-38). The former slots are cut with full immersion milling starting and ending on opposing sides of the board, whereas the latter requires symmetrical exit and milling strategies, a combination of a boring operation with a full immersion milling. These types of slots are not useful for wood-wood joints produced with a 3 axis CNC, since matting tabs would have to be machined on both sides of the board, but they illustrate the possible sequences of assembly steps.

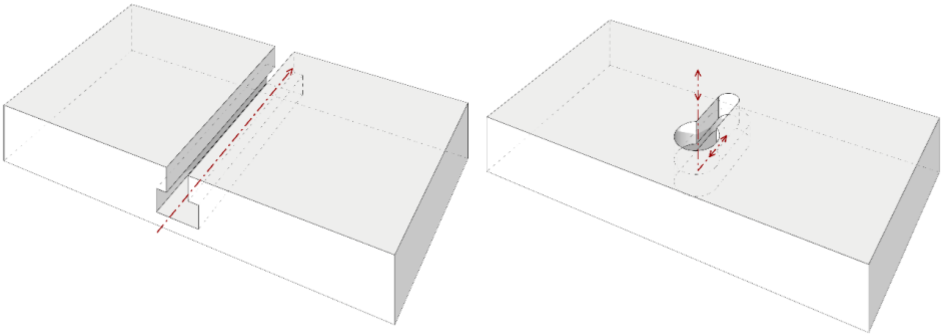


Figure 5-38: T-slot grooves for profiles (left) and for keyholes (right)

A T-slot joint will necessarily be composed of female and male parts: a slot with one overhang and a grooved tab. To connect the parts a sliding movement parallel to the slot length is the most natural solution, but other strategies should also be considered. Also, owing to the special features of the t-slot bits, designing joints for this tool requires meticulous attention to the tool geometry, path and exit strategy. Important dimensions are the tool overhang and the height of the cutting edges, on the neck and head of tool (Figure 5-39a).

Frequently, a flat end mill is used for routing a groove prior to using the T-slot bit. Exploring the combined use of the two bits to produce asymmetrical slots with only one overhang (Figure 5-39b), we were able to produce the mating feature of the structure to the sheathing on the flat-bed CNC. A 6mm flat-end mill was used to carve a pocket or groove on the panel with the thickness of the structure minus the overhang, then the T-slot bit was used to create the mating feature. The overhang is limited to the difference in radii between the neck and head of the T-slot bit. The height of the mating feature (Figure 5-39b) is defined by the depth of the pocket with an upper limit on the overall flute height, 9,5mm with our tool. The mating tab is grooved at the required distance from the edge with a 4mm flat-end mill.

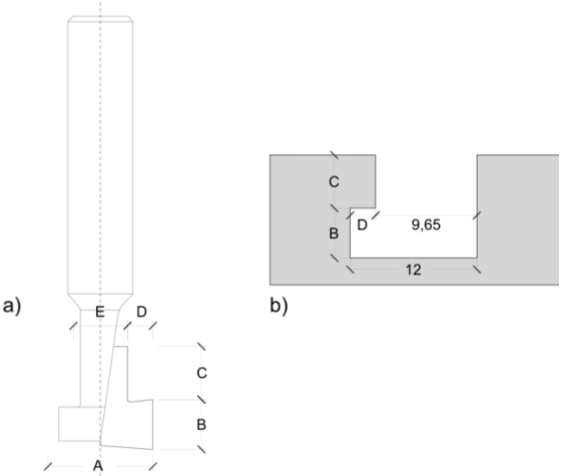
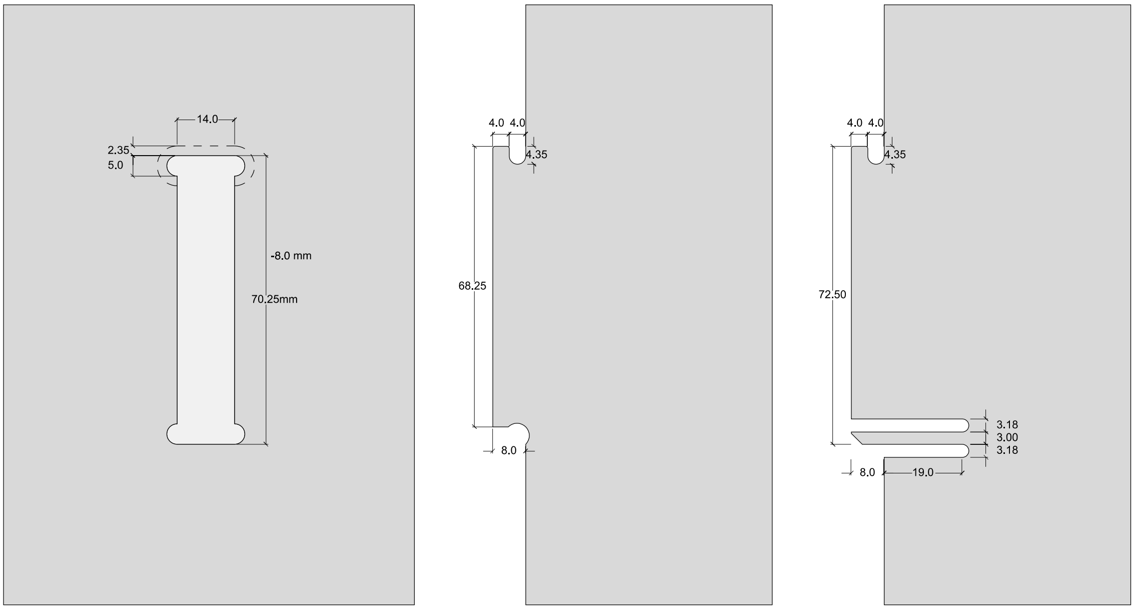


Figure 5-39: 1) T-slot bit parts: A) Head diameter - 9,7mm (B) Head height - 4,6mm (C) Neck height - 4,9mm (D) Overhang - 2,35mm (E) Neck diameter - 5mm; b) Modified T-slot groove for flatbed CNC

Following the logic outlined above, several joint variants were designed and prototyped. Figure 5-40 presents two versions of Type I joints that require small vertical or horizontal movements to be disassembled. A horizontal version of Slot + Tab A was also tested. These can be demounted while the system is completely assembled making use of the gaps between the panels. The T-slot bit is used to create an overhang along the top edge of a vertical or horizontal slot. A mating hook is created on the top of a tab of vertical or horizontal structural member. Since this joint must be assembled and disassembled without visual guidance while holding the panel against a wall, a larger tolerance is needed. Therefore, the panel contribution to the overall structural performance of the wall is significantly reduced.



Slot Tab A Tab B

Figure 5-40: Type I T-Slot joint with a vertical slot and two tab variations

An alternative design with a cantilever was explored to stiffen the connection. To dimension the cantilever, first an overall design was defined with coarse approximations. Care was taken to minimize the length of the cantilever, as it reduces the section of the structure. Then the force required to bend the 25mm cantilever was determined using BASF (2007) design guidelines for snap-fit joints, which allowed to adjust the thickness of the cantilever beam. There are some differences between this joint design and snap-fit joint, particularly the point where the force is applied. However, the general or the improved formulas for the beam deflection still apply.

Based on the calculations several versions of the joint where prototyped to test the assumptions and fine tune the adequate force for assembly. A 3mm thickness was found to be adequate for easier assembly. The design of the tab was adjusted to act as a limiter to the bending of the cantilever.

A simple Type II joint is a full or half panel length slot, but one such joint creates a continuous fragility line along the length of the joint. An alternative is to create discontinuous connection points, which requires a slot with an entry area with the thickness of the structure members (Figure 5-41). The number of assembly movements increases but these are shorter and thus less effort is required to assemble the parts. Several alternative designs for the slot were evaluated, Figure 5-41 presents two alternatives, Slot A and B, the former being easier to assemble and the latter trading ease of assembly by improved structural resistance of the overhang.

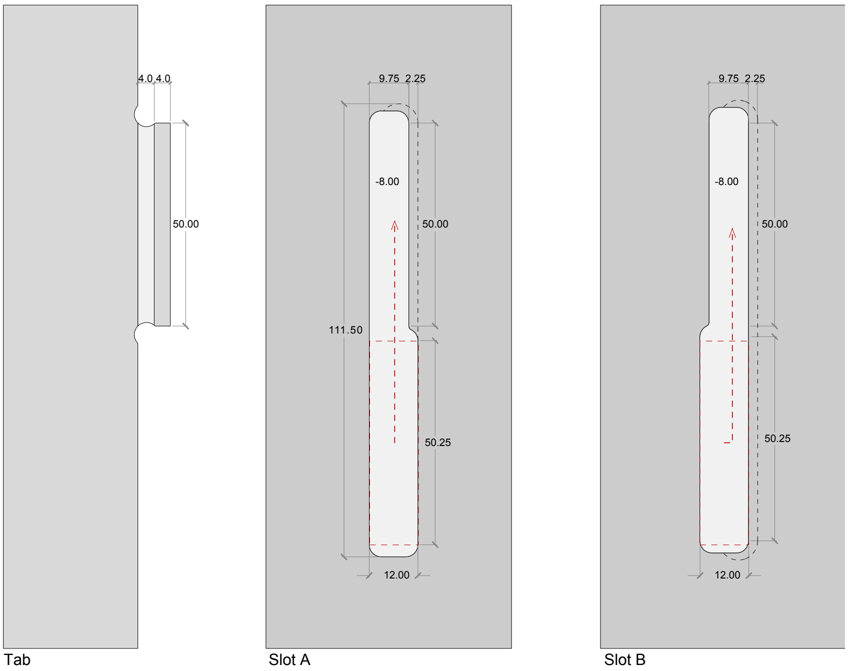


Figure 5-41: Type II T-Slot Joint with a vertical tab and two variations of slot design

Figure 5-42 presents another design of Type II with a shorter overhang and a lateral assembly movement which makes it adequate for situations where there is no constraint to lateral disassembly, such as reflex corners of 2-wall intersections.

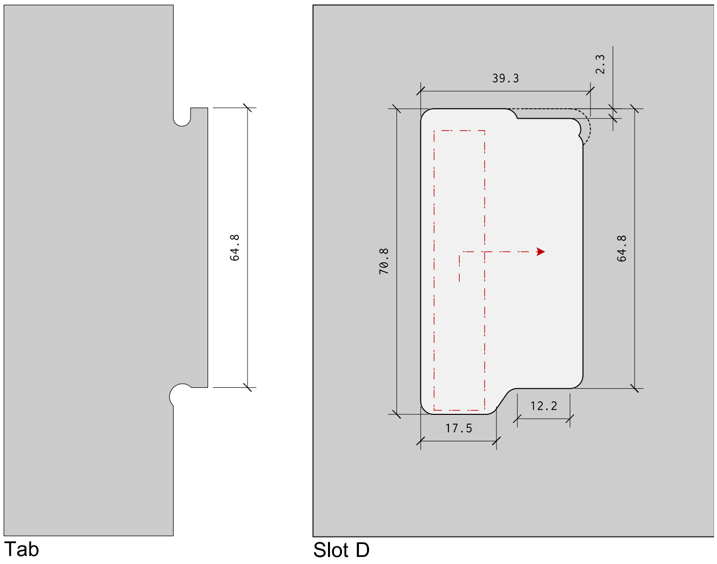


Figure 5-42: Type II T-Slot Joint variation

Prototypes of the above joints and other alternative designs were produced to test the design assumptions and the assembly sequences (Figure 5-43). Some prototypes were produced with birch plywood and others with eucalyptus plywood. These boards are available in a range of thick- nesses: 9, 12, 15, 18, 22 mm. We have selected plywood with 12mm nominal thickness, a good compromise for structural and sheathing uses, with 7 plies and an overall thickness tolerance of ±0,3mm.

The prototypes were milled with an Ouplan 3-axis router with the following tools: a solid tungsten carbide flat bit with a radius of 6mm, operated at a feed rate of 32mm/s and a rotational speed of 14,000 rpm; a T-slot bit with steel body and brazed tungsten carbide teeth operated at a feed rate of 15 mm/s and a rotational speed of 18,000 rpm.

Variations of +0,4mm on the Z-depth of the cut were found to occur and were attributed to warping of the panels and flatness of the CNC bed. These variations can impact he assembly of the joint as the height of the overhang is determined by the plunge of the T-slot bit. To overcome these differences, other than flattening the table, a reduction in 0,4mm of the distance of the groove to the edge of the tab was found sufficient.

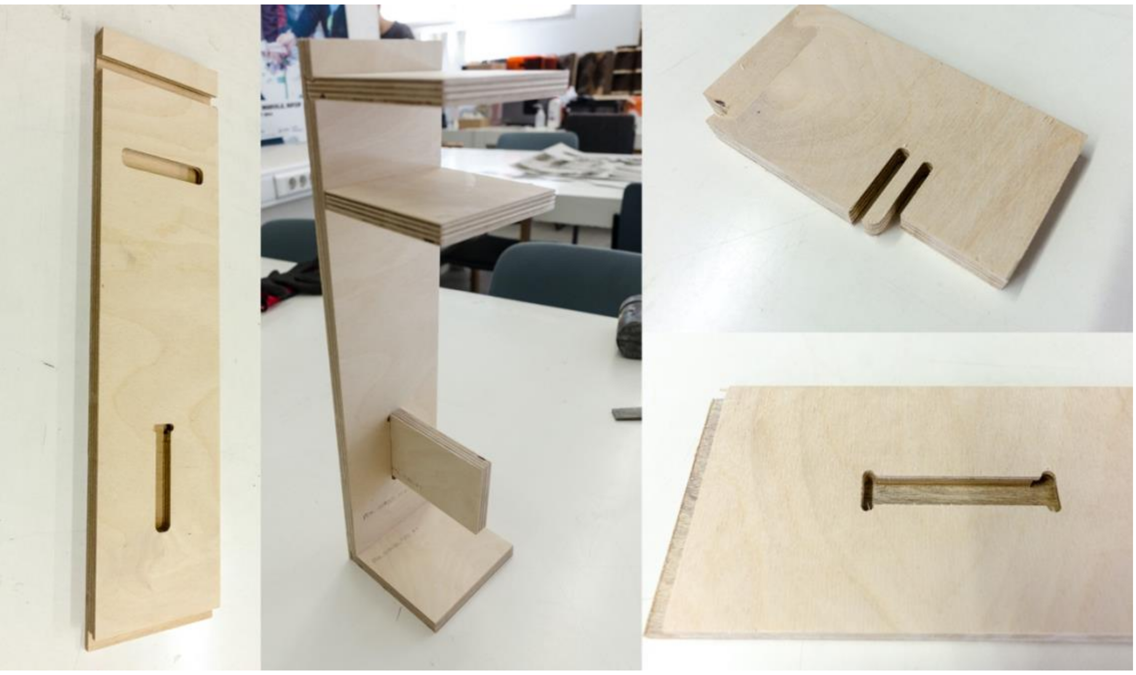


Figure 5-43: Prototypes of several alternative T-Slot joints

The first versions of the Type I tab B were found to be too stiff to be disassembled without damage to the slot (Figure 5-43 top right). Other alternative designs were completely irreversible such as the second joint from the top in the middle of Figure 5-43.

5.3.5 ORW v2.1

Following the first experiments with different types of joints described in the previous section, several changes were introduced to ORW v2.0, with the aim of reducing some of its shortcomings. Yet, the overall design of the system was kept for consistency with the following major system changes: a component of functional type B was introduced, and the connection detail was changed to increase Practicality to type II assembly sequences. The component-to-component structural connection is achieved with a sliding brace that is locked by two connectors (A and B in Figure 5-44), which avoids the need for special edge components.

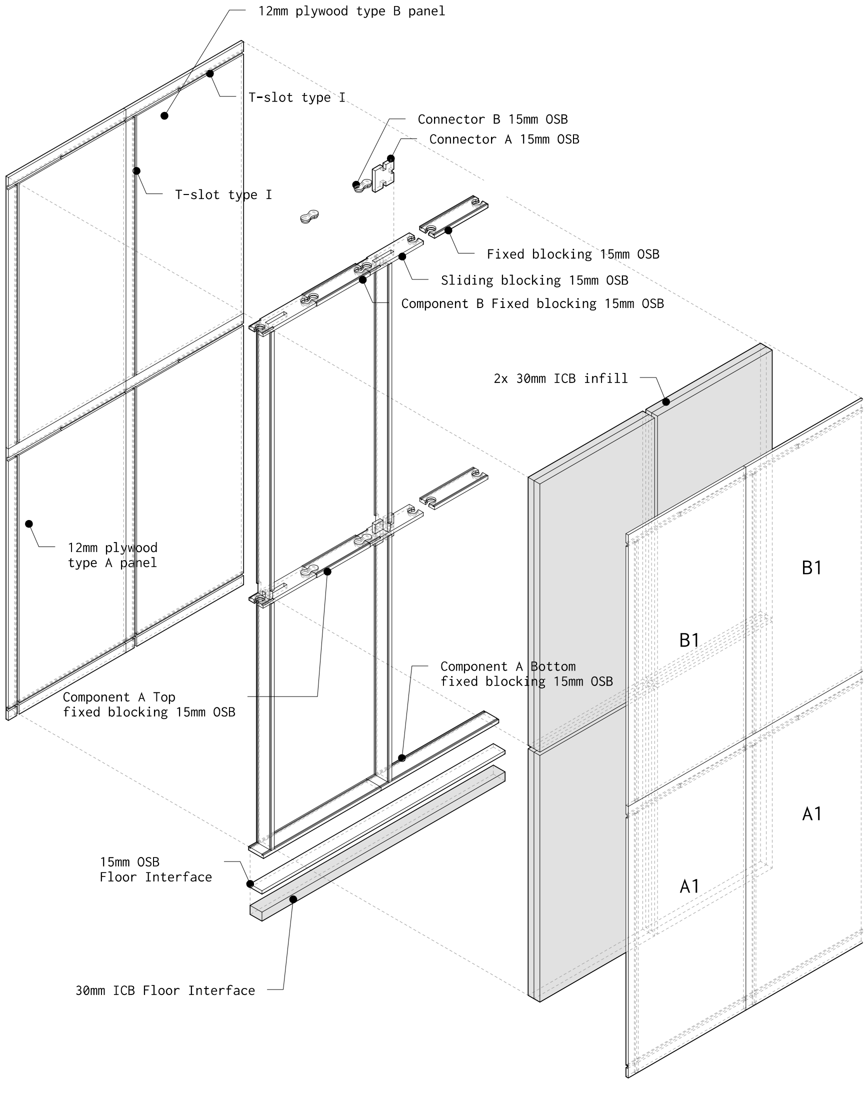
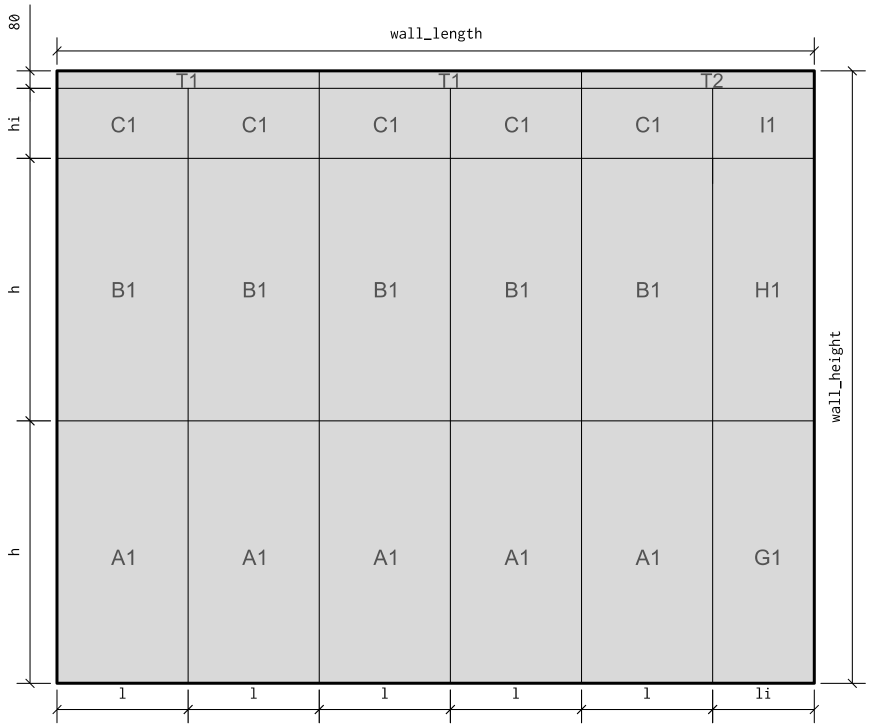


Figure 5-44: Exploded axonometric view of four ORW v2.2 components

Continuous panel-to-structure T-slot type II joints are used, which make the component modules easily transportable and stable, yet panels cannot be removed while the system is assembled. Furthermore, services must be embedded offsite inside the components (type 2 – unplanned integration) and no maintenance is possible after the system is assembled.

Regarding Combinability, there is an increase in the number of standard components for a simple straight wall, 9 including external interfaces, but the requirement for extra asymmetrical edge pieces is eliminated, and connection types are reduced (Figure 5-45).

The special edge components require several changes from the standard component design. C components must have the cork infill protruding upwards or at least level with the top edge of the panel to be assembleable. In the first case, the horizontal bracing must be removed which fragilizes the structure, in the second there must be an edge-edge structure to panel component joint. In both cases, the ceiling interface must have a different design to allow hanging the T type panels that close the system. Unlike, the G component type, components I and H cannot be vertically assembled. If any of the previously described solutions is adopted for C components, I and H components must have different panel-to-structure joints that are either friction-fit or, if there are gaps between the panels, T-slots of type I.



hi = wall_height - 80 / h
- Floor(wall_height - 80 / h)

li = wall_length/ l
- Floor(wall_length/ l)

li_min = 300mm

hi_min = 150mm

Figure 5-45: ORW v2.2 typical elevation with metric dimensional subdivision and functional subdivision

Another limitation of the system is the need to interrupt the wall interfaces to allow the interference of the retracted horizontal bracing of the type A component (Figure 5-46, top right 1). This is problematic since there would be the need to provide large tolerances to accommodate the adjustments provided by the floor interface.

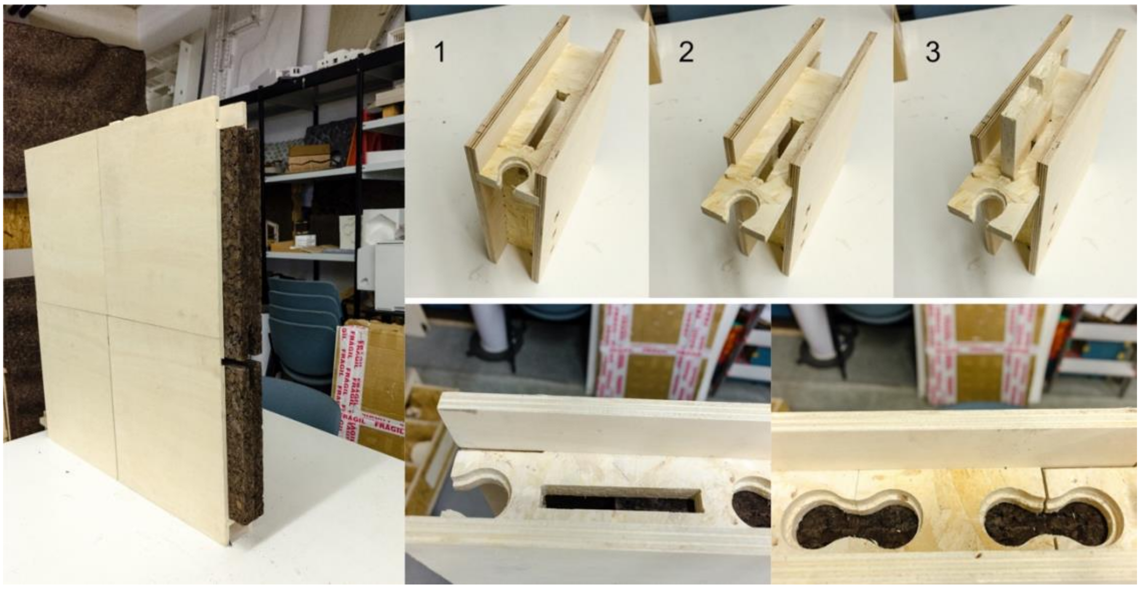


Figure 5-46: (Left) ORW v2.2 prototype of 4 assembled components; (Top right 1 to 3) Component to component assembly moves; (Bottom right) Connector slots

A small section of the wall was prototyped and assembled to validate and test the design assumptions (Figure 5-46 Left).

5.3.6 ORW v3.0

ORW v3.0 emerged after the experiments with snap-fit joints and later was revised with the introduction of T-slot joints in some panel-to-structure connections. These were introduced to improve the handling of the pre-assembled components. For brevity only the latest version is presented.

ORW v3.0 is based on pairs of male-female standard components, A-D respectively (Figure 5-47), E-B, F-C (Figure 5-48). A and C components have a horizontal bracing offset by 40mm from the lower side of the panel which is not present in E-B and F-C pairs. All component types have vertical studs that ensure vertical structural continuity using different means. In female component types A, B and C the vertical studs are connected to panels with T-Slot type II joints and structural continuity is ensured by a connector. In male component types, D, E and F the vertical studs are connected to the panels with an edge friction-fit male-female slot (Figure 5-49). Component type E studs protrude bellow the line of the panels and slot vertically to panels of type D components.

Component-to-component connections are ensured vertically by the previously specified means, and horizontally by panel-to-panel edge snap-fit joints. The slot of the joint is on female components A, B, C and the cantilever on the remaining D, E, F. Since, the male type B and C components have both vertical and horizontal interferences, the system must be assembled column by column, i.e., after the complete assembly of a column of A, B and C components, a column of D, E and F components must be pushed horizontally to connect to the previous column.

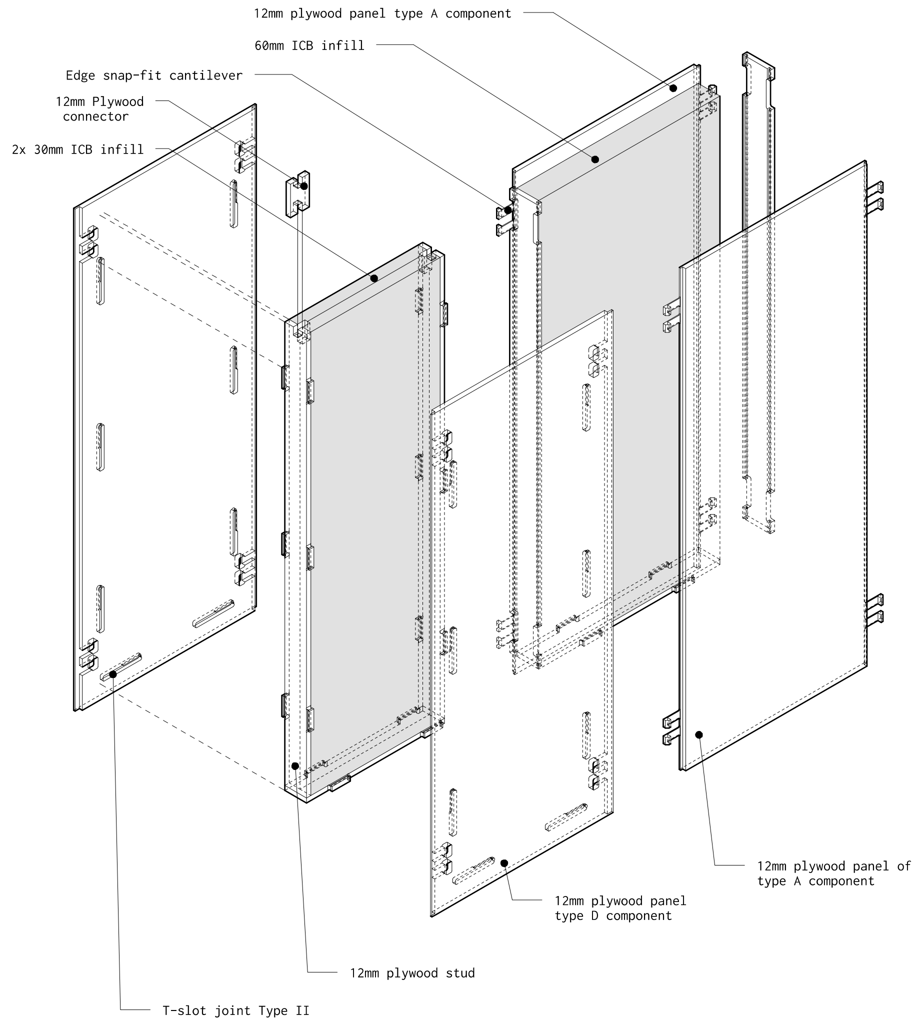


Figure 5-47: Exploded axonometric view of two ORW v3.0 components of type D and A

Since the system is based on horizontal in-plane assembly movements, the last column of components to assemble must be of a different type, i.e., the structure-to-panel connections must be site-disassembleable on at least one side to allow a normal to plane assembly movement. Hence, I, G and H components need to have friction-fit joints between the panel and the structure, since the panel gaps do not have a sufficient size for panel disassembly with T-Slot joints.

Another important limitation of this system that results from its pair component logic is the need for two different designs for end components, or alternatively, enforcing off-standard dimensions in the last two components of the wall to ensure a wall is always divided in odd number of components.

In ORW v3.0, panels perform finish functions but also structural function in connection with the internal component structure. Practicality wise, the number of operations and different operations is reduced compared to ORW v2.0 or v2.1 but the system remains unidimensional sequential in terms of assembly (Type I). Regarding flexibility, services must be embedded offsite inside the components (type 2 – unplanned integration) and no maintenance is possible after the system is assembled. Component separability is of type VI, always unidirectional, and there are three different component-to-component connections and two types of panel-to-structure joints. A simple straight wall requires at least 11 component types, including 2 different types of external interfaces (Figure 5-48).

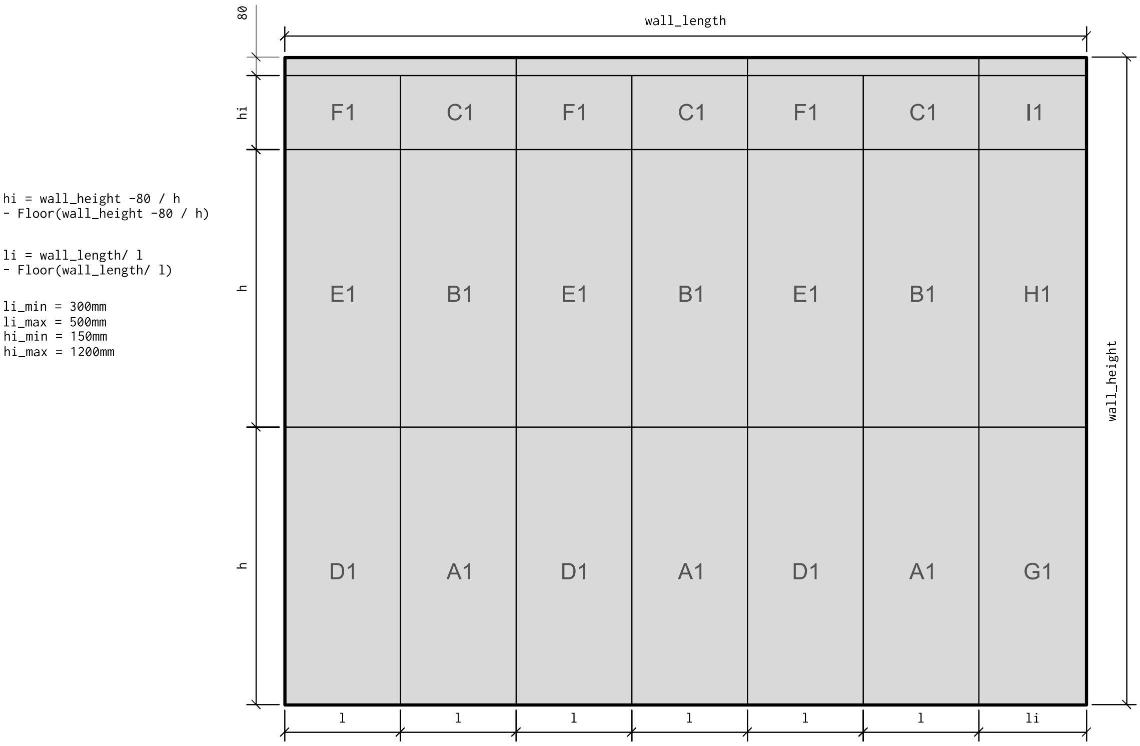


Figure 5-48: ORW v3.2 typical elevation with metric dimensional subdivision and functional subdivision

Considering the discussed limitations of the edge components in system ORW v3, the combinability and hence the reusability of the components is lower than in ORW v2.

Column assembly was not difficulty to achieve with the samples, but we estimate that in normally sized components the added weight would significantly increase the difficulty. Yet, column disassembly is not practical for several reasons: (1) it requires simultaneous release of at least 6 pairs of snap-fit locks, (2) the disconnection of each lock requires a simultaneous push in the cantilever and a pull on the column, (3) D-E-F columns holes for snap-fits may be used to assist in the pull movement during the disassembly operation but A-B-C columns have no points to grab.

Figure 5-49: ORW v3.2 (left) prototype of 4 assembled components, (top middle) A component slots, (top right) broken prongs during post-production, (bottom right) first prototype of ORW v3.

As already discussed, we found edge snap-fit joints have important limitations in plywood. During the sanding of the parts after fabrication, several prongs were broken. Since these joints are important for horizontal load transmission in soft-body impacts, it is very likely that ORW v3 would not perform adequately in safety tests.

5.3.7 ORW v4.0

ORW v4.0 was the developed after the experiments with T-Slot joints and the findings on the limitations of the previous systems, particularly those emerging from the use of asymmetric assembly component designs. In fact, the main goal in the development of ORW v4 was to eliminate the need for special components for any of the edge and corner functional types. Thus, a symmetrical design for the component was adopted, with the structure offsetting equal distances from the edges on all sides (Figure 5-50).

Figure 5-50 presents the type A component design, consisting of plywood structure, plywood panels and cork infill. The T-slot joints were used for panel-to-structure connections. In v4.0, Type I T-slot connections were used on all panel-to-structure connections. The experience from the protypes led us to adopt the Type II T-slot on one of the panels to provide a more stable connection for easier component handling before assembly. Hence, front, and back panels use different types of joints to allow access to the inside of the component during the assembly process and after the wall is built.

Edge T-slots were used for corner connections between all structural members in the original design but where later dropped, since these would interfere with the assembly of Type II T-slot joints. Therefore, one of the panels has mixed functions of structure and finish. To make a bidirectional assembly between components possible a standard rotating connector is used on all sides.

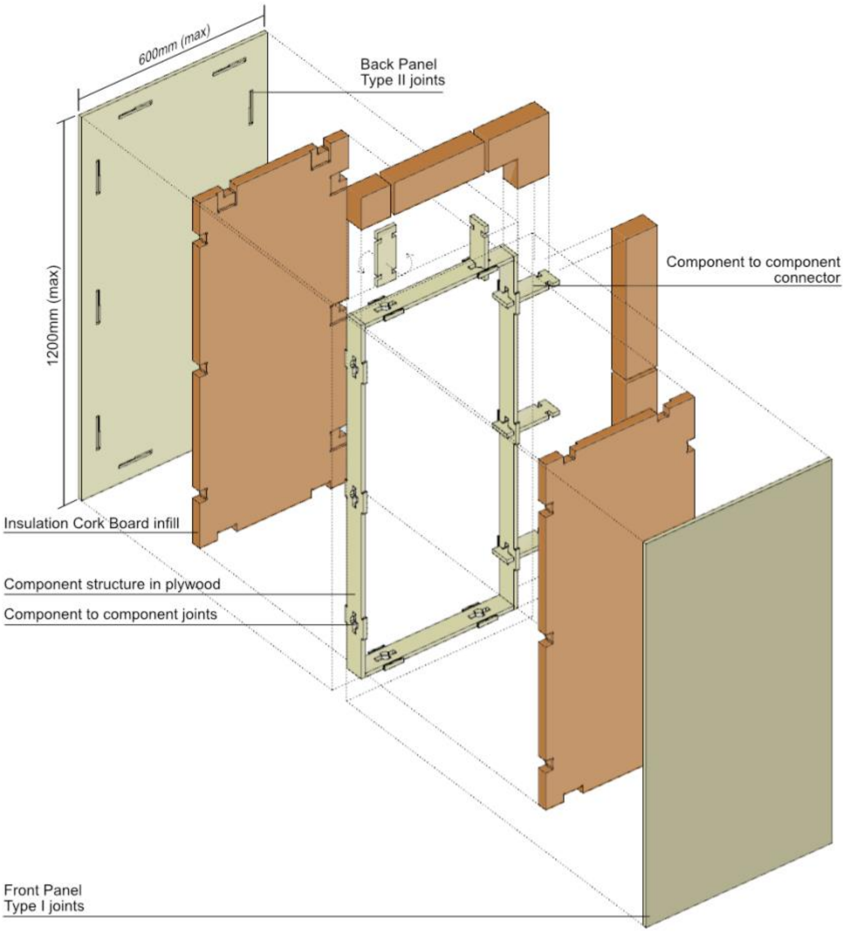


Figure 5-50: Exploded axonometric view of ORW v4 component of type A

Component pre-assembly can be performed on the factory as in (Figure 5-50), while component-to-component assembly is performed onsite by inserting and rotating the connector. To connect the components with the proposed connector only one panel must be removed, but to fill the gap between the structure with infill both component panels must be removed. Yet, since the connection is bi-directionally reversible it can be removed while the wall is assembled, which means any component may be removed while the wall is completely assembled (Figure 5-51).

The external interface components follow the same logic as in previous systems, with a cork compression layer and baseboard for screwing to the walls, ceiling, or floor. The connections between the internal structure and the baseboard can either be achieved using tabs, using the connector slots, or screws (Figure 5-51).

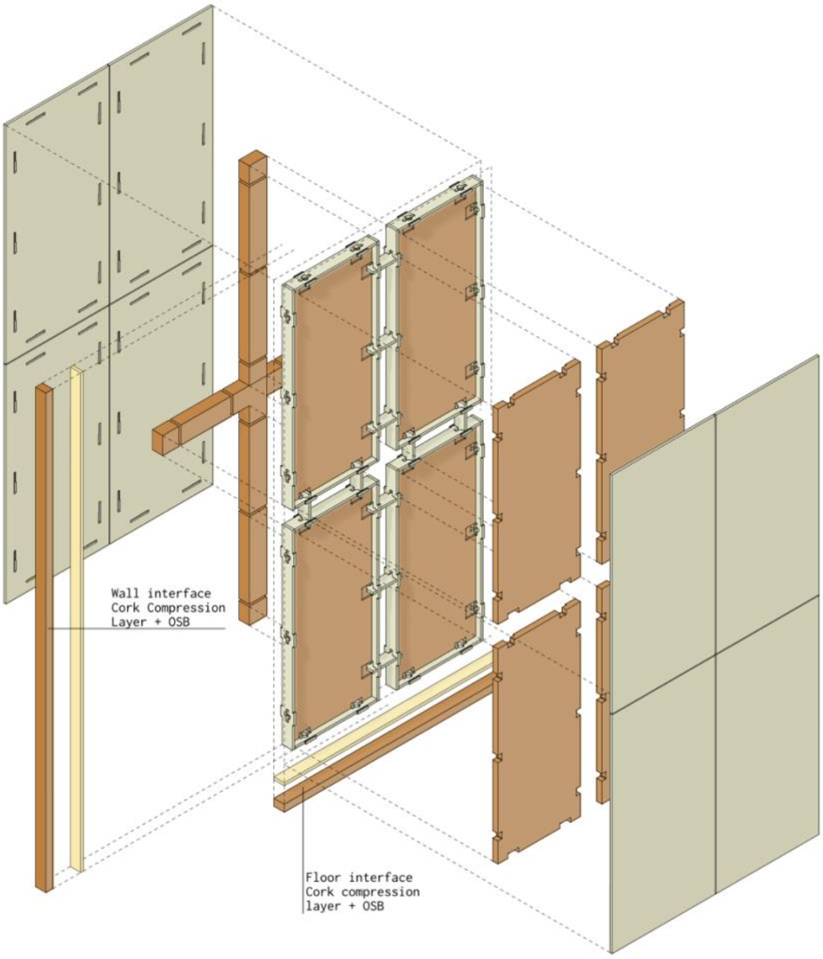


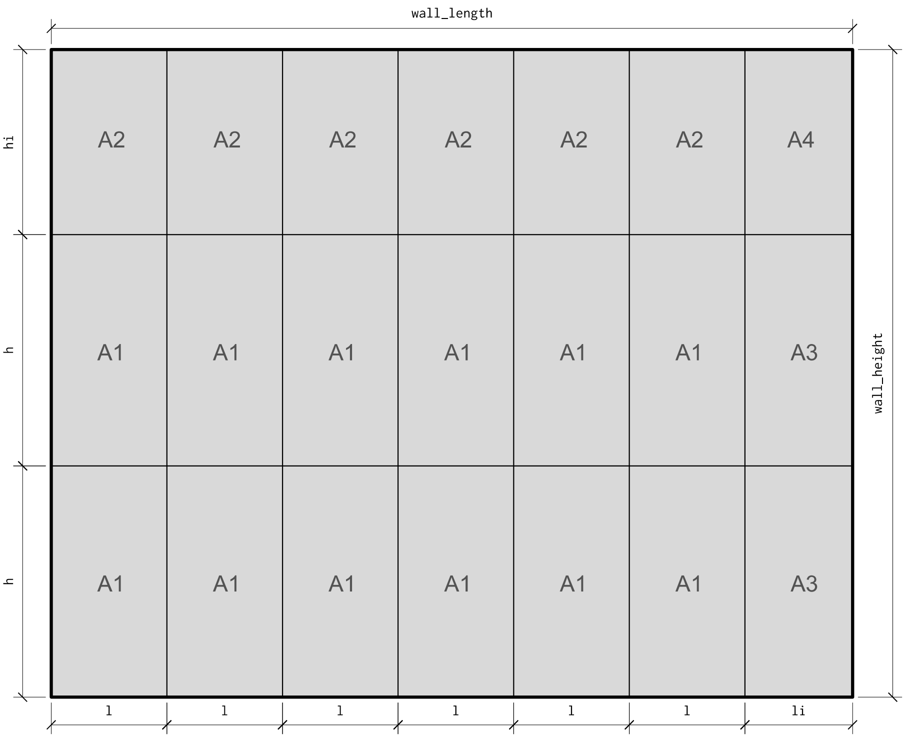
Figure 5-51: Exploded axonometric view of four ORW v4 components and external interface solutions

Regarding Simplicity of assembly/disassembly operations, since there is only one type of component, there is only one set of operations, comprised of component-to-component connection steps, infill placement steps and panel hanging step. The other set of operations is the placement and adjustment of floor/wall/ceiling interfaces which are all the same.

As implied from the previous system descriptions, components are locally demountable. The symmetrical design implies that integer and both metric dimensional subdivisions are possible. The maximum dimensions of the components are set to 1195x595mm, which corresponds to a weight of 21,6kg, and the minimum to 295x295mm. The relatively large minimum dimensions are a consequence of the symmetrical offset of the internal structure.

Concerning Services Integration, ORW v4.0 offers unplanned integration but can easily provide planned integration by reducing infill panel thickness to 20mm per panel, thus providing at least a 20mm thick area the size of the component.

About Modularity, structure-to-panel joints and component-to-component connections can be classified as type X and type VIII respectively. Since there is only one type of component connection, all components are interchangeable and reusable in different arrangements or in other contexts, if they are dimensionally coordinated, which results in a high level of component combinability. In Figure 5-52, components A2, A3, and A4 have non-standard dimensions, hence these are less likely to be reusable in different contexts. But as the components are parametrically defined and have standard connections, new components can be generated to complement parts that have been taken of existing walls to be installed in new configurations in the same space or in other locations. Yet, since opposing panels have different joint types, these cannot be interchanged.



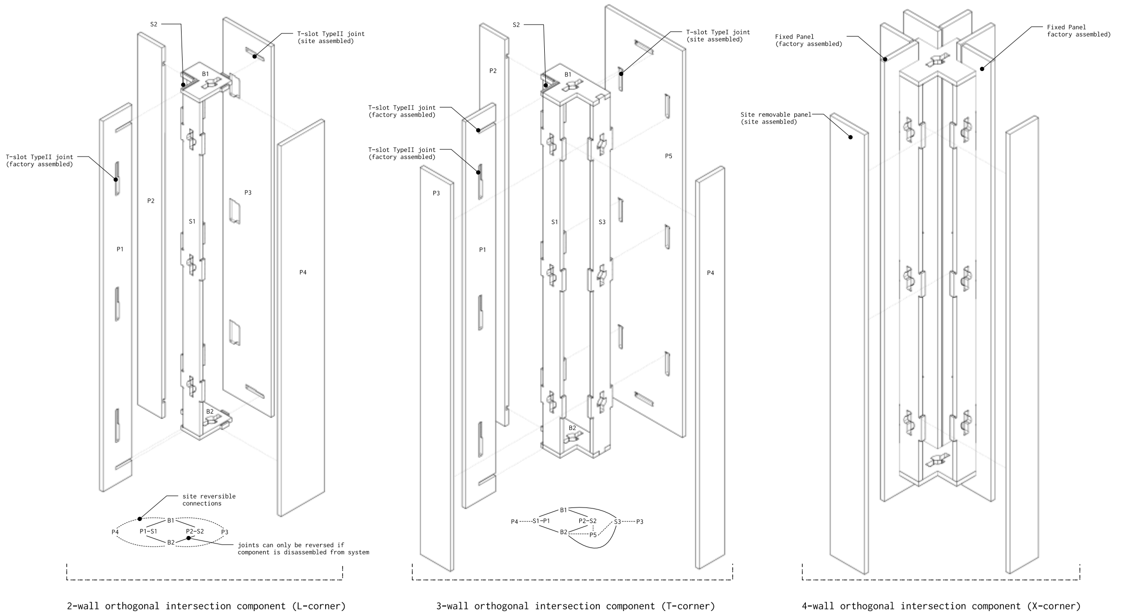
hi = wall_height / h
- Floor(wall_height / h)

li = wall_length/ l
- Floor(wall_length/ l)

li_min = 295mm
li_max = 600mm
hi_min = 295mm
hi_max = 1200mm

Figure 5-52: ORW v4.0 typical elevation with metric dimensional subdivision and functional subdivision

Lastly, Figure 5-53 presents designs for 2, 3, and 4 orthogonal wall intersection components. These components maintain the asymmetric panel connection reversibility logic of the type A system components.



2-wall orthogonal intersection component (L-corner)

3-wall orthogonal intersection component (T-corner)

4-wall orthogonal intersection component (X-corner)

Figure 5-53: Exploded axonometric views of 2, 3 and 4-wall orthogonal intersection components.

A prototype of the proposed system was fabricated and assembled at the VFabLab to test the assembly and design assumptions (Figure 5-54). Local disassembly/assembly of panels (when the wall is totally assembled) with Type I T-Slot joints presented some limitations. Owing to the small size of the panel gaps, 10mm, it is difficult to insert fingers between the panels, hence helping tools are required for the task assembling/disassembling the panels. For disassembly, a screwdriver is sufficient to lift the panel, assembly is more complicated since it requires holding the panel while aligning the slots with the tabs, which are not visible. Suction cups, frequently used to lift glass panels are a professional tool that can be used to easily assemble/disassemble panels with Type I joints.

Figure 5-54: ORW v4.2 prototype of 4 assembled components

The ORW v4.0 system demonstrates that with thoughtful use of digitally fabricated integral joints it is possible to design partition wall systems that are fully reversible and reusable. T-Slot joints open the possibility of digitally fabricating composite components without visible joints which can be decomposed into the different material parts, thus increasing the recyclability, modularity, and serviceability of the product. The latter two aspects determine the degree to which a product can be repaired and thus have its life cycle extended.

Still, the ORW v4.0 system presents some limitations which are all connected with the offset of the structure from the edge of the panels. In fact, placing the structure at the edge of the panels would simplify local panel disassembly, reduce the number of infill small parts, and eliminate the gap between the structural components which complicates assembly sequences.

Table 5-11: Comparison of the design systems according to the criteria defined in Chapter 4

Criteria		Subcriteria	Method of evaluation	ORW 1.0	ORW 2.0	ORW 2.1	ORW 3.0	ORW 4.0
Environmental	**EIM**	**Independence - material**	% of independent parts per system	**0,61**	**1**	**1**	**1**	**1**
	EIF	**Independence - functional**	% of parts with covariant functions per system	**0,86**	**0,88**	**0,89**	**0,88**	**0,92**
Assembleability	**AS**	**Simplicity**		**0,0246**	**0,0351**	**0,0388**	**0,0377**	**0,0563**
			Number of operations (1/n)	0,009	0,018	0,019	0,023	0,013
			Number of different operations (1/n)	0,040	0,053	0,059	0,053	0,100
	AP	**Praticality**		**0,65**	**0,65**	**0,70**	**0,70**	**0,88**
			Assembly/Dissassembly Sequences (Type I to V)	0,2	0,2	0,4	0,4	1
			Tools	0,75	0,75	0,75	0,75	0,75
			Weight per component (Range 15-75kg)	0,75	1	1	0,96	0,89
	AC	**Comunication**		**0,6**	**0,4**	**0,4**	**0,6**	**0,5**
Flexibility	**FG**	**Geometric flexibility**	Levels (Type I to V)	**0,4**	**0,2**	**0,2**	**0,2**	**0,4**
	FS	**Services integration**	Levels (Type I to V)	**0,6**	**0,4**	**0,4**	**0,4**	**0,6**
	FMS	**Modularity - Separability**	Levels (Type I to Type X)	**0,39**	**0,6**	**0,64**	**0,67**	**0,77**
	FMC	**Modularity - Combinability**		**0,075**	**0,1**	**0,135**	**0,1**	**0,235**
			Connection types (1/n)	0,11	0,14	0,2	0,14	0,33
			Component types (1/n)	0,04	0,06	0,07	0,06	0,14
	FP	**Personalization**		**0,75**	**0,7**	**0,65**	**0,5**	**0,75**
			Applicability of joining solutions	0,8	0,8	0,7	0,5	0,7
			Applicability of solution to renovation	0,7	0,6	0,6	0,5	0,8

Table 5-11 summarizes the results of the developed systems considering the proposed criteria in Chapter 4. The results demonstrate that it is possible to achieve hybrid partition wall system designs with digital fabrication and that these can improve the reusability of the components and the simplicity of site assembly without an impact on functional independence or services integration. Combining parametric and modular approaches can provide clear advantages in the reduction of site assembly complexity. Approximating the partition wall system design from the clear subdivision grammars enabled the increase in the combinability which suggests the usefulness of the generic grammar as design tool for meta-designers.

In section 5.1 we have seen that partial MCC systems are more adequate to the challenges of building renovation since they imply less disruption to existing stakeholder roles. Partial MCC systems require open approaches since their context of application is more generic. Yet, the general applicability of any construction system is questionable since cost, sustainability and cultural factors vary from country to country. Hence multiple solutions to different contexts are necessary which reinforces the need for generic principles for the design of customizable and disassemble-able partition wall systems and a workflow to implement them.

Section 5.3 presents the design research which was conducted with the aim of finding generalizable principles for developing partition wall construction systems for open building renovation. The generic grammar provides design principles that are a corollary of the framework of criteria for mass-customizable and disassemble-able partition wall systems discussed in Chapter 4. This enabled the developed partition wall systems that achieve a better balance between modularity and adaptation to context, while abiding to the design principles set by DfD.

The analysis of configurator platforms for MCC revealed that only a few integrate with widespread computational design tools used by architects and fulfill the interoperability requirements necessary for computational designers to develop MCC systems.

In section 5.2.2 we have seen that existing low-key workflows for non-expert users are not sufficiently precise for digital fabrication. Furthermore, these workflows are confusing to non-experts with low experience and experts do not trust them. Thus, it is necessary to develop a low-key workflow for surveying interior spaces that instance-designers can use, whether they are expert or non-expert users, to reliably survey interior spaces. Also, this workflow would ideally integrate with the tools computational designers use to develop design-to-production systems. Which would enable them to deliver survey-to-production configurators for interior spaces on the web.

PART 3: OPEN reWALL: OPEN BUILDING RENOVATION SYSTEM

CHAPTER 6 Designing Open System Workflow for Building Renovation

As analyzed in Part I and II an open system is required to fully address the challenges of building renovation. In the previous section we have seen there is a gap between the practice and theory of MCC systems in architecture. Kolarevic and Duarte (2015; 2019b) argue that all the technologic pieces have been developed, what remains is *"a broader cultural shift in society in how products are acquired"* (Kolarevic & Duarte, 2019a, p. 4). We argue that the prevailing view of MCC in architecture fails to consider the open nature of the AEC industry, in which innovation is mostly socially driven (Habraken, 2003). Thus, it is not that society must evolve to meet the technology, but technology that needs to be revised in a socially meaningful way.

We have shown that most theoretical experiences of developing complete systems of MCC have taken the form of closed prefabrication systems, attempting to capture the entire construction process in a designed overarching system. These attempts were based precisely on the premise that a radical shift in the construction process and the stakeholder's roles was needed (Larson et al., 2004). So, it is not at all surprising that most of the practical examples of MCC in the building industry (Kolarevic, 2015) are precisely from manufacturers of prefabricated housing, whose business was already vertically integrated. The early experiences of Habraken with MCC systems, and his reflections upon them (Habraken, 2003; Kendall, 2015a) indicate that a more open path might be needed. A similar argument is put forth by Ratti and Claudel (2015), who question the authorial role of the architect and call for a more open evolution of the built environment.

6.1 Designing an Open System for Building Renovation System

An open approach recognizes that there are different fields of action of the different stakeholders and that they may overlap. It is at these intersections that there is a need for a common framework of understanding. Clearly the first step to find these intersections is identifying the intended scope of action of each stakeholder. This equates to defining roles and expected tasks in the survey-to-production workflow. At the level of the construction system, several authors have pointed that this should happen at the interface between building components. The logic is straightforward and grounded on the following observations:

- Building systems, components, parts and materials have different life cycles and service lives ((Crowther, 1999a; Durmisevic, 2006b; Sassi, 2004))
- Multiple actors with different experiences and requirements participate in the building process (Habraken, 2003; Havik & Teerds, 2011).
- MCC (Lean, just-in-time, prefabrication) requires building components to be produced before their interfaces can be measured onsite (Scheurer & Stehling, 2020).

Distributing design control is a precondition for MCC, as it is for user participation. Identifying scopes of action also needs to be extended to the design process if we are to develop a design system for generic clients. The first step should be determining which decisions should be imposed at the system level and what is open for the instance-designer to determine. Another important consideration is that survey-to-production systems should not impose constraints that affect other levels, e.g., a survey-to-production system of a partition wall system should not impose constraints on the dimensions of the partitioned space beyond what is necessary to be assembled. Ideally each of these systems should be independent, such that the outputs of one system are the inputs of the next.

An important advantage of the previous approach is reconciling the methods applied in new construction with those in building renovation. As the world building stock grows the need of building renovation will only become more important. In fact, building renovation poses a significantly more complex challenge than new construction. The context is more complex and diverse, and the depth of the interventions is more varied. Which is yet another reason why a distributed open-source effort is what might be necessary to effectively develop survey-to-production systems that respond to each of the building systems requirements.

Thus, a low-key workflow seems to be what is necessary to provide a template for more meta-designers to contribute to the effort.

6.1.1 Designing Survey-to-Production

Larson, Tapia, and Duarte (2001) defined the basic anatomy of a MCC system in architecture as being composed of three sub-systems: a preference engine, a design engine, and a production system. Duarte (2019) has since integrated the preference engine into the design engine, defining it as one of the parts of a *"formulating"* problem. Yet, when this model is applied to the case of building renovation it quickly becomes evident that it does not consider a fundamental aspect in the design and construction process - the collection of the geometrical properties of the physical context.

In Duarte conceptual model, context is an input to the system, which we agree, but if the system is meant to be used by non-expert users how are they supposed to provide this information? Several authors (Huang & Krawczyk, 2006; Mcleish, 2003), including Duarte (2001), have thoroughly dealt with the problem of gathering the user social context and preferences, but surprisingly little has been researched on methods for users to collect the geometrical properties of their context by researchers of MC in architecture.

For mass customization of a product to happen " *we need to link such variation to features of the context, be it physical features of the environment or social and individual features of the product users, to obtain a product with higher performance*"(Kolarevic & Duarte, 2019a, p. 3). So, in our research we revise the model originally proposed by Larson and revised by Duarte to contemplate the survey stage.

We present a revised architecture of a mass-customization system that can be applied to building renovation. The system is composed of three main parts: a survey system, a design system, and a production system. The survey system takes as input information about the design context and instance-designer intents and choices. It generates a model of the context and a design brief, which the design system takes as input to generate a buildable solution for a specific production system. Lastly, the production system takes the buildable design, and materials as input and returns the finished product (Figure 6-1).

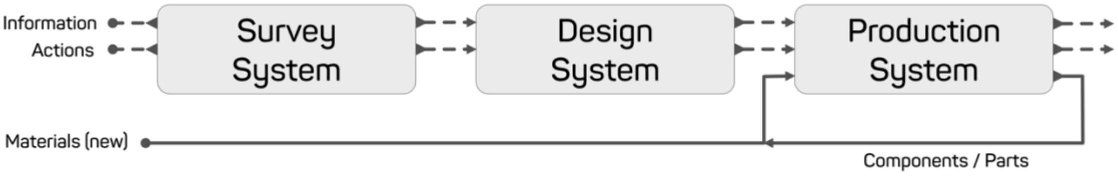


Figure 6-1: Anatomy of an open building renovation MCC system

The Production system is generally envisioned based on new material inputs, yet if the construction system is reusable following the previously outlined principles, the material flows may be circular. This does not imply that material flows through a survey or design system, but that information about these systems is fed to these systems. Yet, some dependencies between the design and production system in the above architecture still need to be resolved for the systems to be independent. There is also the need to bring the model to a less abstract level.

Consequently, we propose a workflow (Figure 6-2) that seeks to indicate how architects or meta-designers may extend their practices to develop survey-to-fabrication systems for generic clients (instance-designers) in specific contexts.

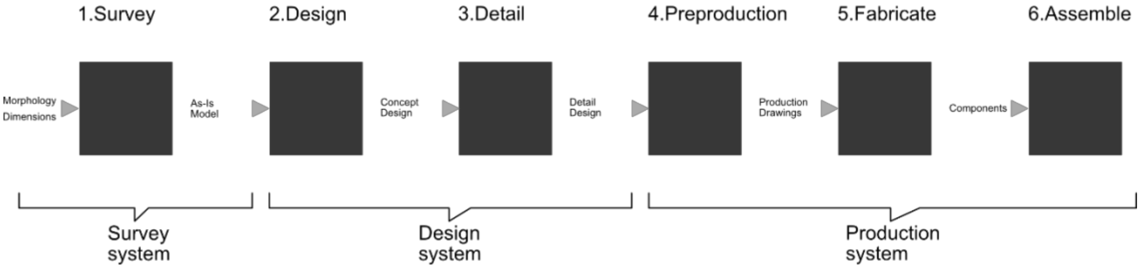


Figure 6-2: Conceptual Model of a Mass Customization Workflow in Architecture

The workflow provides an indication of the processes and steps involved from survey to production fragmenting the 3 systems (Survey, Design and Production Systems) into planning steps that are familiar to building practice. Each of the six identified steps is modeled as a system with clear inputs and outputs that also correlate with common deliverables of each stage in a planning process. Each of these components is a black box within which the instance designer cannot interfere and contains a set of functions that transform the input into the intended output. The disconcerting similarity of the workflow with the common design and construction process is purposeful. We believe it might push the discussion into a more familiar ground to the stakeholders of the AEC industry, hopefully increasing and accelerating the innovation. Furthermore, it is more amiable to modularization: smaller and less complex components are easier to develop, and clear inputs and outputs enable interchangeability.

6.1.2 Stakeholder Roles: Instance Designers and Meta-Designers

Another important aspect that also needs to addressed is the roles that stakeholders may take in developing and using a MCC system. We identify four groups of stakeholders that may take part in the use and design such a system: Users or Instance Designers, Actors or Meta-Designers, Producers and Assemblers (Figure 6-3).

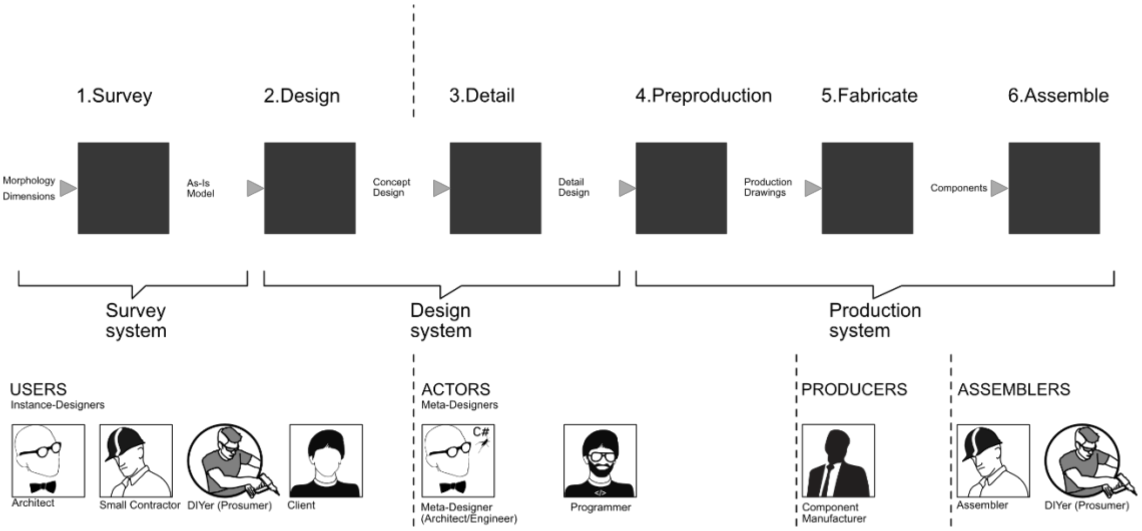


Figure 6-3: Correlation between the Workflow and the stakeholder roles

While the meta-designers are fundamental drivers of the process, important contributions may come from users either by participating in user testing or providing data for the development of the system. Equally important contributions may come from producers and assemblers. The first group will certainly influence the design of the construction system, or the requirements of the deliverables (i.e., the production drawings), while the latter will certainly provide feedback on the assembly process onsite. The users of the MCC system may be designers, other building professionals or clients. The meta-designers are clearly experienced designers (e.g., architects or engineers) with knowledge of programming (visual or textual) or assisted by professional programmers. The producers can be anyone equipped with Digital Fabrication tools, such as CNC mills, laser cutters, waterjet, robotic arms, or 3D printers, that are deemed appropriate for the specific construction system. Lastly, assemblers can be construction professionals or even prosumers. Figure 6-3 maps the roles the possible actors may have along those steps. The fault lines are nuanced for meta-designers whose design control may extend into the first two stages or to both the Fabrication and Assembly stages.

6.1.3 Design strategies for designing mass customization construction systems

This part focuses specifically on how meta-designers may approach the problem of developing each of the steps within the constraints of parametric modelling. These principles also apply to a paradigm of flow programming, for which special care must be taken with feedback loops. This subject has been widely covered in the literature and there are abundant resources that cover the fundamental concepts that are required to develop computational models for design such as:

- Designing with dimensional ranges

- Relating the parametric hierarchies with the construction hierarchy.
- Designing with rules or constraints (morphological, geometrical, topologic)

Yet, working for open contexts poses a significant challenge to parametric design systems. Indirectly manipulating variables by changing values on a slider or a dropdown list may easily become a cumbersome method of providing meaningful input to a design system. For certain applications it may not even be possible to define a specific range other than all positive values in R. While the previous example can easily be covered with a text box, it is not hard to imagine a situation where these text boxes quickly overflow the design interface, becoming unwieldy for the instance-designer to manipulate. A particularly interesting possibility is to allow the instance-designer to draw on the canvas of a web browser. Yet, this possibility requires sound methods to validate instance-designer inputs. Thus, a wider range of tools is necessary for meta-designers to deal with open input contexts.

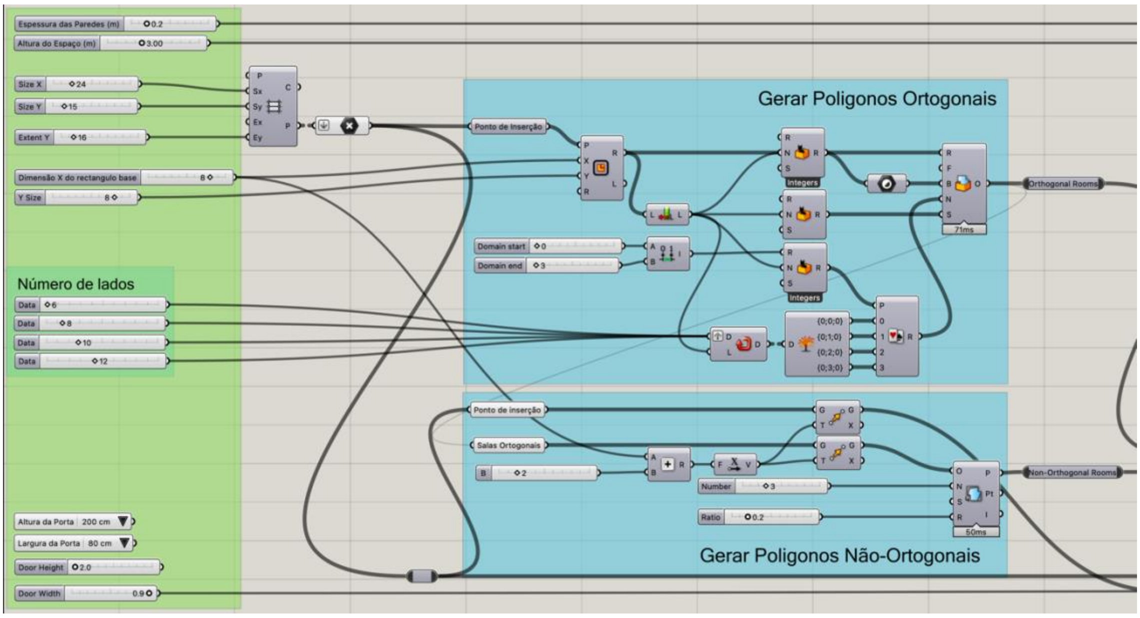
6.1.3.1 Datasets: import or generate

As the inputs become more open, it becomes increasingly difficult for a meta-designer to explore and test the design envelope of their MCC system by direct methods such as manipulating sliders or sets of variables.

One possible approach to address the above issue would be to select relevant cases studies – a corpus or a dataset - that can provide meaningful contextual information on possible solutions. This is a valid and common approach that can be particularly useful at the start of the design of the system to abstract common typological features of a given family of objects.

Yet, a designer selected corpus of inputs may be biased in several ways and fail to include less common and equally valid real cases. Large standard datasets of real cases can overcome this issue at the cost of conciseness. Some datasets of university campus buildings have been in use for some years (Aydemir et al., 2012), and housing datasets of manually designed buildings have recently emerged in 3d and 2d versions (Li et al., 2019).

A third alternative is to generate artificial datasets with random generators. This alternative is the only solution when existing datasets properties do not represent the desired application context for the survey-to-production system. Random polygon generators have been reported in the literature (Tomás & Bajuelos, 2004b) and we have implemented some of these algorithms in grasshopper components. Figure 6-4 presents a definition that can be used to generate random orthogonal and non-orthogonal rooms. In the annexes we include random polygon generator algorithms for orthopolygons and non-orthopolygons.



Espessura das Paredes (m) 0.2
Altura do Espaço (m) 3.00
Size X 24
Size Y 15
Extent Y 16
Dimensão X do rectangulo base 8
Y Size 8
Data 6
Data 8
Data 10
Data 12
Domain start 0
Domain end 3
B 2
Number 3
Ratio 0.2
Altura da Porta 200 cm
Largura da Porta 80 cm
Door Height 2.0
Door Width 0.9

Figure 6-4: A definition to generate a random space dataset for testing design systems

6.1.3.2 Input, Validation, Generation, Output

The architecture of all systems includes the concepts of inputs and outputs, connection, hierarchy, chain of influence adaptability and interchange with the environment (Aguilar, 1973). To design a system is to design its architecture, structure, components, interfaces and defining the input and output data it needs to process to fulfill its purpose. Since each of the components of the system must be independent, the meta-designer needs to validate the data that is provided as input.

Validation also addresses the issues that arise from working with user design input on open-ended scenarios such as a web-browser. All assumptions on the type, relations and properties of the provided data must be verified before the generation of outputs. Hence, we identify at least 4 parts of a proper system: input, validation, generation, and output.

Flipping the matrix gives us a process model that is more aligned with what is commonly expected in flow programming (Figure 6-5).

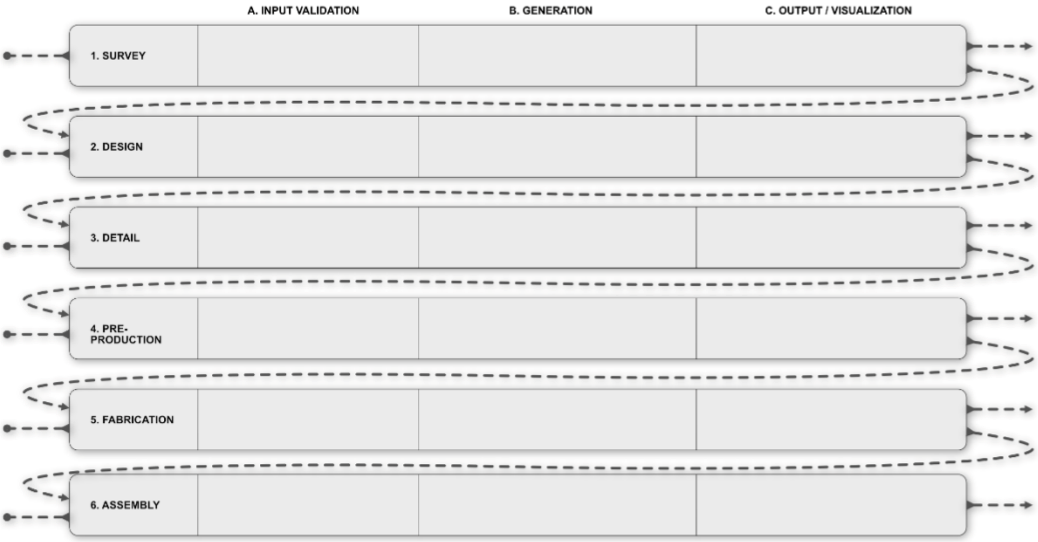


Figure 6-5: Workflow for customizable construction systems

6.2 A low-key workflow survey-to-production configurator for partition walls for building renovation

The possibilities of adding geometrical context as an input to an MCC system go beyond simply situating the design in a given locus.

> *"Perhaps the most important thing I learned from my father was that in any design problem one should seek the solution in terms of the next largest thing. If the problem is an ashtray, then the way it relates to the table will influence its design. If the problem is a chair, then its solution must be found in the way it relates to room cube. if it is a building, the townscape will affect the solution." (Eero Saarinen in Román, 2003, p. 93)*

Architects, as Saarinen points out, have always used context as a driver of the design solution, adjusting prototypical models of objects to their specific contexts. Geometrical context is an important catalyst of customization of building systems. This comes out of practical considerations. While design of buildings, systems and components may be conducted in abstract, the necessity of building them dictates the need of sufficiently accurate and precise models of reality to adjust the design to.

This simple idea is equally valid at whatever scale design is considered, from the level of the city to that of the ashtray. Thus, when designing a survey-to-production system it is important to understand that the larger context determines what can be built. Yet, the reverse is also true. The way we can put materials together limits the construction systems we may have, the methods we may use to build them, and the things we might build with them. Since for sustainability reasons these processes may need to be reversed, we need to also plan for their deconstruction, reuse, or recycling. A conundrum emerges, should we start designing a construction system for MCC from the top-down or from the bottom-up? From the survey of the larger context or from the methods and processes of production? To complicate matters further, at each object scale we decide to focus on there is a "*next largest thing*" and a "*previous smaller thing*".

Figure 6-6 summarizes the conceptual model of the architecture of a survey-to-production system, the information, material, and actions flows and its interactions with the built environment, which is itself composed of multiple nested systems.

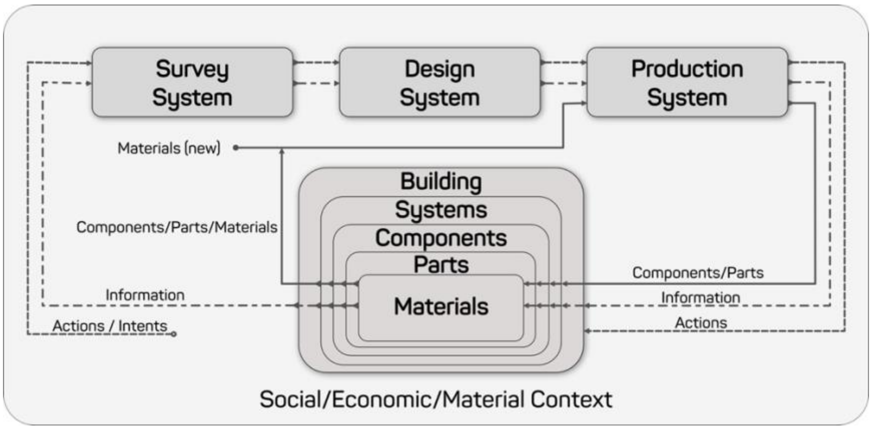


Figure 6-6: Survey-to-production conceptual model

Given the complexity of the feedback relations, we argue that the process and its implementation will necessarily have to be iterative to be inclusive and acceptable to the broadest set of stakeholders. Accessibility is also key to drive adoption and participation; thus, we favour it at the sake of expressiveness.

For the above reasons we developed a low-key survey-to-production workflow, striving to constrain the solutions to widely available tools. For the survey workflow we could not find a workable solution and thus we have developed and implemented algorithms for this purpose, which are presented in the following section. These algorithms were then implemented in a Grasshopper plugin as described in the next section.

6.2.1 An Interactive Survey Workflow

One of the essential inputs of a computational design system for building renovation is the shape of the space boundaries for which the solution is intended. In the specific case of an interior space this is the interior volume of that space. If we assume the interior walls are vertical and the ceiling is flat, this problem may be reduced to surveying the space plan. While this is a simplification, it is likely that it includes the vast majority of interior spaces (Steadman, 2006).

Nevertheless, in our case, even in those instances in which the ceiling is not horizontal or the walls are not vertical, if we constrain ourselves to planar walls, the only relevant boundary is the section of the space on the position of the wall. This is still a planar section that can be surveyed using the same processes that can be used to survey the space plan.

This would be sufficient to capture boundary conditions such as: existence and type of interfaces with existing walls and between new walls, floor, and ceiling; angle of incidence of the new walls with the existing walls; the levelness of the floor, walls, and ceiling. But since the user may want to use the plan of the space to lay out the walls, there is a need for a preliminary step of finding the room plan. Ideally, the building owner should be able to survey the space to be partitioned by providing simple inputs to construct the as-is model of the space to be partitioned.

The traditional empiric methods of survey that architects and construction professionals use could provide an adequate template for that workflow. These methods involve making sketches of the existing space, taking the needed field measurements for latter geometrically reconstructing plans, sections, or elevations. In orthogonal spaces, measuring the perimeter of the space and registering the turn, left or right, at each corner is enough to accurately reconstruct the space. As seen in section 5.2.2 , non-expert users seem to intuitively expect this workflow, even if they lack the proficiency to execute it to bear accurate results.

The tested apps combine these empiric methods with smartphone sensors and camera to provide semi-automated workflows for generating as-is models. These workflows are quick and cost-effective for as-is surveys of some rooms, but the results are not geometrically accurate if the room plan is not an ortho-polygon.

When faced with non-orthogonal rooms experienced surveyors circumvent the problem by using triangulations between internal corners, subdividing the room's polygonal shape into triangles. Our hypotheses are that these processes can be embedded in a semi-automated workflow, that users can execute them on their own, and that the outcome generated is a sufficiently accurate parametric model of the surveyed space for further design steps (Figure 6-7). The workflow builds on existing processes and is divided into three steps, sketch a plan, measure all walls and finish with measuring diagonals of the space (F. J. S. Brandão et al., 2020).

The first step can be easily achieved by asking the user to provide or draw the shape of the room. This should be the baseline method since so many users seem confused by assisted plan generation workflows and some existing apps already offer it. The second step of measuring walls should guide the user to collect and input all the dimensions of the room sides. Our challenge in the third step is to devise an algorithm to assist the users in: (1) the process of selecting which diagonals to take, (2) and the process of generating the geometry of the space from the provided inputs.

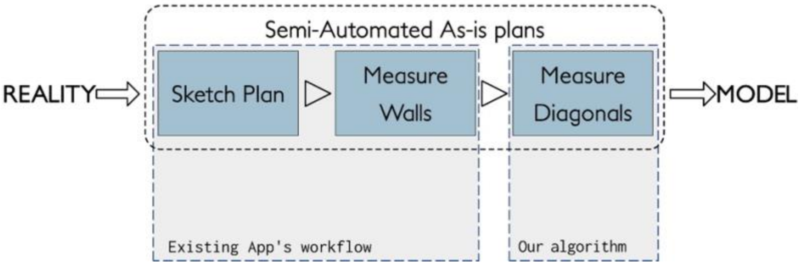


Figure 6-7: Semi-automated workflow for user produced as-is plans. Adapted from Brandão et al (2020)

The semi-automated workflow for as-is plans can be easily extended to the third dimension, assuming a flat ceiling, by adding the room height. Alternatively, as described above, selecting one or more walls to survey its elevation could be an efficient method to survey slightly more complex room ceilings (e.g., ceilings with one or two flat slopes). Other important details would also need to be added to the model (e.g., doors, windows, beams, columns, etc). Figure 6-8 depicts the steps of the complete process from a morphology to the as-is 3d model of the room. Naturally, the process could be extended to include more properties of the existing space.

At the end of the proposed workflow an as-is parametric model of the space is obtained. Notably, since the survey is an explicitly defined parametric model, it might be updated, making it possible to create associative relations between the design and the underlying survey.

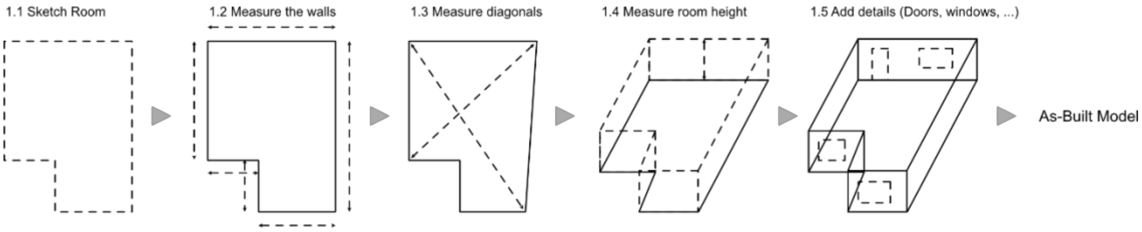


Figure 6-8: Steps of semi-automated workflow for as-is surveys from room morphology to as-is 3d model

The triangulation processes described above have similarities with the classical art gallery problem (AGP) (De Berg et al., 2008; de Rezende et al., 2014). In the AGP problem the objective is the subdivision of simple polygons, i.e., all non-self-intersecting polygons, into a set of non-overlapping triangles. The problem has applications in computer graphics and optimization problems and has been thoroughly researched in computational geometry, a subarea of algorithm design that uses points, lines, polygons and polyhedra as primitives (Shamos, 1978; Veltkamp, 2001).

Algorithms meant to partition the polygon into monotone pieces were proposed by Garey et al. (1978), Bernard Chazelle (1982), with Hertel and Mehlhorn (1985) or Chazelle (1990) proposing deterministic algorithms for any simple polygon. Yet, for these algorithms the polygon must be known à-priori while in our case the triangulation process is how the polygon geometry is determined. Thus, given a known polygonal morphology we want to use triangulation as means to find the internal angle between edges with known lengths.

Divide-and-conquer (Chazelle & Incerpi, 1983) or ear clipping (ElGindy et al., 1993) could be adequate algorithmic strategies for the challenge of selecting diagonals to measure. Yet, room clutter may prevent certain diagonals to be measured onsite by the user, which may cause problems if one of those strategies is followed strictly. Moreover, in our case there is no need to only consider non-intersecting sets of diagonals as in all the previous examples.

Existing approaches do not seem to be immediately applicable to the third step in our workflow. As previous stated, this step can be subdivided into 2 parts: (1) a decision problem – which diagonals to request from the user, (2) and iterative triangulation problem – how to use the diagonals the user can provide. We first present a solution for the second problem in the next section and then provide solutions for the first.

6.2.1.1 Definitions and Preliminaries

Our workflow starts with the creation of a sketch of the room, P_u in Figure 6-9. We assume the user can draw a polygon that is morphologically similar to the existing room and can explicitly control the orthogonality of each corner while drawing the polygon. To achieve this the user must distinguish corner type, i.e., convex corners from non-convex corners, and determine the correct number of sides. Other important assumptions are that users are not able to directly measure angles on site, and room corners are tendentially orthogonal (Steadman, 2006).

More formally, a corner $P[i]$ of a polygon P is of the type convex if the line segment from $\mathrm{P}[i-1]$ to $P[i+1]$ is entirely within the polygon. ElGindy (1993) calls this vertex an ear of the polygon. On the contrary, the corner $P[i]$ is concave if such segment lies entirely outside of P. A convex polygon is a closed polygonal curve that only contains convex vertices while a non-convex polygon contains vertices of both types.

The concept of polygonal similarity is equally important to formalize. We state that polygon P and P_u are morphologically similar *iff* both have n corners and there is a polygonal corner sequence in both polygons, from $P_u[i]$ to $P_u[i-1]$ and $P[j]$ to $P[j-1]$, such that there is a one-to-one match of corner types (Figure 6-9). Note that morphological similarity is scale, translation, and rotation invariant as depicted in Figure 6-9, but not reflection invariant.

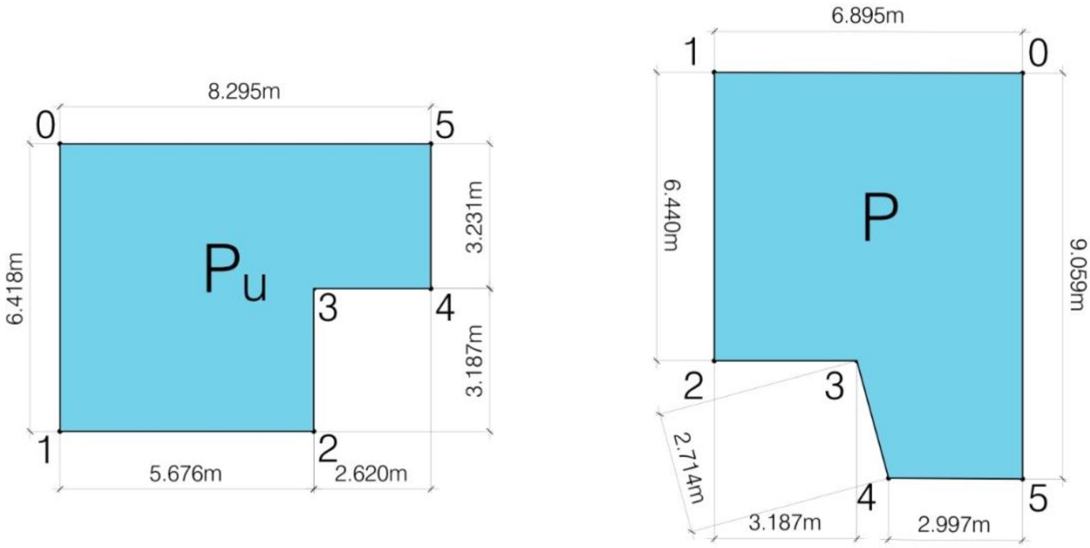


Figure 6-9: P is the actual plan of the room while Pu is a morphologically similar polygon. Adapted from Brandão et al (2020)

Thus, our workflow aims to achieve a geometric transformation of a user provided morphologically similar polygon P_u, the sketch, so that it closely resembles the existing room, the polygon P. Consequently, the following transformations and or conditions are not allowed: transforming a convex corner into a concave one; zero or negative side lengths; or that the sum of any two consecutive edges is equal to or smaller than their diagonal. The output of the process is P_{out} , an approximation to P, given the following user inputs:

1. P_u - a morphologically similar closed polyline to P, with arbitrary side lengths;
2. L_l – A counterclockwise (CCW) ordered list with the length l of each edge of P measured on-site;
3. L_d - A list of iteratively requested diagonals by the algorithm while P_{out} is not closed;

Let P_u be presented in the standard form of a list of $n+1$ points, such that $P_u[0]$ is the first or start point and $P_u[n+1]$ = $P_u[0]$. We may convert this list into a generalized version of the polyline P_u in the form of a list of vectors P_{vec} with length n. The first evident transformation to approximate P is to scale each vector v in P_{vec} by the matching lengths l provided by the user in L_l. This yields a transformed P_{vec} with which we may iteratively construct the polyline P_{out}, an approximation to P. P_{out} is said to be closed if the sum of all vectors in P_{vec} is approximately 0.

$$f(x) = \sum_{i=0}^{n} v_i \approx 0 \qquad \text{(Eq. 6.1)}$$

The above condition is sufficient to test if a vector scalar transformation maintains the polygon closed but does not strictly imply that the polygon is triangulated. If the provided polygon is an ortho-polygon and the assumption that rooms are tendentially orthogonal holds, then we may assume the output polygon P_{out} and the polygon P have corners with approximate angular dimensions and the algorithm can terminate. If the orthogonality assumption does not hold then all internal angles must be triangulated. Conversely, if $f(x) > 0$, the transformations of each vector in P_{vec} generated an open polygonal chain P_{out} with the same internal angles as P_u. Thus, one or more internal angles of P_u are different to those of P and we must triangulate them.

6.2.1.2 Iterative Triangulation

When using empiric methods of survey, architects use iterative triangulation workflows to reconstruct the plan, elevation, or section of the space. Figure 6-10 exemplifies the first two steps in the reconstruction of a plan from a sketch and onsite measurements using geometric processes.

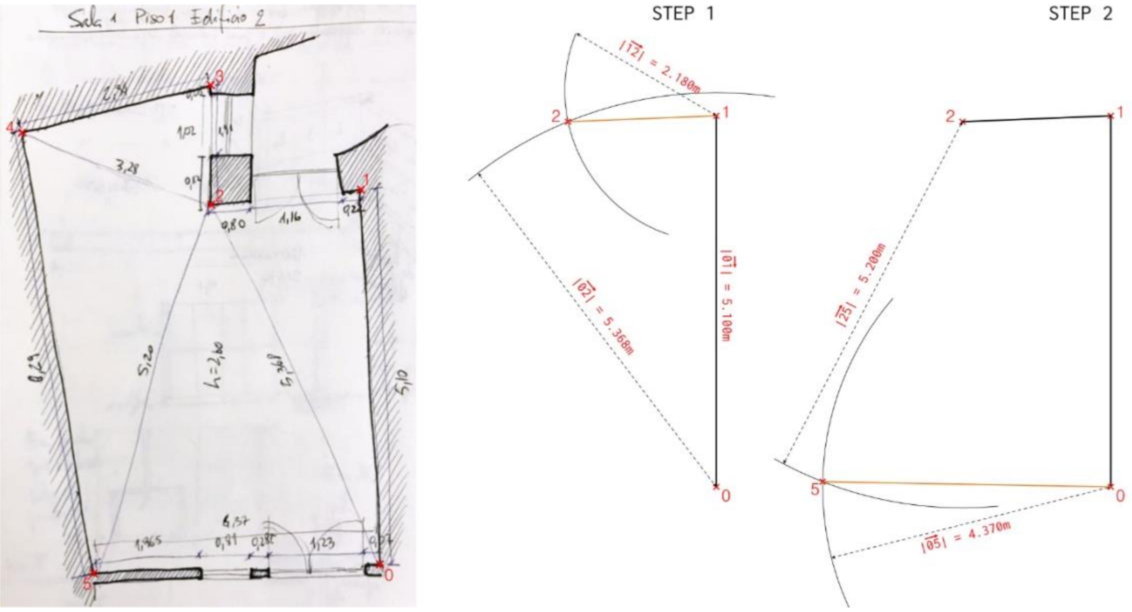


Figure 6-10: First two steps in the manual reconstruction of a plan from a sketch and onsite measurements

By observing and reflecting on these methods we were able to subdivide them into two groups of patterns: triangulation and polygon closure. Polygon closure patterns are in fact a particular case of triangulation, but these are worth separating as they directly relate to the notion of polygon as a closed figure. In other words, triangulation acts locally on the polygonal chain while polygon closure verifies global conditions to close the polygon.

6.2.1.2.1 Triangulation

Unless P is cyclic[30], which is an unjustifiable constraint, its internal angles cannot be deduced from the dimensions of its edges. Hence, we request valid diagonals of P_u and use them to rotate the vectors in P_{vec}. Yet not all diagonals of P_u may be diagonals of P, or vice-versa. Thus, we must allow the current diagonal to be skipped by the user which is also useful if it is impractical to measure the diagonal onsite, e.g., because of room clutter.

We create a list V_s that contains the state of triangulation of each vector or internal corner of the polygon to assist in the triangulation process and the selection of diagonals. As we have seen, there are two processes to triangulate the internal corners of the polygon with user provided diagonals: polygonal chain closure and triangulation.

Polygonal chain closure applies the previously described polygon closure test (Eq. 6.1) locally on polygonal chains and has the previously mentioned limitations. If the room orthogonality assumption holds and the user can explicitly provide orthogonal polygonal chains, we may use this method to mark corners as approximately triangulated.

Let the indices of the endpoints of the user-provided diagonal in P_u be i, j with $i < j$, and $L_d d$ its length (Figure 6-11). The ij and/or the ji polygonal chains are closed *iff* the length of the sum of all vectors in P_{vec} between i and $j-1$ or j and $i-1$ is similar to the diagonal length $L_d d$ within a specific tolerance. In this instance the internal angles of P_u from $i+1$ to $j-1$ are assumed to be approximate to those of P and may be set to triangulated in V_s.

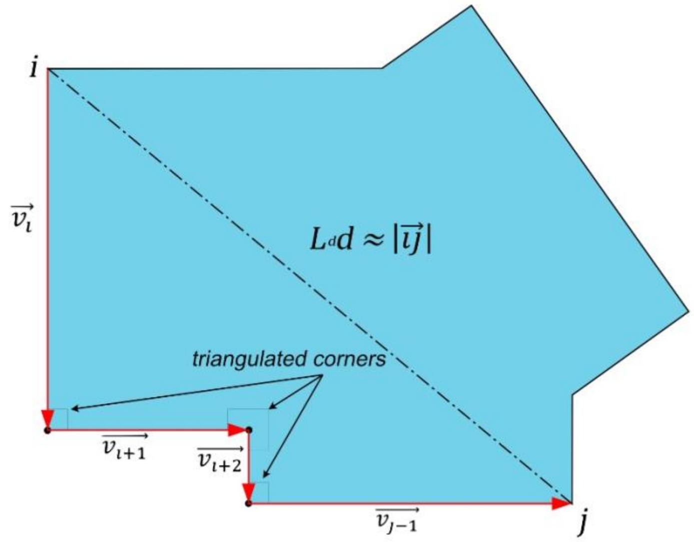


Figure 6-11: Example of an polygonal chain closure on an orthogonal chain ij

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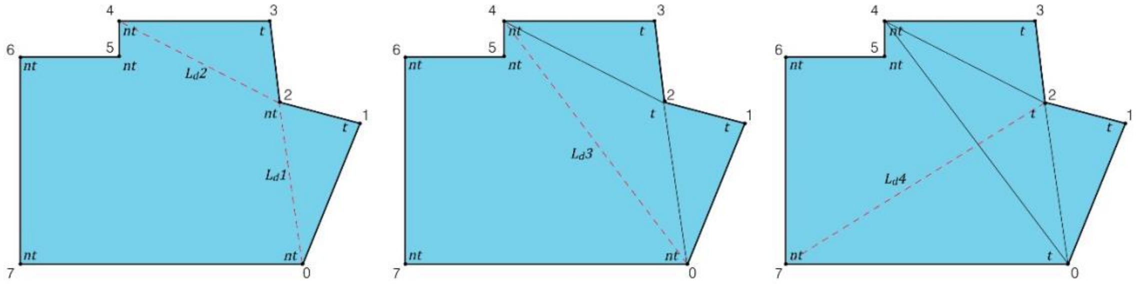
[30] A polygon is cyclic if all its vertices lie on a circumference. All triangles, rectangles or squares are cyclic, but a non-convex simple polygon cannot be cyclic.

Consider Figure 6-12 as example of a possible sequence of triangulation steps. If the orthogonal assumption does not hold, and there is one corner left to triangulate on the polygonal chain from $i+1$ to $j-1$ or from $j+1$ to $i-1$, triangulation may be used. Each of the steps in the sequence bellow represents one triangulation case worth considering. Let the non-triangulated corner be k, t the triangulated corners, nt the non-triangulated corners with i, j the endpoints of the diagonal $L_d d$ such that $i < j$:



Step 1/2: Case 1 Step 3: Case 2 (Pattern101) Step 4: Case 3

Figure 6-12: An example of a sequence of steps in a triangulation process. Adapted from Brandão et al (2020)

- Case 1: In step 1 and 2 diagonals $L_d 1$ and $L_d 2$ are requested and $i + 2 = j$ or $i = (j-2)\ mod\ n$, i.e., the diagonal endpoints i and j, and the polygon corner k form a triangle whose sides are two edges of the polygon and the diagonal. Whatever the state of the triangulation of the corners i or j, the internal angle of the vector ik with kj may be found with the law of cosines (Figure 6-12). This type of triangulation may only occur on the polygon's convex corners, since otherwise the diagonals are external and cannot be measured in practice.
- Case 2: In step 3 the diagonal $L_d 3$ is taken from point 0 to 4, k is an isolated non-triangulated corner such that at least $k-1$ or $k+1$ are triangulated, and neither ik or kj are edges of the polygon. We call this Pattern 101, and this is the quickest process by which a concave corner may be triangulated (Figure 6-12, Figure 6-11).
- Case 3: In the last step the diagonal $L_d 4$ is provided from corner 2 to 7. i or/and j are not triangulated, k is next to the non-triangulated i or j and the number of corners from i to j is larger than 2 in ij or ji polygonal chains. This triangulation case expands the triangulated sequence of corners (Figure 6-12) and may also be used to triangulate concave corners (Figure 6-13).

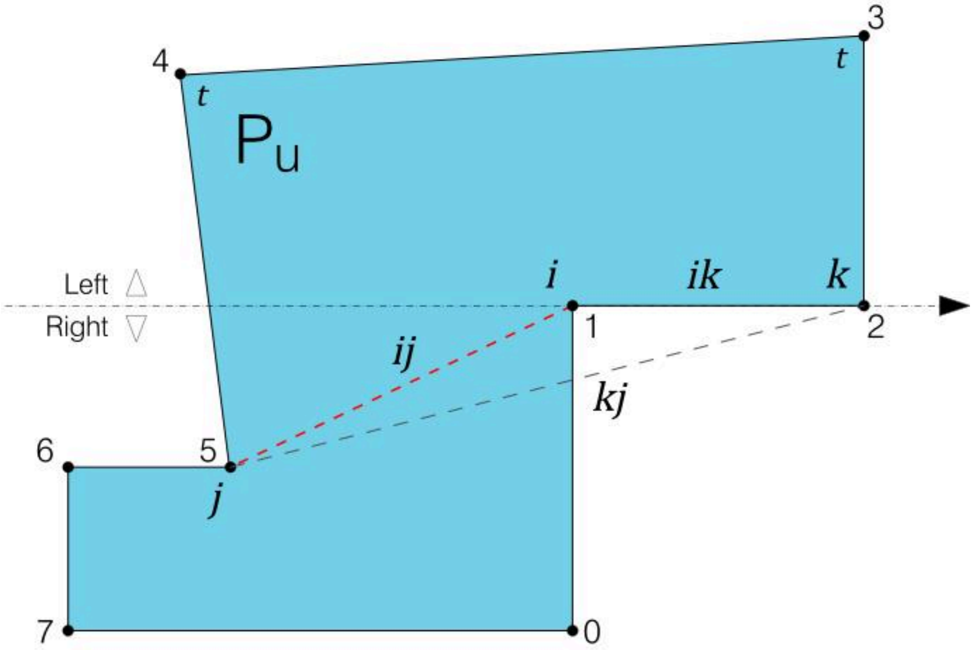


Figure 6-13: An example of a j on the right side of the infinite line from i to k in the triangulation of the ij chain.

We can build algorithms to triangulate each of these cases, or detection algorithms to find these cases in a polygonal chain and request specific diagonals that may be used to accelerate the convergence of the triangulation. Yet, we may process the triangulation of all cases with a single algorithm we call Pattern0.

Assume all corners but one are triangulated from $i+1$ to $j-1$. Let the non-triangulated corner in the ij polygonal chain be k such that $i<k<j$. First, we need to sum all the vectors in P_{vec} from i to k and from k to j to obtain $\overrightarrow{\imath k}$ and $\overrightarrow{k\jmath}$. Next, we find the internal angle β of the vector $\overrightarrow{k\jmath}$ with $\overrightarrow{\imath k}$ so that $|\overrightarrow{\imath k}|$, $|\overrightarrow{k\jmath}|$, $L_d d$ are the lengths of the sides of a triangle and define the new $\overrightarrow{k\jmath}_1(x_1,y_1)$ vector as the rotation of the unit vector $\overrightarrow{\imath k}(x,y)$ by $\pi-\beta$ and scaling by $|\overrightarrow{k\jmath}|$. To do this we use the algorithm NextVector. Lastly, we can triangulate k by rotating all the vectors from k to the next non-triangulated corner (Figure 6-14).

ALGORITHM 1 NEXT VECTOR

```
Input: Origin, $\overrightarrow{\imath k}$, $|\overrightarrow{\imath k}|$, $|\overrightarrow{k\jmath}|$, $L_d d$
Output: $\overrightarrow{k\jmath_1}$

SET nextPoint to the sum of Origin and $\overrightarrow{\imath k}$
COMPUTE angle β with the law of cosines given $|\overrightarrow{\imath k}|$, $|\overrightarrow{k\jmath}|$ and $L_d d$
SET $\overrightarrow{k\jmath_1}$ to $|\overrightarrow{\imath k}|$ unit vector and scale it by $|\overrightarrow{k\jmath}|$
SET $\overrightarrow{k\jmath_1}$ to $R_{kj}(\pi-\beta)$
```

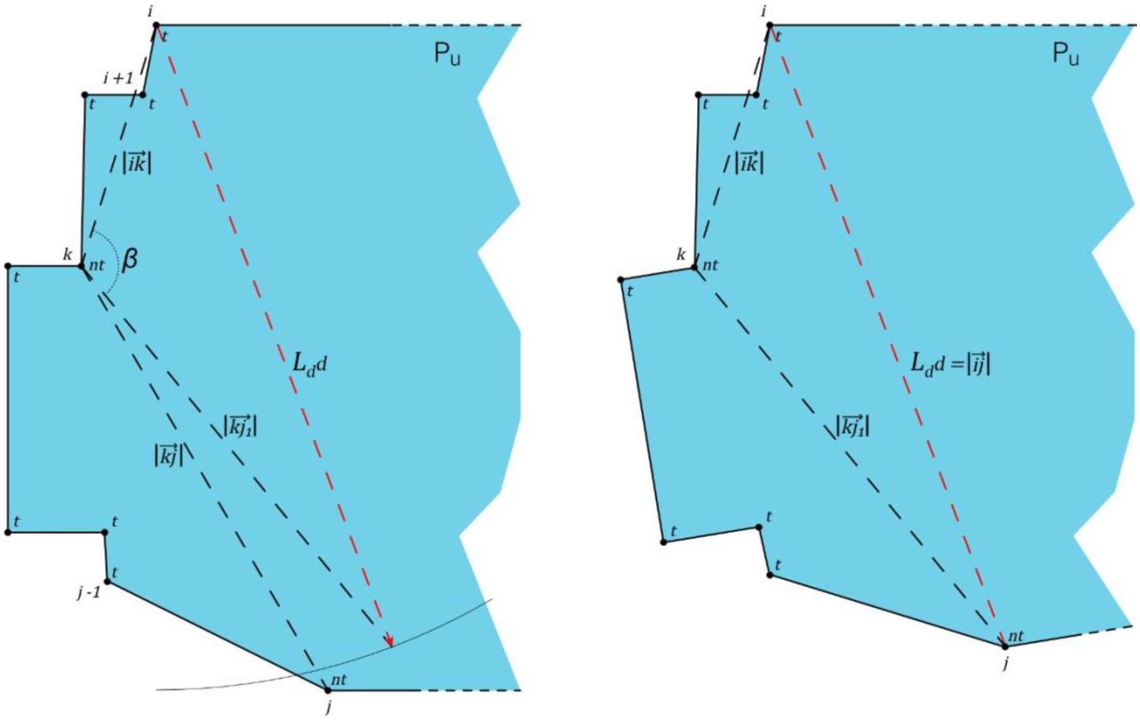


Figure 6-14: Iterative triangulation on the ij chain

The diagonal from i to j is user provided and consequently an interior diagonal of the polygon. Thus, it might seem that j should not be on the right side of the directed line from i to k. Yet, this in not necessarily true and Figure 6-13 presents an example. Assume that corners 3 and 4 are triangulated while corner 2 is not. The diagonal from 1 to 5 is an application of Case 2 and can be used to triangulate the corner 2.

A general algorithm for both chains can be easily obtained by testing if $k > j$ and splitting the vector sums accordingly. Bellow we present such algorithm with the following inputs: a list of vectors P_{vec} with length n; the indices i, j of the diagonal end points; the index k of the non-triangulated corner; the length $L_d d$ of the diagonal; a list V_s with the state of the triangulation of the polygon's corners; a boolean value $itoj = \ i < k < j$; and isLeft, a boolean value that indicates if the corner j is left of the directed line from to k.

ALGORITHM 2 PATTERN0

```
Input: i, k, j, itoj, $L_d d$, Vs, $P_{vec}$, isLeft
Output: $P_{vec}$

SET n to $P_{vec}$ count
SET vector $\vec{ik}$ to 0
SET vector $\vec{kj}$ to 0
IF itoj THEN
    SET $\vec{ik}$ to the sum of the vectors from $i$ to $k - 1$
    SET $\vec{kj}$ to the sum of the vectors from $k$ to $j - 1$
ELSE
    IF k < i THEN
        SET $\vec{ik}$ to the sum of the vectors from $i$ to n
        INCREMENT $\vec{ik}$ by the sum of the vectors from $i$ to $k$
```

```
        SET $\overrightarrow{kj}$ to the sum of the vectors from $k$ to $j - 1$
    ELSE
        SET $\overrightarrow{ik}$ to the sum of the vectors from $i$ to $k - 1$
        SET $\overrightarrow{kj}$ to the sum of the vectors from $k$ to $n$
        INCREMENT $\overrightarrow{kj}$ by the sum of the vectors from $k$ to $j - 1$
    END IF
END IF

SET the $\overrightarrow{kj_1}$ to NextVector (Origin, $\overrightarrow{ik}$, $|\overrightarrow{ik}|$, $|\overrightarrow{kj}|$, $L_a d$)
IF $\overrightarrow{kj_1}$ is invalid
    ABORT: Diagonal is larger than the sum of the sides
END IF
IF isLeft not true
    Reflect $\overrightarrow{kj_1}$ about the plane defined by the origin and the normal vector $p(x_2, y_2) = R_{ik}(\pi/2)$
END IF

SET the $\theta$ to the angle of $\overrightarrow{kj}$ with $\overrightarrow{kj_1}$
SET lastIndex to the index of the last fixed corner in $V_s$ after $k$
IF lastIndex > k
    FOR each vector in $P_{vec}$ from k to lastFixed
        Rotate the vector by $\theta$
    END FOR
ELSE
    FOR each vector in $P_{vec}$ from k to n
        Rotate the vector by $\theta$
    END FOR
    FOR each vector in $P_{vec}$ from 0 to lastFixed
        Rotate the vector by $\theta$
    END FOR
END IF
```

Pattern 0 may be used until n-1 elements of V_s are triangulated, leading to the convergence of P_{out} into P. When there is only one internal corner of P_{out} left to triangulate, there is only one triangulated polygonal chain. A triangulated polygonal chain is rigid and if the user provided measurements of diagonals and lengths are precise, P_{out} equals P and is a closed polygon. In practice, user onsite measurements will be affected by several factors that lead to precision errors. Consequently, a strategy for closing the polyline in the presence of a closing error must be provided.

6.2.1.2.2 Polygon Closure

The convergence of P_{out} into P may be terminated earlier without user input or loss of precision if any two or three corners are not triangulated. We call these situations Pattern 00 and Pattern 000 and both are used empirically by architects while drawing the room plan surveys.

Pattern 00 is very easy to see in quadrangular shapes which only require a single diagonal to be rigid (Figure 6-15). Since the figure is closed, i.e., its edge forms a closed loop, and the diagonal creates two rigid polygonal chains with matching endpoints, there is only one possible solution even though corners 0 and 2 have not been triangulated by any diagonal.

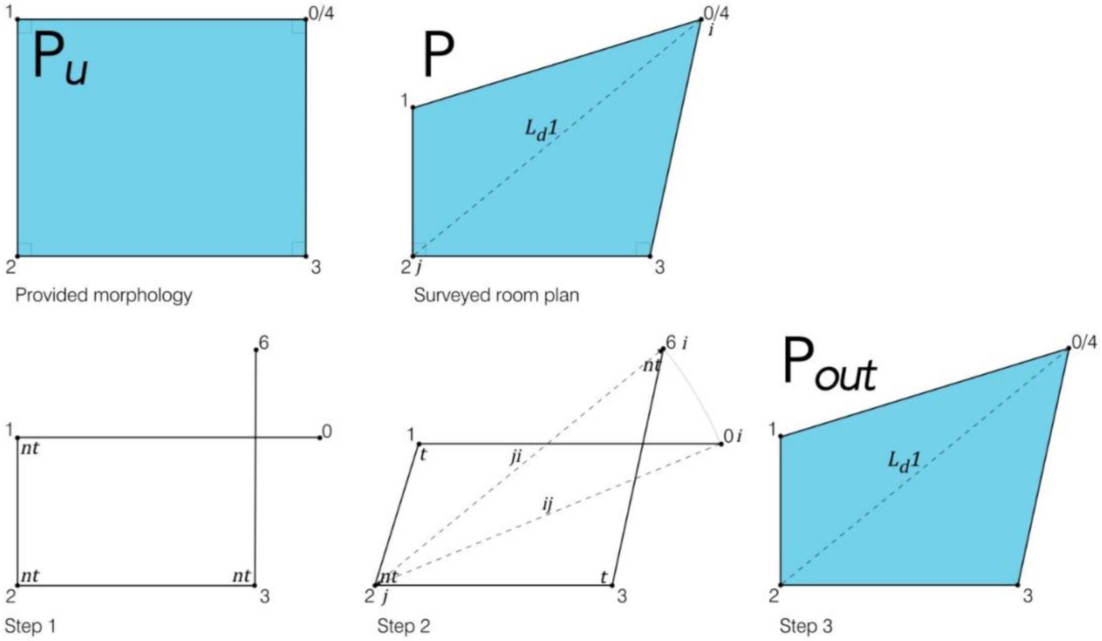


Figure 6-15: An example of triangulation of a polygon terminating with Pattern00 algorithm. Adapted from Brandão et al (2020)

Given a room morphology P_u and side lengths L_l (Figure 6-15), in step 1 we scale each side of the polygon P_u by the measured lengths of P, which does not construct a closed loop. Suppose L_d1 - the length of the diagonal from corner 0 to 2 - is requested. By the application of Pattern 0 we can triangulate corner 1 and corner 3, by rotating $\overrightarrow{12}$ and $\overrightarrow{30}$ respectively so that $L_d1 = |\overrightarrow{ij}|$. But the polygon is not yet closed since the corners 2 and 0 remain non-triangulated (Figure 6-15 Step 2) and thus cannot be rotated using Algorithm 01. Since $|\overrightarrow{ij}| = |\overrightarrow{ji}|$, we may rotate all the vectors on the polygonal chain ij or ji so that $\overrightarrow{ij} = -\overrightarrow{ji}$. Note that choice of which polygonal chain to rotate only affects the rotation of P_{out}.

The algorithm Pattern 00 implements the previously described strategy and may be applied to any polygonal chain with only two non-triangulated corners whatever their relative position. Let i be the index of the first undefined corner and j the index of the second one with $i < j$.

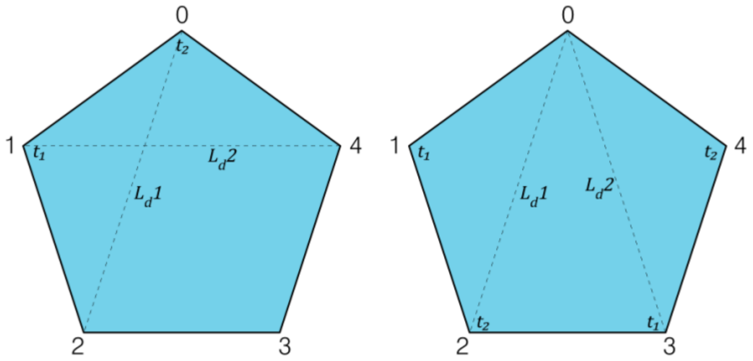
ALGORITHM 3 PATTERN 00

```
Input: $P_{vec}$, $i$, $j$
Output: $P_{vec}$

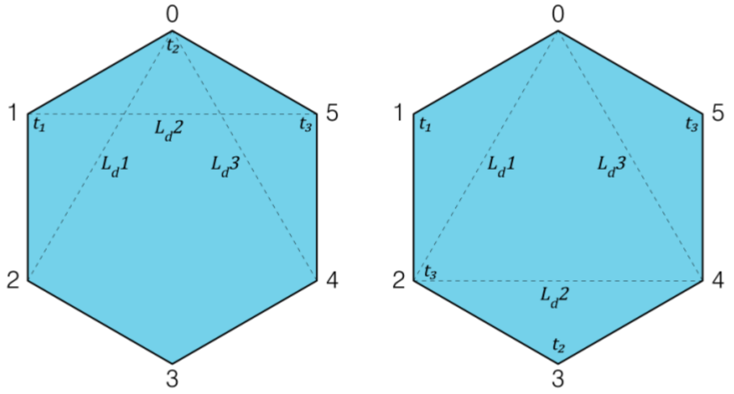
```

```
SET $\overrightarrow{ij} = 0$
SET $\overrightarrow{ji} = 0$
SET $n$ to the length of $P_{vec}$
FOR each vector in $P_{vec}$ from $i$ to $j$
    Add current vector to $\overrightarrow{ij}$
END FOR
FOR each vector in $P_{vec}$ from $j$ to $n$
    Add current vector to $\overrightarrow{ji}$
END FOR
FOR each vector in $P_{vec}$ from 0 to $i$
    Add current vector to $\overrightarrow{ji}$
END FOR
COMPUTE internal angle α of $\overrightarrow{ij}$ with $-\overrightarrow{ji}$
FOR each vector in $P_{vec}$ from $i$ to $j$
    Rotate current vector by angle α
END FOR
```

In quadrangular shapes, Pattern 0 and Pattern 00 are sufficient to ensure that only one diagonal is required to triangulate the polygon, thus keeping the triangulation process within n-3 diagonals. But 4-sided polygons are an exception since any single diagonal can triangulate both polygonal chains. Yet, for a n-sided polygon only some sets of n-3 diagonals that can triangulate n-2 corners using the Pattern 0. Figure 6-16 presents some examples in regular convex polygons.



a) 5-sided not triangulated b) 5-sided triangulated



c) 6-sided not triangulated d) 6-sided triangulated

Figure 6-16: Sequences of n-3 diagonals in regular 5 and 6-sided polygons
(t_i denotes triangulated corners by an $L_d i$ diagonal)

In Figure 6-16 b) note that diagonal L_d2 can triangulate the corner 4 using Pattern 0 Case 1 and corner 2 using Pattern 0 Case 3. Similarly, in Figure 6-16 d), diagonal L_d3 can be used to triangulate both corner 5 and 2, thus leaving a Pattern 00 to close the polygon. Also note that by reusing previously provided diagonals it is alternatively possible to triangulate all other corners in Figure 6-16 d).

In Figure 6-16 a) and c) none of the provided diagonals may be used to triangulate corners 2, 3 and 4 with Pattern 0 or Pattern 00. Yet, in both cases there are only 3 rigid polygonal chains, that is, there are only three corners left to triangulate. Since the figure is closed and each corner type is known from the provided morphology, there is only one possible solution to the problem that can be found by the law of cosines. We call this a Pattern 000 and it is independent of the relative position of the non-triangulated corners in the polygonal chain.

Figure 6-17 presents a situation where a triangulation process derives a Pattern 000 where all non-triangulated corners are separated. A sequence of diagonals $[L_d1, \dots, L_d7]$ triangulates 7 corners of P_u using Pattern 0, thus generating a Pattern 000 composed by corners 0, 3 and 6. Let corner 0 be i, corner 3 be j and corner 6 be k (Step 1 in Figure 6-17). We can determine $\overrightarrow{ij}, \overrightarrow{jk}, \overrightarrow{ki}$ by adding the vectors from i to $j-1$, from j to $k-1$ and k to $i-1$ respectively. Using $|\overrightarrow{ij}|, |\overrightarrow{jk}|, |\overrightarrow{ki}|$ as sides of the triangle, the angle β at j can be found with the law of cosines and used to define $\overrightarrow{jk_1}$. The internal angle between $\overrightarrow{jk}$ and $\overrightarrow{jk_1}$ can then be used to rotate all the polygon's sides from 3 to 5 to obtain the result in step 2 in Figure 6-17. By repeating the previously described process we may also triangulate k and close the polygon, thereby approximating P.

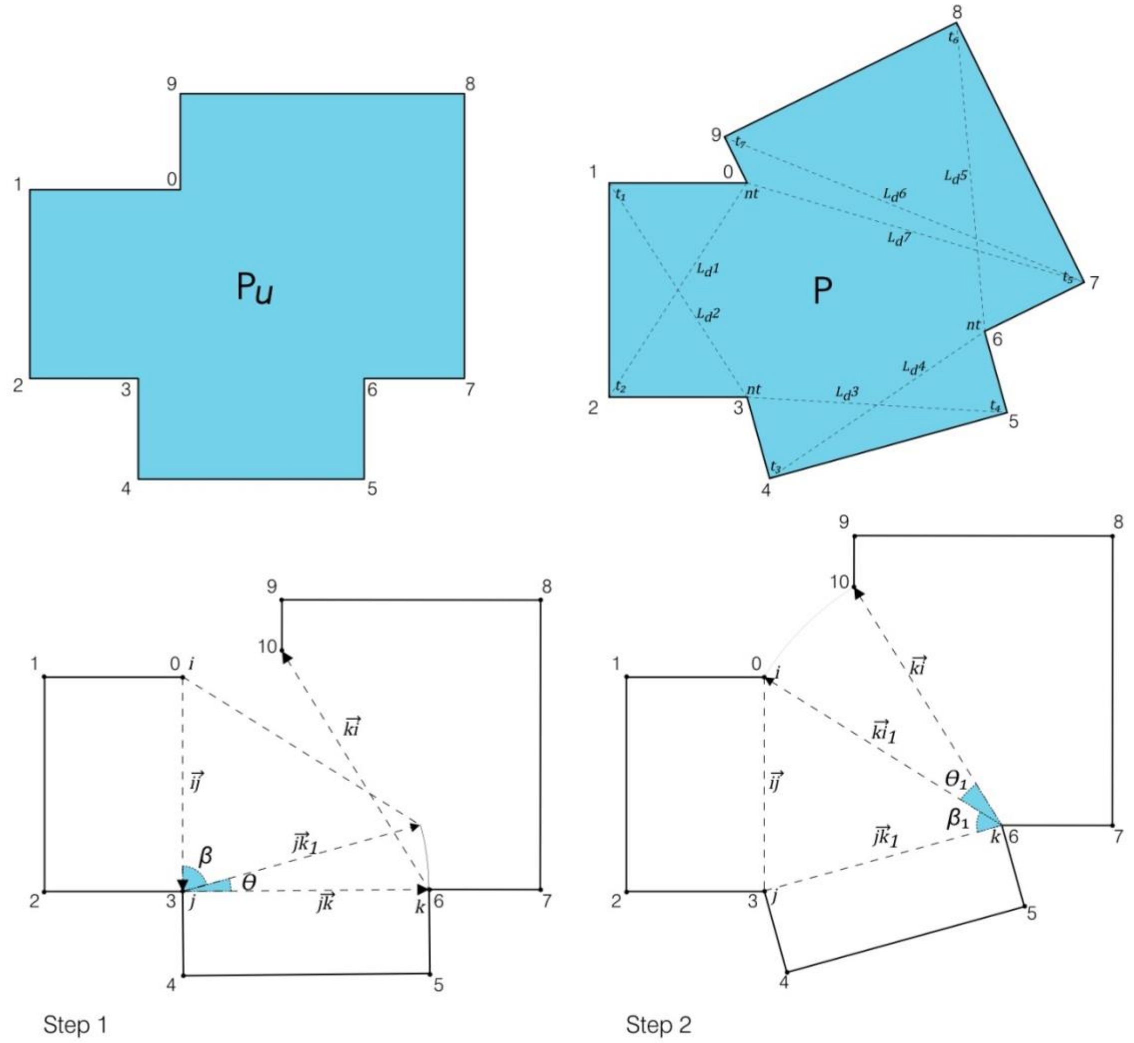


Figure 6-17: Application of the algorithm Pattern000. t_i *denotes triangulated corners by an* $L_d i$ *diagonal and nt is a non-triangulated corner*

The algorithm bellow, Pattern000, implements the described strategy for a general case. Let i, j and k be the indices of the three non-fixed corners found in the polygonal chain defined by P_{vec} with $i < j < k$.

ALGORITHM 4 PATTERN 000

```
Input: $P_u$, $P_{vec}$, $i$, $j$, $k$
Output: $P_{vec}$

SET $\vec{ij}$ = 0, SET $\vec{jk}$ = 0, SET $\vec{ki}$ = 0, SET $n$ to the length of $P_{vec}$
FOR each vector in $P_{vec}$ from $i$ to $j-1$
    Add current vector to $\vec{ij}$
END FOR
FOR each vector in $P_{vec}$ from $j$ to $k-1$
    Add current vector to $\vec{jk}$
END FOR
FOR each vector in $P_{vec}$ from $k$ to $n-1$
    Add current vector to $\vec{ki}$

END FOR
```

```
FOR each vector in $P_{vec}$ from 0 to $i-1$
    Add current vector to $\overrightarrow{ki}$
END FOR
IF $|\overrightarrow{ij}| + |\overrightarrow{jk}| > |\overrightarrow{ki}|$ and $|\overrightarrow{jk}| + |\overrightarrow{ki}| > |\overrightarrow{ij}|$ and $|\overrightarrow{ki}| + |\overrightarrow{ij}| > |\overrightarrow{jk}|$
    COMPUTE $\overrightarrow{jk_1}$= $NextVector$(Origin, $\overrightarrow{ik}$, $|\overrightarrow{ik}|$, $|\overrightarrow{jk}|$, $|\overrightarrow{ki}|$)
    IF $P_u[k]$ is right of $P_u[i]$ to $P_u[j]$
        Reflect $\overrightarrow{jk_1}$ about the plane defined by the vector $\overrightarrow{ij}(x,y)$ and the normal vector
        $\vec{p}(x_2,y_2)$ such that $\vec{p}(x_2,y_2) = R_{ik}(\pi)$
    END IF
    COMPUTE internal angle θ of $\overrightarrow{jk}$ and $\overrightarrow{jk_1}$
    FOR each vector in $P_{vec}$ from $j$ to $k-1$
        Rotate current vector by angle θ
    END FOR
    COMPUTE $\overrightarrow{ki_1}$ = $NextVector$(Origin, $\overrightarrow{jk}$, $|\overrightarrow{jk}|$, $|\overrightarrow{ki}|$, $|\overrightarrow{ij}|$)
    IF $P_u[i]$ is right of $P_u[j]$ to $P_u[k]$
        Reflect $\overrightarrow{ki_1}$ about the plane defined by the vector $\overrightarrow{jk}$ $(x,y)$ and the normal vector
        $\vec{p}(x_2,y_2)$ such that $\vec{p}(x_2,y_2) = R_{jk}(\pi)$
    END IF
    COMPUTE internal angle $\theta_1$ of $\overrightarrow{ki}$ with $\overrightarrow{ki_1}$
    FOR each vector in $P_{vec}$ from $k$ to $n-1$
        Rotate current vector by angle $\theta_1$
    END FOR
    FOR each vector in $P_{vec}$ from 0 to $i-1$
        Rotate current vector by angle $\theta_1$
    END FOR
END IF
```

Pattern 000 expands the sets of diagonals that can triangulate the polygon as seen in Figure 6-16. Yet, this does not imply that any set of diagonals that can triangulate any set of n-3 corners with Pattern 0 might be used by Pattern 000 to close the polygon. In fact, Pattern000 will fail if the $\overrightarrow{ij}$, $\overrightarrow{jk}$ and $\overrightarrow{ki}$ are collinear or measurement imprecision creates an invalid triangle. On the other hand, both Pattern00 and Pattern000 reduce the polygon's closing error caused by user measurement imprecision.

6.2.1.3 Diagonal Sorting

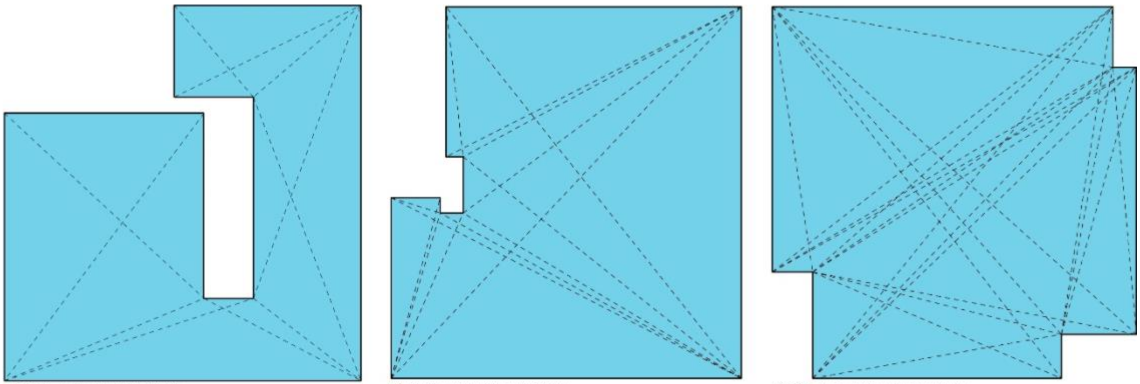
Diagonal sorting or selection is a decision problem. To effectively triangulate a polygon with n sides, only $n-3$ diagonals are needed but not all sets containing $n-3$ valid internal diagonals can triangulate the polygon. Consequently, randomly selecting a set is not a possible strategy.

Also, as we have seen in the previous section, the sketch P_u and the actual room plan P need to be morphologically similar but this does not imply all internal diagonals P_u are internal diagonals of P. Morphologically similar polygons may have different sets of internal diagonals (Figure 6-18 a and b) and the user may not be able to measure some of them on the field. Thus, if we use a sorting strategy that reduces the set of diagonals to be requested, e.g., to one non-self-intersecting set, we may run out of diagonals to be requested.

On the other hand, the number internal diagonals of the polygon do not increase at the same rate as the number of sides. In general, the number of diagonals of a n-sided polygon, with $n \geq 3$ is given by the expression $n(n-3)/2$. In convex polygons all these diagonals are internal but in non-convex polygons only part of them is. Thus, asking the user to take all diagonals can quickly become tedious as the number of room sides increases. Furthermore, requesting less than $n-3$ diagonals introduces a different decision problem on how to determine which ones are best.

6.2.1.3.1 Processing Order

Another important aspect to be considered is that of the diagonal processing order. If a specific algorithm only considers diagonals in the order they are provided, then the number of viable sets of diagonals that can triangulate the polygon in n-3 steps significantly reduces and the number of possible sets increases. If the processing order matters then the number of possible sets is given by the arrangement of n-3 diagonals from all valid diagonals of the polygon, which is several orders of magnitude larger than the number of combinations (Figure 6-18). Also, for morphologically similar polygons, as the number of internal diagonals increases so does the number of possible arrangements and combinations (Figure 6-18 a and b).



a) Path orthogonal polygon
Sides = 10
Diagonals = 11 diagonals
Arrangements $_{11}P_7$= 1663200
Combinations $_{11}C_7$ = 330

b) Path orthogonal polygon
Sides = 10
Diagonals = 14 diagonals
Arrangements $_{14}P_7$= 17297280
Combinations $_{14}C_7$ = 3432

c) General orthogonal polygon
Sides = 10
Diagonals = 22 diagonals
Arrangements $_{22}P_7$= 859541760
Combinations $_{22}C_7$ = 170544

Figure 6-18: Combinations and arrangement of sets of 7 diagonals for different 10-sided orthogonal polygons

Thus, an interactive triangulation algorithm needs to reconsider previously measured diagonals to increase the probability that a given set can effectively triangulate the polygon. If all user provided diagonals are stored, it is a simple procedure to check if in the current state of triangulation any of the previously used diagonals may be reused to further the triangulation. Algorithm 5 provides such mechanism to check if a diagonal can triangulate Pu, given the indices of its end points, i and j such that $i < j$, V_S a list containing the current state of the triangulation, and n the number of corners of the polygon, it returns the index of the non-triangulated corner k and whether it is on the ij chain of the polygon.

ALGORITHM 5 INTERNAL TRIANGLE

```
Input: $V_S$, $i$, $j$, $n$
Output: $k$, $ij$

BEGIN
    SET $ij$ to true
    SET $P1$ to -1
    SET count to the number of non-triangulated corners from i+1 to j-1 in $V_S$
    IF count equals 1
        FOR $m = i + 1$ to $j - 1$
            IF $V_S m = 0$
                RETURN m
            END IF
        END FOR
    END IF
    SET count to the number of non-triangulated corners from j+1 to i-1 in $V_S$
    IF count equals 1
        SET $start$ to $j + 1 \bmod n$
        IF $i = 0$
            SET $end$ to $n - 1$
        ELSE
            SET $end$ to $i - 1$
        END IF
        IF $start \le end$
            FOR $l = start$ to $end$
                IF $V_S l = 0$
                    $ij$ is false
                    RETURN $l$
                END IF
            END FOR
        ELSE
            FOR $m = start$ to $n - 1$
                IF $V_S m = 0$
                    $ij$ is false
                    RETURN $m$
                END IF
            END FOR
            FOR $p = 0$ to $end$
                IF $V_S p = 0$
                    $ij$ is false
                    RETURN $p$
                END IF
            END FOR
        END IF
    END IF
    RETURN $P1$
END
```

Note that the previous algorithm can be used to test if any diagonal can triangulate the polygon, whether it has been provided or not, and given the current state of triangulation.

As we progress in triangulating the polygon, certain diagonals can no longer contribute to further the process. This is a particularly relevant problem if polygonal chain closure described in section 6.2.1.2 is used, since the aim is to triangulate large parts of the polygonal chain, but is applicable in general. Consider Figure 6-19, L_d1 was requested, and its' length is approximately that of the length of the sum of vectors from i to j and all the corners from i to j are orthogonal. If the orthogonality assumption holds, we can set the corners from $i + 1$ to $j - 1$ as triangulated. The diagonal processing list L_k contains $L_k a$ and $L_k b$, two valid internal diagonals of P_u that might be requested next, yet they will not triangulate any of the corners from *j* to *i*. Thus, we might increase the likelihood of triangulating P_u with $n - 3$ diagonals if we remove these diagonals from the list.

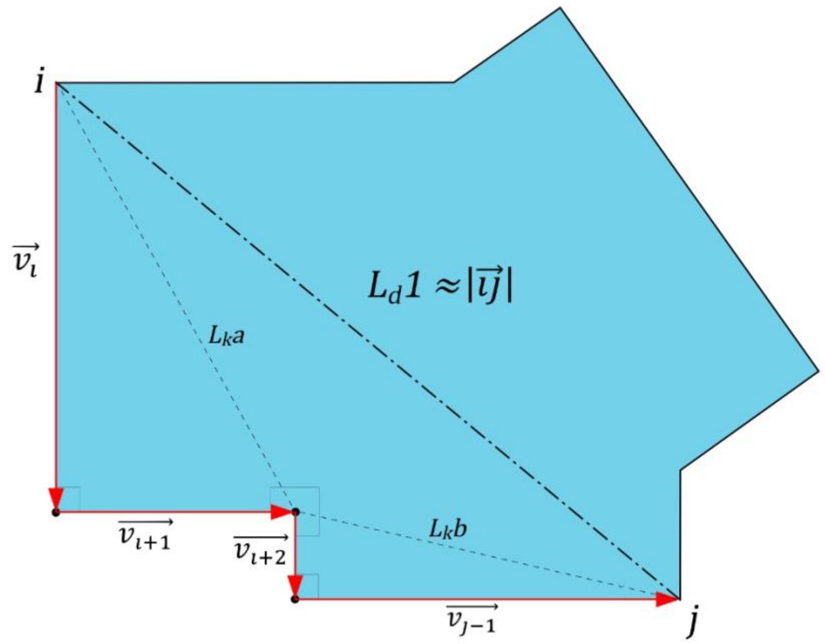


Figure 6-19: Example of two redundant diagonals in a triangulation process

Let L_k be an ordered list containing diagonals to requested, $ijIsTri$ and $jiIsTri$ boolean values that indicate if the current diagonal has triangulated the ij or/and the ji chains of P_u, i and j the indices of the endpoints of the diagonal, such that $i < j$, and D_{ij} a matrix storing the lengths of all the diagonals of P_u that have been provided by the user. Algorithm 6 provides a method to remove all the diagonals of the processing list L_k from *i* to *j* and/or *j* to *i* that have not been requested and will not contribute to the iterative triangulation process.

ALGORITHM 6 REMOVE DIAGONALS

```
Input: $L_k$, $ijIsTri$, $jiIsTri$, $i$, $j$, $D_{ij}$

BEGIN
    SET $matrixSize$ to the length of the $D_{ij}$
    IF $ijIsTri$
        FOR $n = i$ to $j - 1$
            FOR $m = n + 2$ to $j$
                IF the diagonal length is not stored in $D_{ij}[m, n] = 0$
                    SET $k = n * matrixSize - n * \frac{n+1}{2} + m$
```

```
                    REMOVE k from $L_k$
                END IF
            END FOR
    END IF
    IF $jiIsTri$
        FOR $n = j$ to $matrixSize - 1$
            FOR
                IF the diagonal length is not stored in $D_{ij}[m,n] = 0$
                    SET $k = n * matrixSize - n * \frac{n+1}{2} + m$
                    REMOVE k from $L_k$
                END IF
            END FOR
        END FOR
        FOR $n = 0$ to $i$
            FOR $m = n + 2$ to $i$
                IF the diagonal length is not stored in $D_{ij}[m,n] = 0$
                    SET $k = n * matrixSize - n * \frac{n+1}{2} + m$
                    REMOVE k from $L_k$
                END IF
            END FOR
            FOR $m = j$ to $matrixSize - 1$
                IF the diagonal length is not stored in $D_{ij}[m,n] = 0$
                    SET $k = n * matrixSize - n * \frac{n+1}{2} + m$
                    REMOVE k from $L_k$
                END IF
            END FOR
        END FOR
    END IF
END
```

Algorithms 5 and 6 will contribute to increase the likelihood a given set diagonals triangulates P_u. Yet, as discussed in section 6.2.1.2 , a Pattern 101 can be used to triangulate concave corners. Indeed, we may attempt to detect such patterns and change the diagonal processing order to request a diagonal that may triangulate the isolated non-triangulated corner as demonstrated in Figure 6-12.

As before, let V_s be a list that contains the state of the triangulation of each corner of the polygon P_u, with a 0 value for a non-triangulated corner and 1 a triangulated corner, and n the number of corners of the polygon. Algorithm 7 returns the index k of the center of the last Pattern101 in P_u, i.e., the last isolated non-triangulated corner.

ALGORITHM 7 PATTERN101

```
Input: $V_s$, $n$
Output: $k$

BEGIN
    SET $start$ to -1
    IF $n < 4$
        RETURN $start$
    END IF
    FOR $i = 0$ to $n$
        SET $r = (i + 1)$ mod n
```

```
        SET $s = (i + 2) \bmod n$
        IF $V_s[i] = 1$ and $V_s[r] = 0$ and $V_s[s] = 1$
            SET $start = r$
        END IF
    END FOR
    RETURN $start$
END
```

For a given 101 Pattern there may be more than one possible diagonal that can be used to triangulate the corner at index k, thus a specific strategy is needed to select which diagonal to request first.

6.2.1.4 RoomSurvey 4

RoomSurvey 4 (RS4) was our first interactive triangulation algorithm to assemble all the previously presented iterative triangulation algorithms. Previous attempts only contained partial solutions and for brevity are not discussed. RS4 assumed that rooms are mostly orthogonal polygons and users are explicitly capable of controlling whether the polygon angles are orthogonal or not, thereby providing morphologies that are mostly orthogonal polygons as inputs to the algorithm.

If the orthogonality assumption holds, then the problem becomes one of finding the corners which are not orthogonal. In this instance, if the user provided morphology contains some non-orthogonal angles it is safe to assume the user is aware these corners are not orthogonal. It is also safe to assume that the provided non-ortho angle is not accurate, since the user does not have the tools to measure non-ortho angles on site.

In general, for a constant measurement error longer diagonals can reduce the angular error caused by measurement precision. Likewise, diagonals that form 45 degrees angles with the closest side minimize the angular error of the triangulation process. The polygon’s largest diagonals are more likely to meet the last criteria and provide a quick route to triangulate large sections of the polygonal chain using Equation 1.

Consequently, the selected pre-sorting heuristic (Figure 6-20) was to measure the longest diagonals first. As rooms tend to be mostly orthogonal, the longest diagonal would be a quick way of reducing the search of non-orthogonal angles by eliminating parts of the polygonal chain. Yet, if the polygon contains some non-orthogonal corners, then these should be requested first.

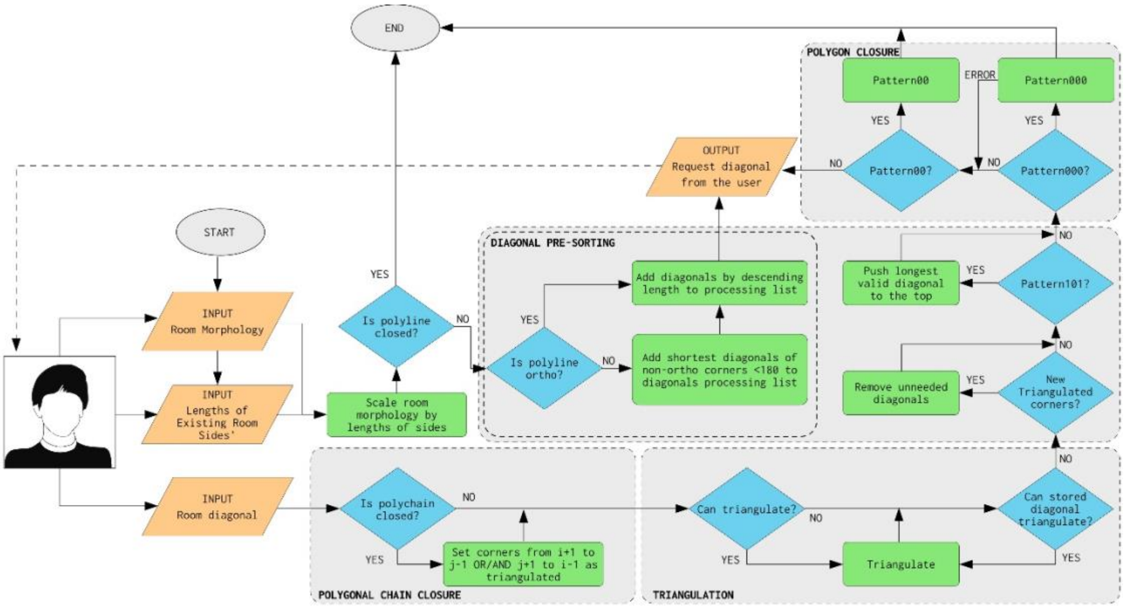


Figure 6-20: RoomSurvey 4 flowchart

The algorithmic workflow starts with the input of some morphology and an ordered list of side lengths of the actual room. If the user provided polygon is closed within tolerance, the provided polygon's angles are considered correct and the process terminates returning the scaled morphology back to the user, else diagonals are requested. A list of possible diagonals to request is built with the previously described pre-sorting heuristic favoring longer diagonals for ortho-polygons. If the provided morphology already displays non-orthogonal angles, the shortest diagonals of these corners are requested first in the following order: (1) shortest diagonal of each convex non-orthogonal corner, ordered by angular dimension in ascending order excluding orthogonal angles; (2) the longest diagonals.

For each diagonal provided by the user, RS 4 first checks if it closes the polygonal chain, if not, it attempts triangulation with Pattern 0. Then it checks if some already provided diagonal can triangulate any corner with Pattern 0. If the current diagonal was successful in triangulating some polygonal chain, the RemoveDiagonals algorithm is run. Then Algorithm 7 searches for 101 patterns, if one is found the position of the longest diagonal that triangulates it is changed on the processing list to be requested next. Lastly, at every cycle RS 4 checks if Pattern000 or Pattern00 can be used to close the polygon.

6.2.1.5 RoomSurvey 5

In RS 4, the polygonal chain closure test is applied before triangulation since the aim was to prioritize orthogonality over triangulation. This implies that polygonal chain closure with the selected tolerance of 7,5mm is applied in any instance independently of the nature of the angles in the corners or the state of the triangulation. It is not clear what is the practical impact of this design choice in the reconstruction precision of the polygon.

By reversing the order in which Triangulation and Polygonal Chain Closure are used, RoomSurvey 5 implements the assumption that triangulation is always more precise than checking polygonal closure with a given tolerance (Figure 6-21).

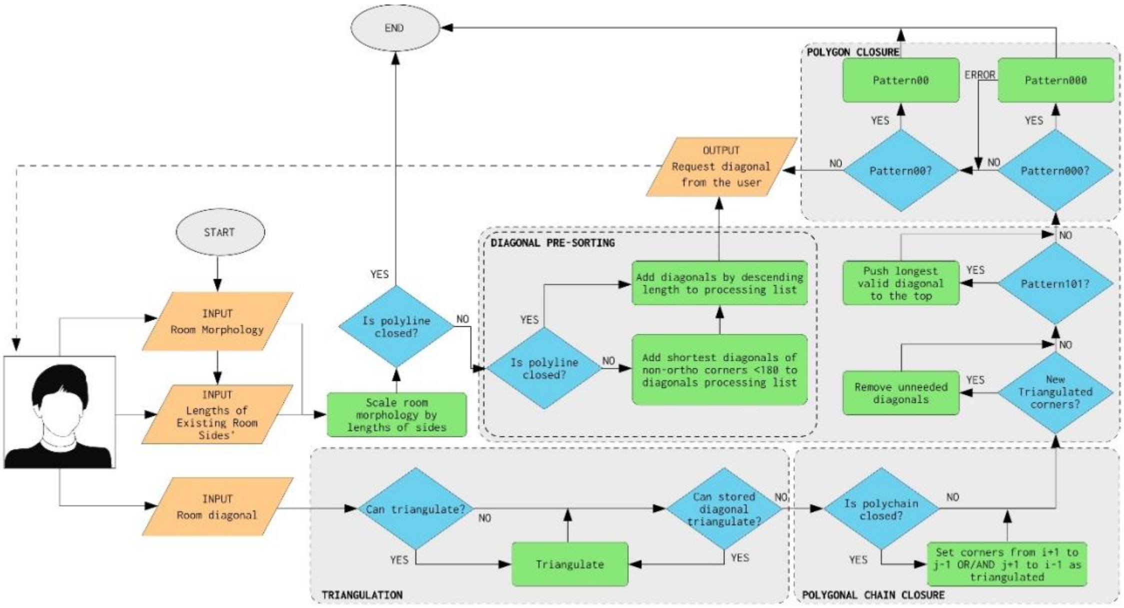


Figure 6-21: RoomSurvey 5 flowchart, shifting the processing order of Pattern0 and polygon chain closure.

6.2.1.6 RoomSurvey Strict

If the method used to draw the morphology is constrained to orthogonal directions, the user is only able to provide orthogonal morphologies. The alternative possibility is that this drawing method offers no type of orthogonal constraint and thus the user will only be able to provide non-orthogonal polygons. Another possible situation is that even if the drawing method provides both mechanisms the user is not able to recognize that there are non-orthogonal corners in the room and thereby only provides orthogonal polygons.

In all the above cases, the assumption that users can control the orthogonality of the polygon' corners does not hold. Yet, whatever the drawing process used the implications are different if the input morphology is completely orthogonal or if it is totally non-orthogonal.

In the second case, RoomSurvey 4 or 5 will shift to asking shorter diagonals. While there might be precision issues with polygonal chain closure, the shorter diagonal method will likely keep the requested diagonals close to n-3.

In the first case, both algorithms will request longer diagonals. In that instance, as the number of non-orthogonal corners and room sides in the actual room increases, there is a growing likelihood that the longer diagonals will not close any polygonal chain. Thus, leading to an increasing number of requested diagonals to the user.

In both cases the use of polygonal chain closure in RoomSurvey 4 or 5 is questionable, but the pre-sorting heuristic is particularly problematic in the first case. Figure 6-22 presents an alternative algorithm RoomSurvey Strict (RSS).

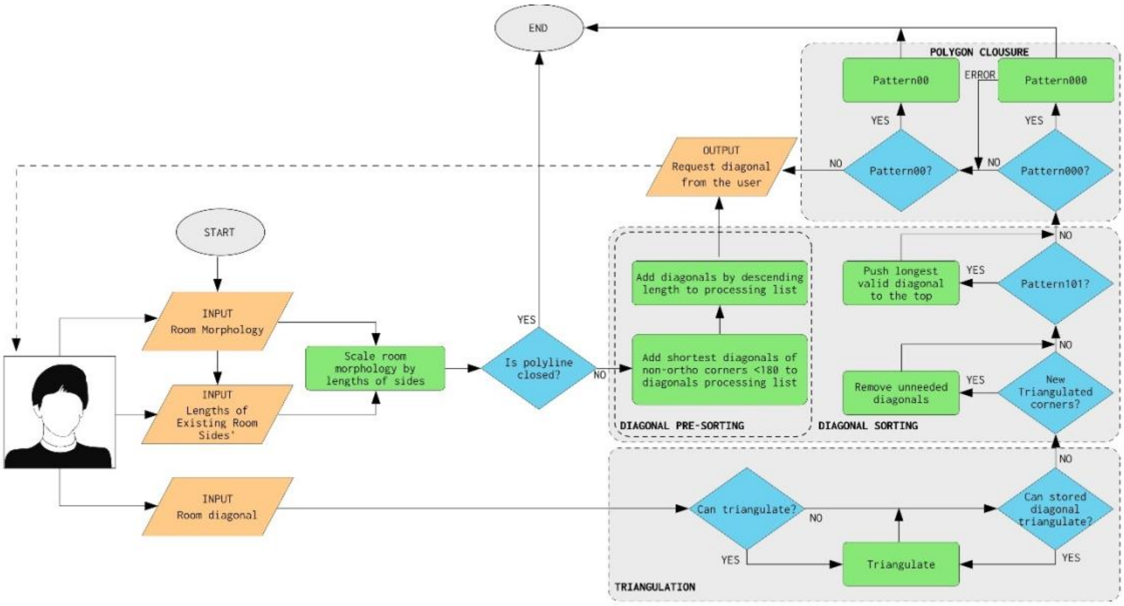


Figure 6-22: RoomSurvey Strict flowchart

RSS will request the diagonals off all convex corners first, independently of whether they are orthogonal or not. Also, it does not make any assumptions regarding the orthogonality, hence it only closes the polygon when all corners have been triangulated.

6.2.1.7 RoomSurveyor

All the previously discussed algorithms were initially implemented in Grasshopper components for testing purposes. Ultimately, they were bundled in a plugin – RoomSurveyor - with other components that were developed in the context of this thesis (F. J. S. Brandão, 2022a). The plugin was published on the Food4Rhino platform and integrated with ShapeDiver with the aim of providing tools for meta-designer to develop interactive workflows of space survey in web configurators.

Several explanatory blog posts[31] and instruction videos were produced to introduce and explain possible survey workflows, including examples of configurators implemented in

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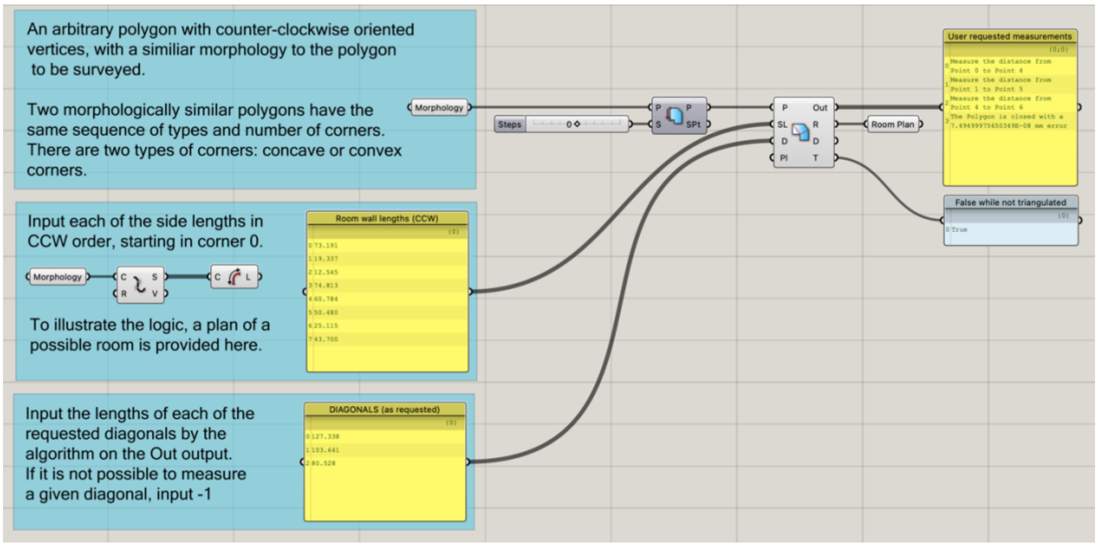
[31] https://filipebrandao.pt/2021/03/08/roomsurvey-workflow/
https://filipebrandao.pt/2021/03/09/roomsurveyor-shapediver/
https://filipebrandao.pt/2021/04/12/surveying-a-wall/
https://www.youtube.com/watch?v=hh2excGYI0A

ShapeDiver detailing the requirements to assemble low-key survey workflows in web browsers. Figure 6-23 presents the minimum required setup for using one of the RoomSurvey triangulation algorithms in Grasshopper.


An arbitrary polygon with counter-clockwise oriented vertices, with a similiar morphology to the polygon to be surveyed.

Two morphologically similar polygons have the same sequence of types and number of corners. There are two types of corners: concave or convex corners.

Input each of the side lengths in CCW order, starting in corner 0.

To illustrate the logic, a plan of a possible room is provided here.

Input the lengths of each of the requested diagonals by the algorithm on the Out output. If it is not possible to measure a given diagonal, input -1

Room wall lengths (CCW)
(0)
0 73.191
1 19.337
2 12.545
3 74.813
4 60.784
5 50.480
6 25.115
7 43.700

DIAGONALS (as requested)
(0)
0 127.338
1 103.641
2 80.528

User requested measurements
(0;0)
0 Measure the distance from Point 0 to Point 4
1 Measure the distance from Point 1 to Point 5
2 Measure the distance from Point 4 to Point 6
3 The Polygon is closed with a 7.49499975650349E-08 mm error

False while not triangulated
(0)
0 True

Figure 6-23: The minimum required definition for implementing RoomSurvey interactive triangulation algorithms

During the development of this work, ShapeDiver did not provide the possibility for drawing on the canvas of the web browser. This limitation forced the instance-designer to draw the room morphology by other means and provide it as a file input. To demonstrate the intended use of the system a simple JavaScript web app was developed and is available online[32]. The source code is available on Github[33] (F. J. S. Brandão, 2022b).

Figure 6-24 details the minimum workflow for surveying an interior space. Instance-designer exposed inputs/outputs are written in bold.

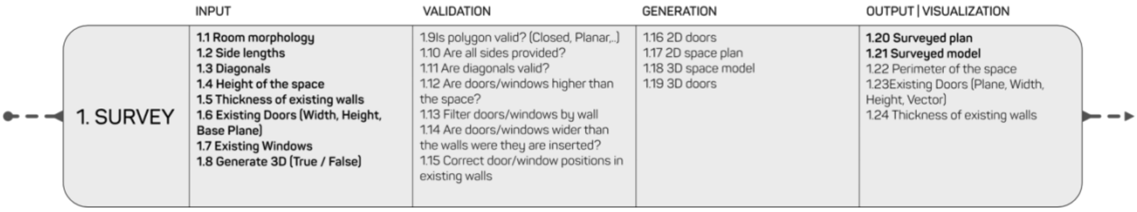

	INPUT	VALIDATION	GENERATION	OUTPUT | VISUALIZATION
1. SURVEY	**1.1 Room morphology** **1.2 Side lengths** **1.3 Diagonals** **1.4 Height of the space** **1.5 Thickness of existing walls** **1.6 Existing Doors (Width, Height, Base Plane)** **1.7 Existing Windows** **1.8 Generate 3D (True / False)**	1.9Is polygon valid? (Closed, Planar,..) 1.10 Are all sides provided? 1.11 Are diagonals valid? 1.12 Are doors/windows higher than the space? 1.13 Filter doors/windows by wall 1.14 Are doors/windows wider than the walls were they are inserted? 1.15 Correct door/window positions in existing walls	1.16 2D doors 1.17 2D space plan 1.18 3D space model 1.19 3D doors	**1.20 Surveyed plan** **1.21 Surveyed model** 1.22 Perimeter of the space 1.23Existing Doors (Plane, Width, Height, Vector) 1.24 Thickness of existing walls

Figure 6-24: Survey Design workflow (in bold) instance-designer exposed input and outputs.

The meta-designer must decide how the instance designer provides the inputs to the workflow and implement algorithmic workflows to address the identified steps in Validation and Generation. Beyond providing the needed visualization outputs (identified in bold) for the instance designer, decisions must also be made on how to pass relevant output data for the succeeding design and production stages. At least, the perimeter of the space (1.22 in Figure 6-24), the positions and properties of door and/or window components, and the thickness of

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[32] https://filipebrandao.pt/2021/03/10/rs-and-sd-with-json/
[33] https://github.com/filipejsbrandao/roomsurveyorJS

the external walls are needed. The above workflow was implemented in Grasshopper and is available in Annex M.

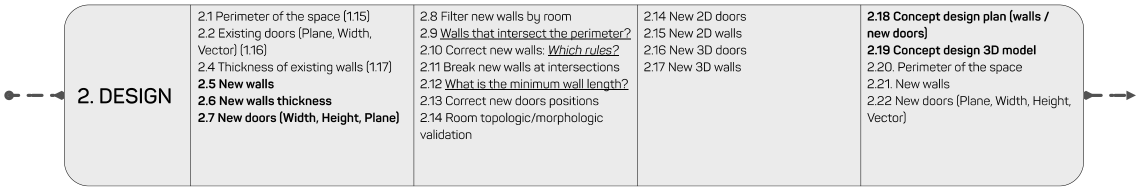
6.2.2 An Interactive Design-to-Production Workflow

One of the problems that needs to be tackled in a mass-customization system is the process by which the instance designer expresses its design intent. The two most common approaches in the literature are: eliciting responses from the user that can provide meaningful insight into his/her needs or provide a set of controls the user may use to manipulate the variables of the computational model. The first approach makes it difficult for the user to directly control the design while the second imposes topological constrains on what the design system may express. A third possibility is to allow the instance-designer to express its intent by drawing or manipulating geometric primitives. Since the user is frequently not aware of design rules or regulations that make a design valid, constraint validation methods will be necessary.

We adopt the third approach. An interactive survey workflow was developed in the previous section and next we detail a general design-to-production workflow to complement it. Concept design validation methods have been already discussed in the literature; hence we focus on concept design validation aspects that pertain to construction systems.

6.2.2.1 Concept Design Workflow

In this step the instance-designer must be able to design the subdivision of a space by interactively placing building sub-systems, e.g., walls or doors, to partition and connect the resulting spaces (Figure 6-25). Each building subsystem will have specific geometric properties that can be conveyed by the selection of options or ranges, e.g., door width. Yet, some of the needed geometric properties can only be provided by other geometric primitives, e.g., a wall requires at the very least a guiding line. Those properties can be provided interactively by the instance-designer.



	INPUT	VALIDATION	GENERATION	OUTPUT | VISUALIZATION
2. DESIGN	2.1 Perimeter of the space (1.15) 2.2 Existing doors (Plane, Width, Vector) (1.16) 2.4 Thickness of existing walls (1.17) **2.5 New walls** **2.6 New walls thickness** **2.7 New doors (Width, Height, Plane)**	2.8 Filter new walls by room 2.9 Walls that intersect the perimeter? 2.10 Correct new walls: *Which rules?* 2.11 Break new walls at intersections 2.12 What is the minimum wall length? 2.13 Correct new doors positions 2.14 Room topologic/morphologic validation	2.14 New 2D doors 2.15 New 2D walls 2.16 New 3D doors 2.17 New 3D walls	**2.18 Concept design plan (walls / new doors)** **2.19 Concept design 3D model** 2.20. Perimeter of the space 2.21. New walls 2.22 New doors (Plane, Width, Height, Vector)

Figure 6-25: Concept design workflow (in bold) inputs and outputs exposed to the instance-designer

6.2.2.1.1 Validate

As previously discussed, this choice requires the introduction of an input validation step that checks that each input is reasonable and that the combination of all inputs results in a reasonable and legal design. This process must be done interactively, i.e., for every instance-design action. In the case of partition walls this will involve at least ensuring (1) the walls are inside the room, (2) that the new walls divide the space in legal and reasonable way, (3) verify the new walls are valid concept designs of the specific partition system, (4) ensure that building subsystems such as doors or windows are nested in walls.

The main purpose in step 1 is to ensure that the walls start/end at the space boundaries or inside the space. This can be verified with point in polygon algorithms for the 2D case. In case, the walls end outside the space boundaries, the two main options are to ignore the wall or to change the designed wall to comply with the restriction, which may be achieved in 2D cases by either intersecting the wall with the room boundary or to project the external endpoint to the nearest wall. In more complex 3d spaces, this requires intersection of the wall plane with the enclosing volume.

In the second validation step, as previously discussed, we focus on buildability issues such as, sufficient space for assembly/disassembly of the walls or external interface restrictions, e.g., the new partition wall cannot terminate against an existing door or window, or the incidence angles must be within a specific range. These rules may be enforced with morphological or geometric algorithms, e.g., by verifying distances to corners of different types (convex / concave) of the room polygon, windows, and doors, or minimum distances between new walls.

The aim of the third step is twofold: to ensure all wall panes have the minimum allowed dimensions for system components and to allow the verification of internal door inclusion in the new partition walls. The first aspect derives from the fact that system components will have limits for minimum size, the second from the fact that doors can only occur at specific positions in the wall, e.g., a door cannot overlap 2-wall intersection, and the rules for each specific partition system will add further restrictions.

The last step simply “snaps” the doors to position according to restrictions of door placement of each specific system.

The last three validation steps are conflicting with system independence, in the sense that they verify aspects that are critical to the detail design system. Yet, from an interactivity point of view it is important that the limitations are explicit to the instance-designer. Other alternatives are to allow concept design stage changes at later stages or to force back and forth design iterations, which are a natural part of a design process. Yet, since all the aspects can also be important for different reasons at the concept design stage, we opt to include them here. System independence may still be achieved by exposing their ranges as inputs.

6.2.2.1.2 Generate

The concept design generation step is concerned with the actual transformation of the user inputs into a valid wall design concept to output. There are at least two types of relevant outputs: geometry representing the design concept and useful data for subsequent design stages and production stages. It is important to note that the outputs for visualization are needed in the interactive instance-designer design process. Thus, these should be kept to the minimum relevant information for the aim at hand. Clearly, partition walls can be represented as 3d volumes with door/window voids removed, and new door/window elements as simplified 3d objects.

Regarding the outputs for subsequent systems, the relevant information is the minimum necessary to generate the wall geometry and identify its external and internal interfaces, which is at least the space volume, the new walls, and doors. There are several alternatives to represent the needed information depending on the complexity of the design and the space envelope. Assuming a non-orthogonal room plan with level floor and ceiling, and a design containing planar and vertical partition walls, the minimum required information for subsequent design steps consists of the space perimeter (e.g., a closed polyline), the baseline and height of each wall section (e.g. a center line and number) and the door base plane, width and height. If for instance the space envelope already has sloped ceilings, or these have different heights, a volume (e.g. a BRep) for each wall might be more convenient since this information is already processed in the concept-design step.

6.2.2.2 Detail Design Workflow

The interactive inputs for the instance-designer at this stage will at least include options of the partition wall system, such as materials and finishes, but the meta-designer may also choose to expose other options regarding the type of subdivision or even different construction systems to choose from (Figure 6-26). Other possibilities include using the space functional subdivision as a constraint on the materials and finishes those partitions may have.

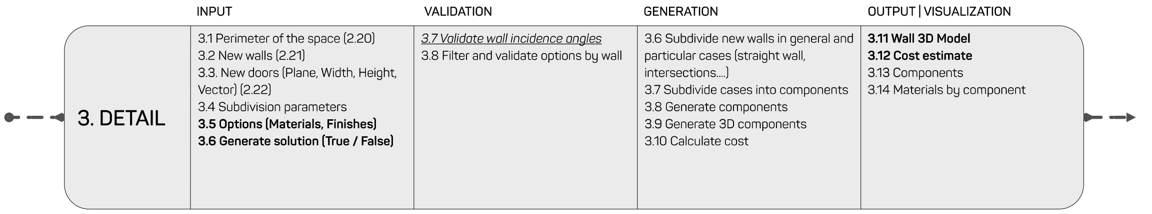


Figure 6-26: Detail Design workflow, (in bold) inputs and outputs exposed to the instance-designer

6.2.2.2.1 Validate

The requirements for validation will vary according to the breath of instance-designer interaction. If no open inputs are provided there is limited need for validation steps since most aspects will have already been dealt with in the concept design step. Otherwise, there might be the need to validate aspects that pertain to the specific constraints of the selected partition wall construction system. Aspects such as the angle of incidence of a new partition wall with existing walls or between new walls need to fall within specific ranges. Similarly, walls must have minimum dimensions

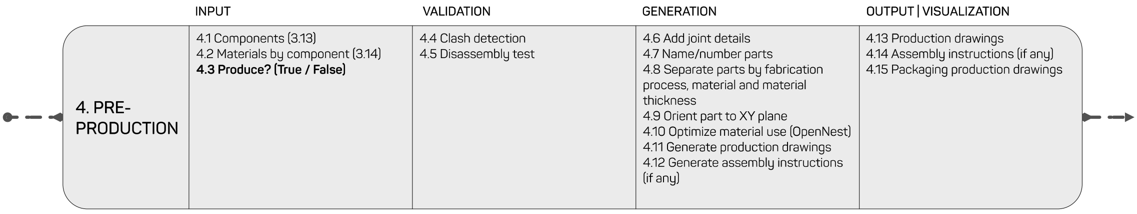
6.2.2.2.2 Subdivisions

The generation step of the Detail Design System main goal is to subdivide the new partition walls into components. To this end meta-designers must subdivide the partition walls into the wall sections identified in the generic grammar in section 5.3.1 , e.g., external interfaces, planar wall sections, doors/windows, wall intersections. A simple approach is to first identify the external interfaces, then the internal interface particular cases, such as intersections and end-walls and then the general cases of planar walls. The next step is to divide the each of the cases into components according to the functional and dimensional rules of the system.

This information can then be used to generate simplified 2D and 3D geometry of the relevant partition system for visualization in the configurator. It is crucial to optimize the generation of 3d geometry to include only the relevant information for instance-designer evaluation. The subdivision into relevant components which results of the generation step is a data output to the succeeding Production System. Another important output at this stage is the cost estimate based on the generated design.

6.2.2.3 Pre-Production Workflow

The pre-production stage deals with more computation intensive tasks that do not require user interaction. Critical user input at this stage may be to approve the design and submit it to production (Figure 6-27). In our experiments we have also found it less cumbersome to concentrate the generation of internal component parts and joining details, which are not relevant for visualization, at this stage. This approach can also bring advantages when generating geometry for nesting and fabrication. While we assume this workflow will be run in a resource constrained context, it is entirely possible that the more intensive parts be computed elsewhere.



	INPUT	VALIDATION	GENERATION	OUTPUT | VISUALIZATION
4. PRE-PRODUCTION	4.1 Components (3.13) 4.2 Materials by component (3.14) **4.3 Produce? (True / False)**	4.4 Clash detection 4.5 Disassembly test	4.6 Add joint details 4.7 Name/number parts 4.8 Separate parts by fabrication process, material and material thickness 4.9 Orient part to XY plane 4.10 Optimize material use (OpenNest) 4.11 Generate production drawings 4.12 Generate assembly instructions (if any)	4.13 Production drawings 4.14 Assembly instructions (if any) 4.15 Packaging production drawings

Figure 6-27: Pre-Production workflow, (in bold) inputs and outputs exposed to the instance-designer

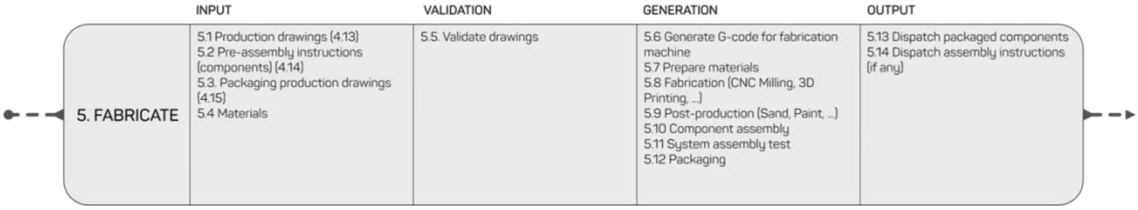
Useful validation steps at this stage can be customized testing methods to verify design compliance, such as using clash detection or disassembly simulations. Unlike in the previous systems, these validation steps are mostly intended for quality control.

As previously stated, at the pre-production generation step all the internal parts can be added with the appropriate joint details. For the partition systems we have designed, all these generation steps can be achieved with 2d geometry. Critical aspects to prepare production are naming / numbering parts, and separate them by material, material thickness, and fabrication process. Each numbered part in the filtered set can then be grouped and oriented to the XY plane for nesting. Nesting is by far the most computationally intensive task. In our experiments with OpenNest we have found that to achieve reasonable computation times the efficiency of the nesting needs to be reduced. Hence, there is a strong motivation to search for alternatives such as custom nesting procedures or a secondary offline optimization process. Also, since the system is modular it has a high degree of repetition of parts, and thus can benefit from alternative packing methods that also consider other criteria such as the effort of sorting the parts at the production stage or the efficiency of the component pre-assembly process (Chen & Sass, 2017).

The production drawings are the result of the above processes, but meta-designers will need to coordinate with fabricators on standards. Other types of generators may be leveraged at this stage to produce the packaging or the assembly instructions if needed for the specific system, likewise those aspects must be validated with the intended assemblers of the partition system.

6.2.2.4 Production Workflow

At the production workflow there will be material inputs to consider beyond the outputs of the previous step (Figure 6-28). The key actors at this stage are the producers, responsible for the execution of the needed steps to deliver the outputs for assembly. Although meta-designers can still contribute to streamlining workflows, there are important difficulties that have already been discussed in the literature in automating the generation of G-code for production (Scheurer et al., 2014). Custom CAD-CAM interfaces can be created for a specific parametric model if the machine is known à-priori but since these are laborious to test, there must be a strong motivation by both actors to collaborate towards this goal.



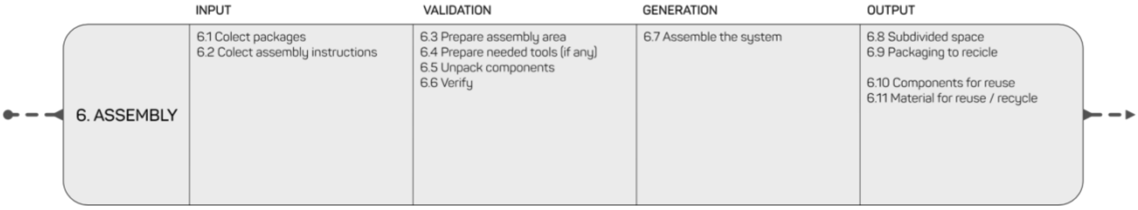
	INPUT	VALIDATION	GENERATION	OUTPUT
5. FABRICATE	5.1 Production drawings (4.13) 5.2 Pre-assembly instructions (components) (4.14) 5.3. Packaging production drawings (4.15) 5.4 Materials	5.5. Validate drawings	5.6 Generate G-code for fabrication machine 5.7 Prepare materials 5.8 Fabrication (CNC Milling, 3D Printing, ...) 5.9 Post-production (Sand, Paint, ...) 5.10 Component assembly 5.11 System assembly test 5.12 Packaging	5.13 Dispatch packaged components 5.14 Dispatch assembly instructions (if any)

Figure 6-28: Production workflow

There are existing CAD-CAM workflows and plugins for Grasshopper, such as BarkBeetle or Woodpecker, that can be used to generate G-Code for 3-axis milling that can provide very good starting points to automate this process. Yet currently the supported machines are limited.

6.2.2.5 Assembly workflow

The envisioned assembly workflow (Figure 6-29) starts with the delivery of the flat packages to the site containing the pre-assembled components. The validation steps should not be more elaborate than assembling furniture.



	INPUT	VALIDATION	GENERATION	OUTPUT
6. ASSEMBLY	6.1 Colect packages 6.2 Colect assembly instructions	6.3 Prepare assembly area 6.4 Prepare needed tools (if any) 6.5 Unpack components 6.6 Verify	6.7 Assemble the system	6.8 Subdivided space 6.9 Packaging to recicle 6.10 Components for reuse 6.11 Material for reuse / recycle

Figure 6-29: Assembly workflow

Ideally the simplicity of the system should reduce the need for elaborate step-by-step instructions, yet this should be nonetheless provided in simple graphic descriptions. Since the users of the system become acquainted with the assembly process, they are more likely to be able to repair and disassemble the system for reuse if or when the need arises, creating new outputs for further survey-to-production cycles.

CHAPTER 7 Open reWall: Survey-to-production workflow testing

In the previous chapters we have presented prototypes of mass customizable and disassemble-able partition walls construction systems and a generic grammar that can be used as a template for further design iteration. We have also argued that for open building renovation to be possible the MCC conceptual model needs to be revised to include the survey stage. We proposed a low-key survey workflow that can be integrated with current computational design approaches to build a survey-to-production system.

In Testing Survey section we present the tests that have been conducted to validate the survey workflow with instance-designers and computational performance tests. In Testing System we detail and report the result of an international workshop that was conducted with the aim of validating the use of the workflow and the development of partition wall construction systems with the generic grammar by meta-designers.

7.1 Testing Survey

This section reports the tests that have been conducted to determine the validity of the proposed low-key survey workflow by instance-designers and the accuracy of the attainable results. In the first experiment we verified that there were many app design usability issues that interfered with the execution of the survey workflow. We concluded that clearer step-by-step instructions were needed coupled with more accurate geometric methods of surveying.

We revised the testing methodology accordingly to validate the above hypothesis and expand the usability test cases to include limit conditions. The purpose is to determine the usability of the workflow and the accuracy of the algorithm in practice. The next section reports this usability testing experiment with non-expert users and expert users and finishes with a comparison of the user generated plans with Terrestrial Laser Scans of the selected spaces.

7.1.1 Usability Testing

The usability testing was conducted in two rooms in two to-be renovated buildings with different groups of non-expert and expert users. Then, the plans each user created were compared with the Terrestrial Laser Scan (TLS) of each respective room (Brandao et al., 2019).

Room 1 is in a 4-building complex in the historic center of Braga, in the North of Portugal. Room 2 is situated in a building within the UNESCO protected historic center of Porto. Both buildings are representative 19th townhouses from the North of Portugal, with stone party walls and stone street and backyard façades, tilled pitched roofs, wood floors, located in a narrow plot.

In the Porto building all rooms have at least one internal angle that is +/- 2 degrees than 90 or 270 degrees albeit by a small margin, but only 3 out of 11 have more than 4 sides. The 4-building complex in Braga was already included in the study reported in section 5.2.2 , and details of the building room properties are available in Table 5-4.

Both rooms were selected for the challenges they place to survey, namely: higher geometric complexity, clutter, and challenging wall finishes. In Room 1 all internal angles are non-orthogonal by over +/- 5 degrees and is representative of the typical situations found in the first group of buildings while Room 2 should be a limit case that might impose some challenges to our algorithmic and workflow approach.

The TLS point-clouds were obtained in separate campaigns but performed with the same FARO FOCUS S120 station, a Leica GPS 1200 GNSS station and a Leica 1203 TCRP total station. The Braga 4-building complex campaign included the 4 buildings interiors, backyards, street, and backyard façades and took 3 days to complete. It resulted in a point-cloud with 258 scans grouped in 23 clusters. The Porto building survey covered the building interiors and neighbouring streets. This survey was completed in 1 day and produced a point-cloud composed of 113 scans grouped in 6 clusters.

A typical exterior scan took 8 minutes to complete while an interior one was completed in 2 minutes. Room 1 and 2 surveys were accomplished with 3 and 8 scans respectively. The point clouds of each campaign were aligned in SCENE, from which horizontal sections of each of the selected rooms, at the heights of 50cm and 150cm from the floor, were exported in DXF format. Each of these sections were then used to draw 2D plans for comparison with the user designed plans using the methods described in the section 5.2.2.3 .

7.1.1.1 Experiment Protocol

Room 1 was surveyed by a group of 5 non-expert users and 5 expert users, and 3 non-experts and 6 expert users surveyed Room 2. We sought to have an equally distributed gender sets of users and experts, containing members representative of several age groups. The participants age ranged from 16 to 68 years old, and there were 5 females and 6 males in the expert group, and 5 males and 4 females in the non-expert group.

The experience protocol included the following tasks for each participant: (1) Draw the room plan on paper, (2) Watch a presentation with best measuring practices, (3) Draw the room plan with an application then measure the room sides, (4) Watch a different presentation with best measuring practices (Figure 7-1), (5) Measure the room and input the side dimensions to our algorithm, (6) Measure the request diagonals.

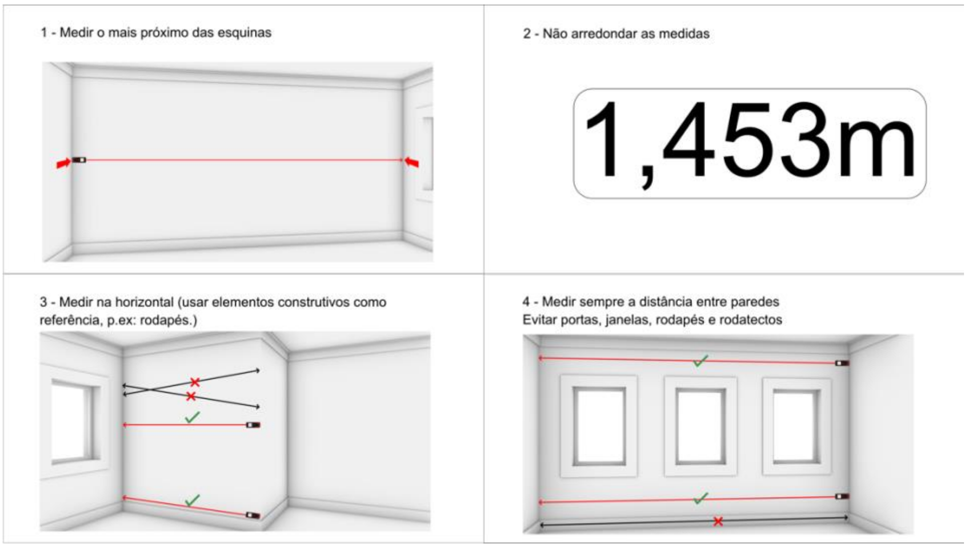


Figure 7-1: Summary of the presentation with measuring instructions

The selected application for this test was the one that most users favored in the first experiments, and which displayed the best results overall. Since the purpose was to test the quality of the results, we chose to assist the users if doubts emerged in the process. RS4 algorithm was used to collect user measurements and request diagonals.

Figure 7-2: Usability Testing on Room 2 on the left and on Room 1 on the right. Adapted from Brandão et al (2019)

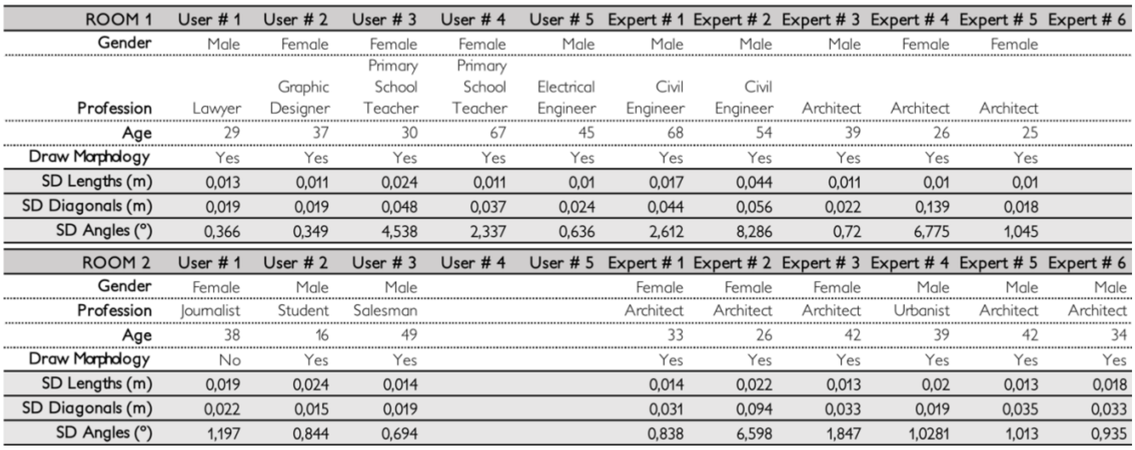
A Leica D2 laser distance meter was provided to the participants, which has sum, subtraction and max/min measurement functions. A brief explanation of the functions was provided to all users and experts before the start of the experiment.

7.1.1.2 Performance Evaluation

All expert and non-expert users could sketch the room plan morphology on paper by hand, except for User#1 in Room 2 (Table 7-1). Regarding step 3, as reported in the first experiment, most had difficulties understanding the workflows of the mobile application. The experts were able to overcome their difficulties while the non-expert users requested assistance. At this step, User#1 in Room2 also required more assistance than the other participants with application camera workflow. This user was able to complete the sketch of the room, only after having been provided with explanation that the workflow involved pointing the camera at the room corners and clicking an on-screen button to add the corner. After having completed the plan with the workflow successfully, User#1 could say how many sides the room had but was still not able to draw the room plan on paper.

The measurement step for both workflows, the app and RS4 survey workflow, was completed without any input from the researcher. The TLS plan at 1,50m was selected for comparison purposes in both rooms since most users' measurements were taken around this height, with a few exceptions to circumvent obstacles. Table 7-1 shows the standard deviation of measurements taken in the second-round relative to a TLS plan, which were provided by the participants onsite to RS4 algorithm to calculate the needed diagonals. Surprisingly, non-expert users' measurements were better than those by experts.

Table 7-1: Summary of users and experts' profiles and respective standard deviation (SD) of measurements. (Brandão et al,2019)

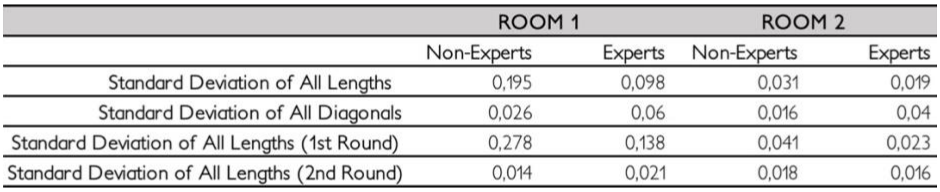


ROOM 1	User # 1	User # 2	User # 3	User # 4	User # 5	Expert # 1	Expert # 2	Expert # 3	Expert # 4	Expert # 5	Expert # 6
Gender	Male	Female	Female	Female	Male	Male	Male	Male	Female	Female	
Profession	Lawyer	Graphic Designer	Primary School Teacher	Primary School Teacher	Electrical Engineer	Civil Engineer	Civil Engineer	Architect	Architect	Architect	
Age	29	37	30	67	45	68	54	39	26	25	
Draw Morphology	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
SD Lengths (m)	0,013	0,011	0,024	0,011	0,01	0,017	0,044	0,011	0,01	0,01	
SD Diagonals (m)	0,019	0,019	0,048	0,037	0,024	0,044	0,056	0,022	0,139	0,018	
SD Angles (°)	0,366	0,349	4,538	2,337	0,636	2,612	8,286	0,72	6,775	1,045	

ROOM 2	User # 1	User # 2	User # 3	User # 4	User # 5	Expert # 1	Expert # 2	Expert # 3	Expert # 4	Expert # 5	Expert # 6
Gender	Female	Male	Male			Female	Female	Female	Male	Male	Male
Profession	Journalist	Student	Salesman			Architect	Architect	Architect	Urbanist	Architect	Architect
Age	38	16	49			33	26	42	39	42	34
Draw Morphology	No	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes
SD Lengths (m)	0,019	0,024	0,014			0,014	0,022	0,013	0,02	0,013	0,018
SD Diagonals (m)	0,022	0,015	0,019			0,031	0,094	0,033	0,019	0,035	0,033
SD Angles (°)	1,197	0,844	0,694			0,838	6,598	1,847	1,0281	1,013	0,935

Comparing both measurement rounds (Table 7-2) reveals non-expert users improved significantly from the first to the second round of room measurements. Experts also improved, albeit by a smaller margin. The exception to this trend was Expert # 2 in Room 1 which showed shaking anxiety causing tremors on the right arm during the second measurement round. Diagonal measurements were significantly better for non-expert users in both rooms. We explain non-expert higher performance with the willingness to follow the recommended best practices, which are reinforced by the repetition of the task and presentation. While measuring diagonals, few experts cared to use of the laser distance meter max/min measurement feature, yet most non-expert users used it. We also noted a tendency in experts to round the measurements despite recommendation not to.

Table 7-2: Global and per round measurement accuracy in wall lengths and diagonals in both rooms. (Brandão et al, 2019)



	ROOM 1		ROOM 2	
	Non-Experts	Experts	Non-Experts	Experts
Standard Deviation of All Lengths	0,195	0,098	0,031	0,019
Standard Deviation of All Diagonals	0,026	0,06	0,016	0,04
Standard Deviation of All Lengths (1st Round)	0,278	0,138	0,041	0,023
Standard Deviation of All Lengths (2nd Round)	0,014	0,021	0,018	0,016

The plans generated by RS4 algorithm from the measurement of users and experts for Room 1 are shown in Figure 7-3 and the results for Room 2 are presented in Figure 7-4. The standard deviation (SD) for each user was computed in comparison to the dimensions of the sides of that horizontal section of the TLS point cloud. At the end of each row, we display the standard deviation for each metric across all users of each group.

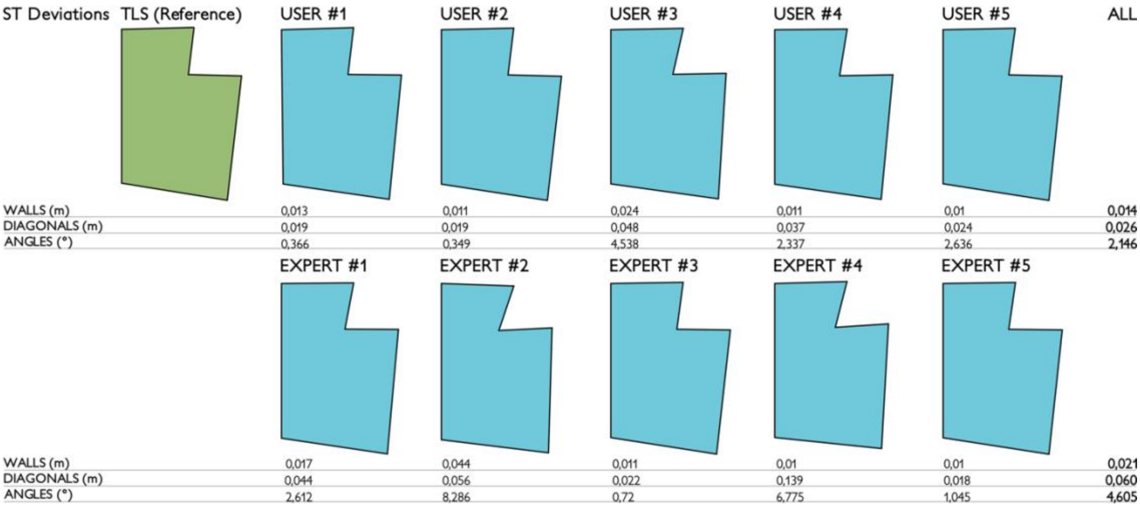


Figure 7-3: Comparison of non-expert user and expert user plans with a simplified horizontal section of the reference terrestrial laser scan point cloud of Room 1. Adapted from Brandão et al (2019)

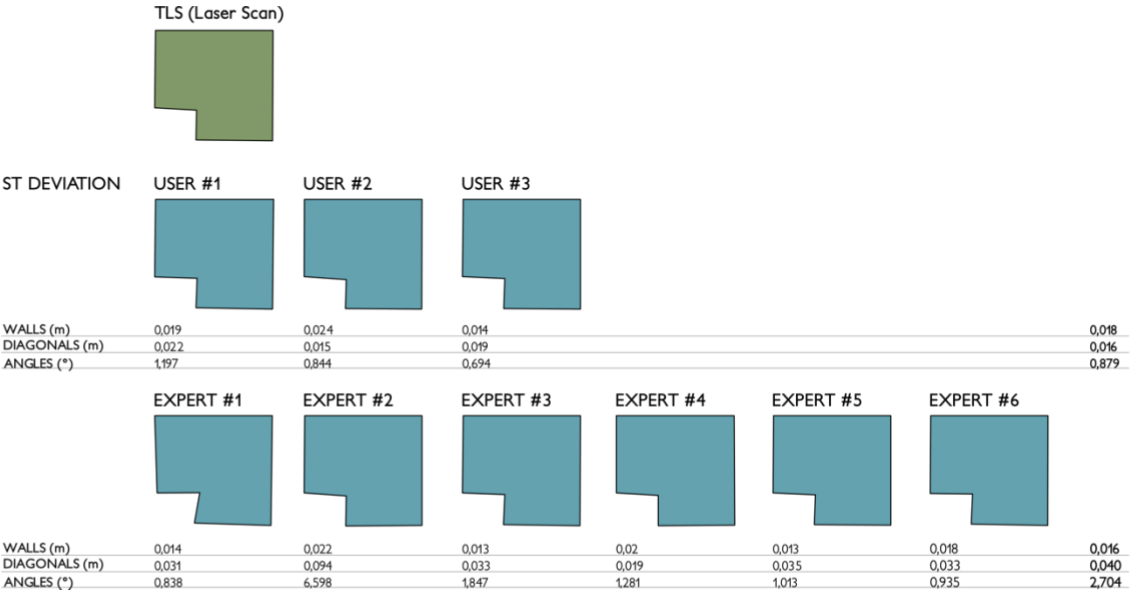


Figure 7-4: Comparison of non-expert and expert user plans with a simplified horizontal section of the reference TLS point cloud of Room 2

For comparison purposes, Figure 7-5 shows the TLS plan of both rooms at 1,5m height and the plans are generated by several versions of the algorithm with the diagonals and side lengths measured in TLS plan, with and without rounding to millimeters. The synthetical results show that the error introduced by the algorithm in the experiment is at worse one order of magnitude smaller than total error users could achieve with the RS4 algorithm.

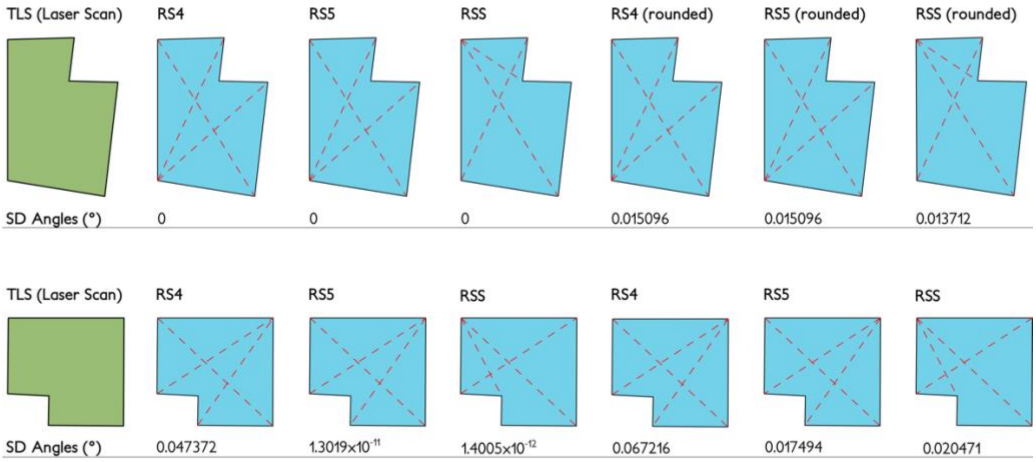


Figure 7-5: Algorithms precision benchmark with dimensions measured in TLS survey

To determine the feasibility of using the user produced plans to design the subdivision of the space and the production of partitions walls with digital fabrication, the space subdivision experiment detailed in Chapter 5 is repeated with each of the plans in Room 1. The space is subdivided into three rooms, a bedroom, an ensuite bathroom and a corridor to connect the interior door to the exterior door and serving both spaces. The following subdivision rules where used: (1) divide the space with a wall parallel to the east party wall offset by 1.42m; and (2) divide the larger space with a wall parallel to the south partition wall offset by 1,8m (Figure 5-19). The first rule places the wall between the interior window and door on one side and next to the exterior door on the other. The latter rule creates a bathroom for a bathtub, with 1,80x0,8m standard dimensions, a toilet, a wash basin, and a bidet. Onsite, the parallelism of the last wall should ideally be maintained because of the bathtub while the corridor wall might rotate. Table 7-3 presents the fitting error of the walls to the TLS plan. Most of the walls would fit onsite within the tolerance +/-3cm of ORW v4 system.

Table 7-3: Fitting of the walls generated over the user and expert plans to the TLS plan. (Brandão et al 2019)

ROOM 1	User # 1	User # 2	User # 3	User # 4	User # 5	Expert # 1	Expert # 2	Expert # 3	Expert # 4	Expert # 5
Wall 1 Length Diff (m)	0,026	0,032	0,037	0,002	0,036	0,032	-0,012	0,018	-0,009	0,023
Wall 2 Length Diff (m)	-0,015	-0,013	-0,015	-0,011	-0,015	-0,015	-0,012	-0,003	-0,015	0

7.1.1.3 Discussion

The user testing experiment demonstrated that most non-expert users could identify the morphology of the space and draw it on paper which validates our low-key survey system approach. The quality of the plans produced by our survey workflow is dependent on user measurement precision yet providing measuring instructions seems sufficient to allow non-experts to achieve on average equal or better results than expert users with our algorithm.

Usability testing confirmed this is a valid approach in practice and that all users could produce a plan which is significantly similar to the existing room, with sufficient geometrical accuracy for the design stage in non-orthogonal rooms. Yet, the space subdivision experiment has shown the limits of this survey workflow for digital fabrication, which depending on the partition wall system tolerance, it might need an extra survey stage for fabrication.

Also, Room2 results indicate that when small angular differences to orthogonality are present the impact of measurement imprecision can make our approach less effective than existing applications methods in terms of overall angular standard deviation. This might be a consequence of our deterministic approach for finding the internal angles of each corner using triangulations. Yet, the benefit is that given a set of measurements, angle turns, and user provided diagonals, our algorithm will always produce the same polygon.

The presented algorithm can be easily integrated in more traditional contexts by architects or other building professionals as a low-key solution to assist the building survey stage for building renovation. Reducing the need for repeated visits to the site for measurement checking, allowing the plan design stage to take place onsite.

This algorithm demonstrates a possible way of generating as built plans parametrically to integrate in mass-customization workflows for building renovation with simple inputs from users. It is not as precise as TLS systems but can be cost effective alternative to increase accuracy in as-built surveys.

7.1.2 Experimental Tests

This section presents experimental work to determine the accuracy, correctness, and typical behaviour of the proposed algorithms for interactive survey. In the previous section it was claimed that accuracy of the results is bound by user error. This experiment sought to validate the claim and determine what other features of the algorithm introduce further error. Also, it aimed to expand the scope of cases tested in number of sides and complexity of the boundary beyond what is feasible with the intended use of the algorithm. This allowed us to have a better understanding of the limitations of the interactive algorithm and the proposed survey workflow, both in terms of their usability and accuracy.

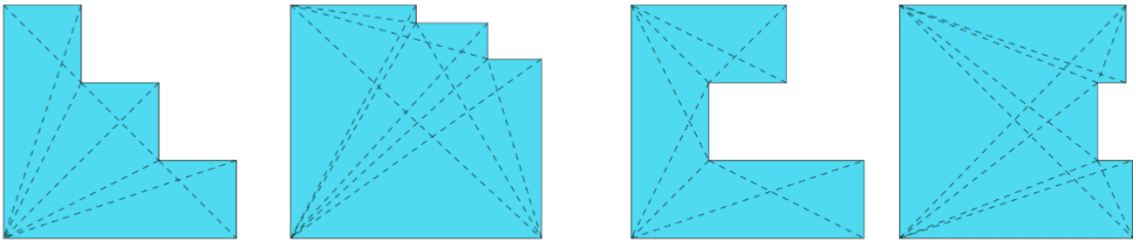
The proposed interactive algorithms in Chapter 6 take as input a morphologically similar polygon to the plan of the space to survey. The input polygon may be orthogonal (ogon) or non-orthogonal simple polygon (n-gon), which is dependent both on the user and the tools that are provided in the drawing interface. The output is a triangulated polygon that approximates the shape of the existing space, the goal polygon. Hence a critical aspect is to determine the algorithmic performance in the geometric transformation of the input polygon into the goal polygon, i.e., how close the output is to the goal polygon. Since this is an interactive process that requires the user to provide diagonals, another critical aspect is the number of requested diagonals to achieve the outcome.

If the input polygon contains non-orthogonal corners, all versions of the algorithm default to requesting the shortest diagonal of each non-orthogonal convex corner of the user provided polygon. Thus, all versions of the algorithm will likely show similar performance. Similarly, input-goal pairs of ogons are trivial and don't even require the algorithm to be used. Consequently, to evaluate performance we will focus on input-goal pairs of n-ogons and n-gons respectively. This will also be representative of the performance of the algorithm in orthogonal polygonal chains of non-orthogonal polygon inputs.

7.1.2.1 Experiment Protocol

To perform the above tests a sufficiently large set of input and goal polygons with very specific properties is required. Crucially, input and goal polygons must be morphologically similar. It is also useful to have a sufficiently diverse set of inputs with different number of sides, corner type combinations and number of internal diagonals. Orthogonal polygons, or ogons for short, are a class of polygons whose edges meet at right angles, and, except for quadrilaterals, will necessarily contain concave corners. O'Rourke (1983) has proven that the expression $n = 2r + 4$, where r is the number of concave corners, holds for all n-vertex orthogonal polygons. Thus, input-goal pairs must be polygons with even number of sides.

HouseExpo (Li et al., 2019) or Cubicasa5k (Kalervo et al., 2019) are examples of floorplan databases of existing buildings. Yet, both datasets are designed for pixel-based workflows in their specific fields of application, robot navigation and drawing plan image recognition and classification, respectively. As such they are unfit to test our workflow. Using random polygon generators is a common approach that ensures all branches of the algorithm are tested and overcomes the issue of lack of data with practical relevance (Dailey & Whitfield, 2008; Eder et al., 2020). Tomás and Bajuelos (2004a, 2004b) have proposed quadratic-time random n-ogon generation algorithms, INFLATE-CUT and INFLATE-PASTE, which provide control over n. These algorithms are designed to generate ogons in general position, a class of ogons known as grid ogons with vertices at integer coordinates. This implies that the generated polygons will not necessarily contain all possible variations in the number of internal diagonals for a given morphology (Figure 7-6). We foresee that increasing the number of internal diagonals in the input morphology might have an impact in the algorithmic performance of the presented algorithms. Thus, it is important to have a dataset with varying numbers of diagonals (Figure 7-6).



grid 6-ogon
8 internal diagonals

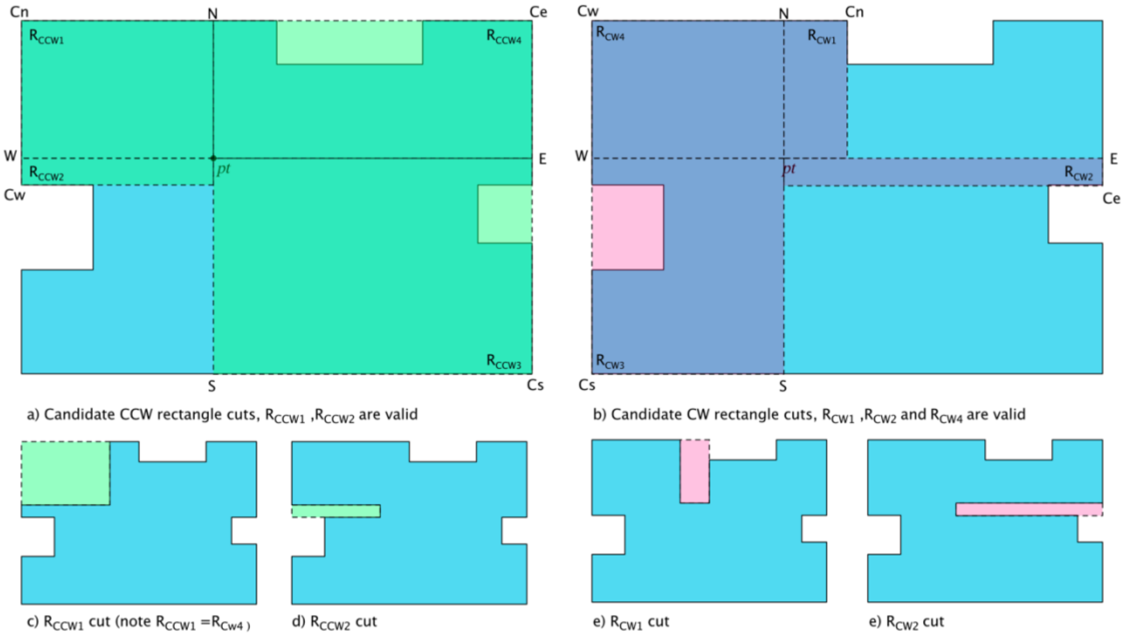
6-ogon
10 internal diagonals

grid 6-ogon
8 internal diagonals

6-ogon
10 internal diagonals

Figure 7-6: Grid 6-ogons and 6-ogons internal diagonals for similar morphologies

To address this issue, we implement the algorithmic approach of cutting and pasting quadrilaterals described by Tomás and Bajuelos for floating point coordinates with some constraints to reduce the likelihood of small edges. CutPaste removes or adds a rectangle to O if a randomly generated point pt is inside or outside the ogon, respectively. The process to determine the rectangle is as described by Tomás and Bajuelos. First, the closest projection of pt onto O is determined for each orthogonal direction N, W, S, E (Figure 7-7). Contrary to Tomás and Bajuelos, we construct all the possible rectangles in CCW and in CW directions, 8 in total, with pt and C as diagonally opposite corners (Figure 7-7 a) and b)). We exclude coincident rectangles, those that contain any vertex of O, or whose border overlaps more than 2 vertices of O. To prevent small features, we also exclude rectangles with both side lengths smaller than t.



a) Candidate CCW rectangle cuts, R_{CCW1} ,R_{CCW2} are valid

b) Candidate CW rectangle cuts, R_{CW1} ,R_{CW2} and R_{CW4} are valid

c) R_{CCW1} cut (note R_{CCW1} =R_{CW4})

d) R_{CCW2} cut

e) R_{CW1} cut

e) R_{CW2} cut

Figure 7-7: a) Candidate rectangles in CCW for cutting b) Candidate rectangles in CW c) d) e) f) alternate cuts.

Finally, we select one candidate rectangle at random to subtract or add to the ogon (Figure 7-7). If the option to maximize area of the ogon is selected, we choose the transformation with smallest area.

ALGORITHM 9 RANDOMOGON

```
Input: $O$, t, A, n, s
Output: O

BEGIN
    SET $r$ to $n - 2 - 2$
    SET $maxX$ to the height of $O$
    SET $maxY$ to the width of $O$
    FOR $i = 0$ to $r - 1$
        SET done to $false$
        DO
            DO
                SELECT x at random such that $x \in \mathbb{R}\{0, maxX\}$
                SELECT y at random such that $y \in \mathbb{R}\{0, maxX\}$
                SET pt to (x,y)
            WHILE square distance to $O$ closest point is not smaller than $t^2$
        WHILE CUTPASTE(pt, O, maxX, maxY, A, s, t) fails for pt
    END FOR
    RETURN O
END
```

The above procedure can generate the required ogons, the input morphologies, for our tests which can be stored in a database, yet it is also necessary to generate morphologically similar goal pairs for each of the inputs with m non-orthogonal corners, such that $2 \leq m \leq n$. We achieve this by randomly shifting $m - 1$ vertices of an input n-ogon along its edges.

DeOgonize transforms c random corners of an n-ogon O by moving each vertex O_{curr} along the direction of the previous edge $\overline{O_{curr}O_{prev}}$ and returns P with m non-orthogonal corners, with $m = (c+1)\ mod\ n$. For each corner O_{curr}, the vector $\overrightarrow{mv}$ is chosen at random between unit $\overrightarrow{O_{curr}O_{prev}}$ or unit $\overrightarrow{O_{prev}O_{curr}}$ and with magnitude between $0 < mag < |\overline{O_{curr}O_{prev}}| / 2 * ratio$. Choosing, the former vector introduces the likelihood of generating self-intersecting polygons (Figure 7-8). To prevent this, each candidate transformation is checked against intersection with O. If there is an intersection, a third of the minimum perpendicular distance to the intersection point or to the corner of O that lies within the triangle [pt, Ocurr, Onext], if any, is chosen as the magnitude of the transformation.

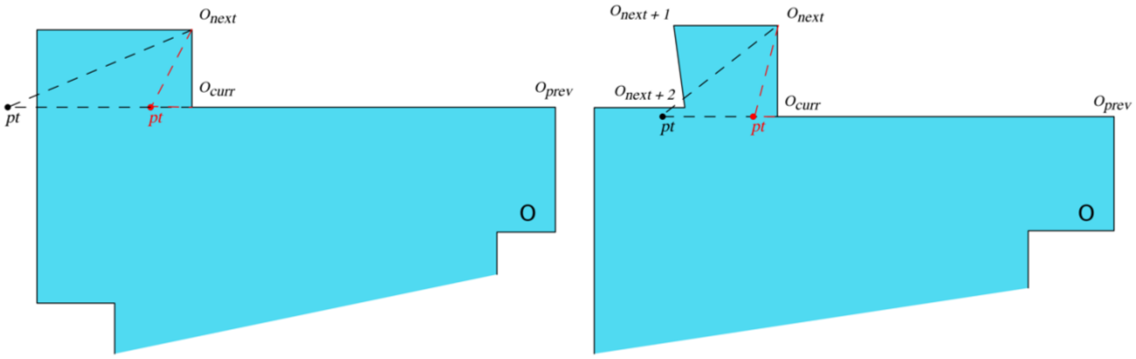


Figure 7-8: Self-Intersection cases in DeOgonize

ALGORITHM 11 DEOGONIZE

```
Input: $O, m, r$
Output: $P$

BEGIN
    SET $n$ to the number of corners in O
    SET $c$ to $(m - 1)\ mod\ n$
    SET $L$ to contain $c$ random indices of $O$ corners
    FOR $i = 0$ to $c - 1$
        SET $curr$ to $L_i$
        SET $next$ to $(curr + 1)\ mod\ n$
        SET $prev$ to $(curr - 1)\ mod\ n$
        SET $\overrightarrow{mv}$ to unit $\overrightarrow{O_{curr}O_{prev}}$ or unit $\overrightarrow{O_{prev}O_{curr}}$ at random
        SELECT $0 < mag <= eprev / 2 * r$ at random
        SET pt to $O_{curr} + mv * mag$
        IF the line $\overline{O_{next}pt}$ or $\overline{O_{curr}pt}$ intersects $O$
            SET $ccx\_dist$ to the perpendicular distance from $\overline{O_{curr}O_{next}}$ to the closest intersection
            IF any corner of $O$ is inside the triangle defined by $[Pt, O_{next}, O_{curr}]$
                SET $dist$ to the perpendicular distance from $\overline{O_{curr}O_{next}}$ to the closest point inside O
                IF $ccx\_dist < dist$
                    SET $dist$ to $ccx\_dist$
                END IF
                SET pt to $O_{curr} + mv * dist / 3$
            END IF
        END IF
```

```
            INSERT pt at $O_{curr}$
            REMOVE point at $O_{curr+1}$
        END FOR
        RETURN $O$ as $P$
    END
```

There is still the likelihood that the combined set of transformations changes the morphology of the polygon flipping one or more corners from convex to concave or vice-versa. The likelihood is reduced as ratio decreases, yet we simply remove these polygons by comparing them with the original ogon morphology, i.e. ensuring the sequence of turns is equal. It is important to note that the above algorithm does not ensure that the output polygon has m non-orthogonal corners.

With previously described algorithms we assemble two workflows, the first to generate n-ogons, with $n \in (6, 8, 10, 12, 14, 16)$, and a second to transform those n-ogons into n-gons with m non-orthogonal sides (Figure 7-9). For each generated polygon we determine and store the number of sides, internal diagonal count, the turns at each corner and a morphological type for each ogon. We remove ogons with sides shorter than 1 cm and store the ogons in a CSV file for each n. For each set of ogons of size n we generate the corresponding number of non-orthogonal polygons with m transformations

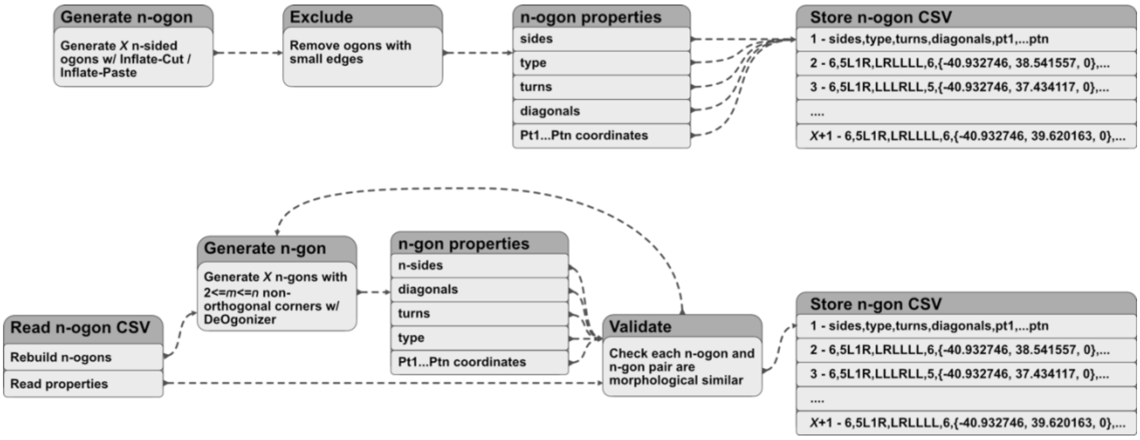


Figure 7-9: Random n-ogon/n-gon pairs generation methodology

The ogon dataset contains 2650 ogons and 39100 n-gons. We then tested each algorithm presented in Chapter, RoomSurvey4 (RS4), RoomSurvey5 (RS5) and RoomSurveyStrict (RSS), in their versions 0.7.1 (F. J. S. Brandão, 2022a), against the dataset with the methodology in Figure 7-10, collecting the result of the transformation, the number of diagonals that were requested, those that were provided, and all the errors in the process.

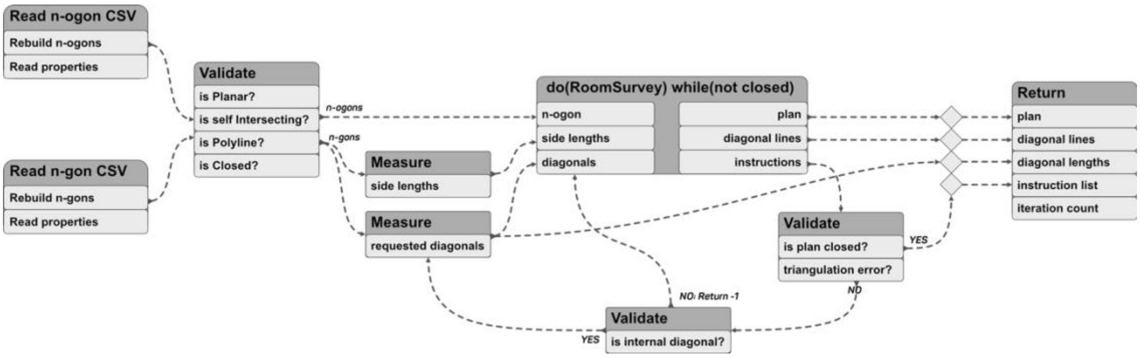


Figure 7-10: RoomSurvey workflow testing methodology

Beyond the triangulation closing error reported by the algorithm, we also compute the similarity between the goal polygon and the algorithm result using angular deviation as in the tests on the previous section. We measure the delta between the each expected internal angle and the algorithm result and compute the standard deviation of internal angles for each pair. Yet, large angular error may not necessarily imply a significant difference in the shapes. Large angular error may be concentrated on small polygon edges.

Since the triangulation process can rotate the polygon, the metrics must be robust to rotation and translation, yet we can ensure that there is a match in both polygons starting point. Hence, we collect other measures such as the turning function (Arkin et al., 1991; Cakmakov & Celakoska, 2004) and area deviation to facilitate the analysis.

7.1.2.2 Survey Workflow Performance

Figure 7-11 shows the percentage of success in the triangulation process by algorithm version. RS4 performed worst of all the versions showing an exponential increase in the rate of triangulation failure as the number of polygon sides increases. RS5 shows a similar albeit marginally improved profile, which is attributable to prioritizing Triangulation over the Polygon Closure shortcut. RSS, which eliminates the latter shortcut, only had 19 triangulation errors in 32000 16-gons. The fact that RSS still shows some instances of triangulation errors suggests that the Polygon Closure shortcut is not the cause of all the triangulation errors, thus there is still room for improvement in the precision of the triangulation process.

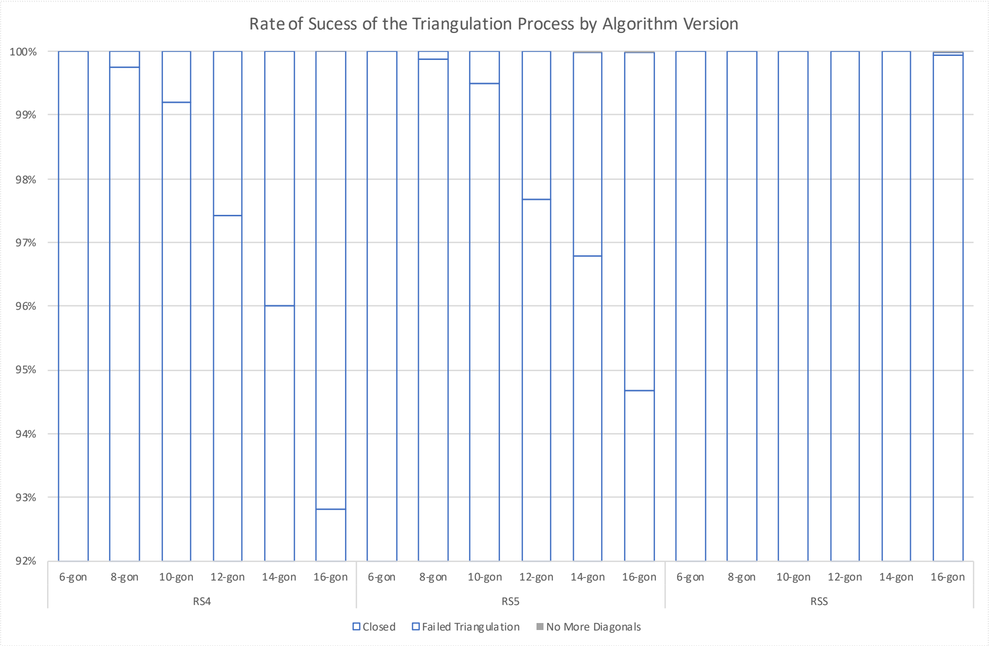


Figure 7-11: Rate of Success of the Triangulation Process by Algorithm version

On 16-gons there were some cases, 2, 6 and 4 cases for RS4, RS5 and RSS respectively, in which the algorithms failed to terminate the process due to lack of internal diagonals to request. The failure is caused by a transformation of the morphology that reduces the common set of internal diagonals between both polygons such that there is no set of diagonals that can fully triangulate the polygon. Thin ogons (Tomás, 2013) are more likely to show the issue as these naturally contain less diagonals.

All algorithms triangulate 6-sided polygons with less than 3 diagonals. Figure 7-12 shows the performance of each algorithm per dataset of 8-gon and 10-gon as the number of non-orthogonal corners increases. RS4 and RS5 frequently complete the process with less than n-3 diagonals for small numbers of non-orthogonal corners, with RS5 showing marginally better performance. Yet, in both algorithms the number of provided diagonals seems to be correlated with the mean number of non-orthogonal corners per dataset. While for all 8-gons at worse 8 diagonals are requested, for some 10-gons more than n diagonals must be provided.

RSS performance is independent of the number of non-orthogonal corners for 8 and 10-gon datasets. On 8-gons, RSS requires n-2 diagonals in 1,65% cases, while for 10-gons 3,8% of the cases require more than n-3 yet less than n diagonals.

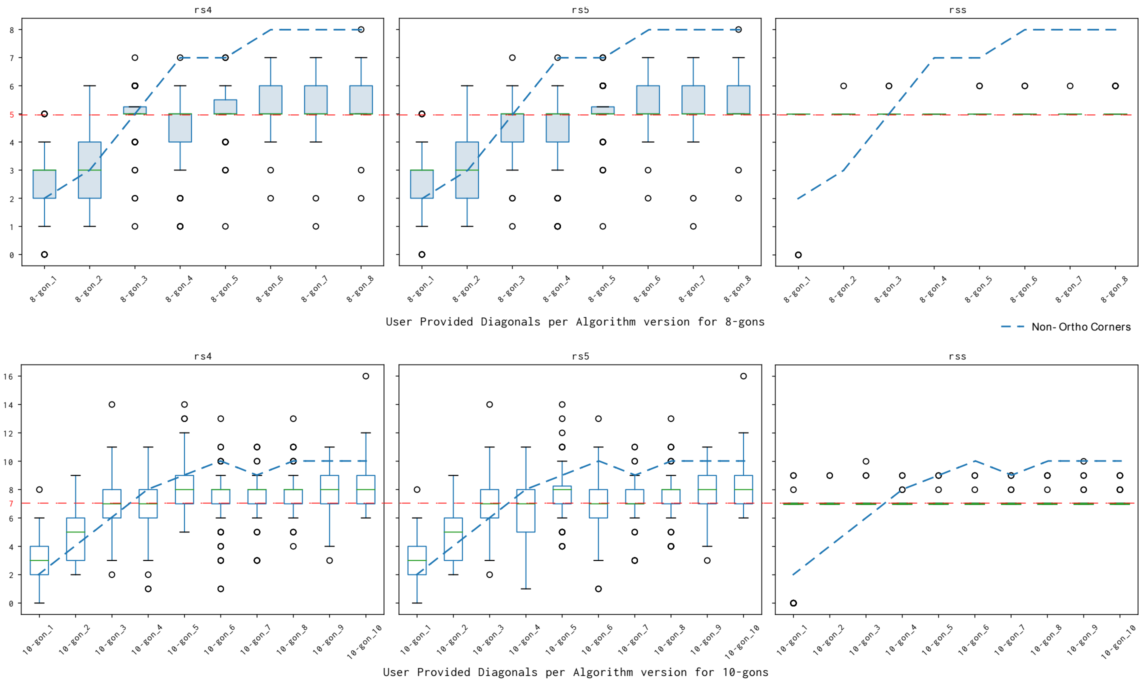


Figure 7-12: Number of user-provided diagonals for 8-gon and 10-gon datasets. Dashed blue – Mean non-orthogonal corners per dataset

Figure 7-13 shows the performance of the algorithms on larger polygons, 12-gons, 14-gons and 16-gons. The insights from the smaller polygon datasets are reinforced. RS4 and RS5 have similar performance, showing a correlation between the number of requested diagonals and the number of polygon non-orthogonal corners. Both perform best on polygons with up to 3 non-ortho corners. On more complex polygons, both algorithms show a large spread on the number of needed diagonals, with outliers requiring 2 times n diagonals in 12-gon and 14-gon and 3 times n diagonals in 16-gons. On 12-gons more than 84% of the cases require n or less diagonals, yet this number decreases as the number of sides increases. This demonstrates that the Polygon Closure shortcut is a viable approach only if the number of non-orthogonal corners is expected to be small.

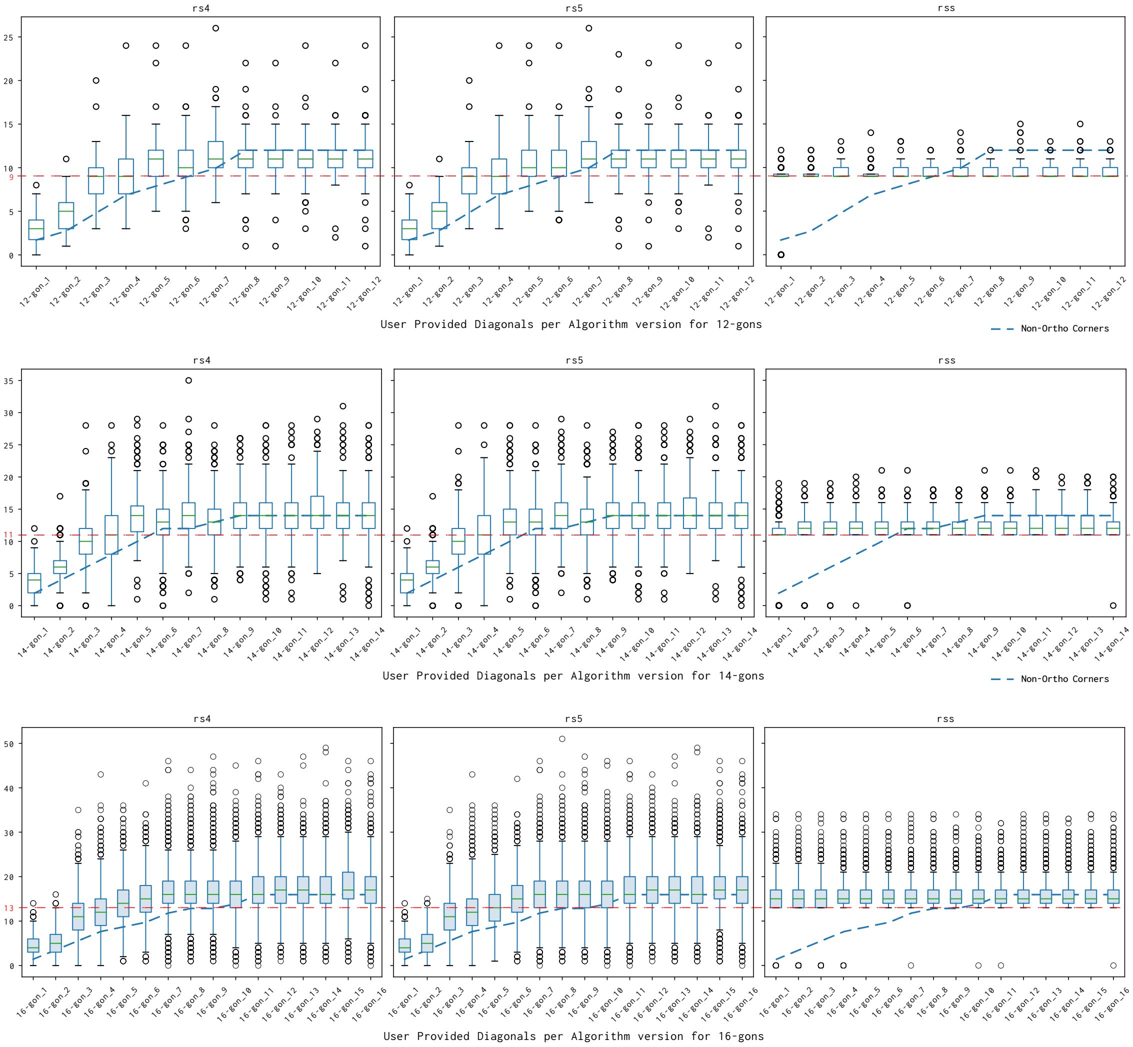


Figure 7-13: Number of user-provided diagonals for 12-gon, 14-gon and 16-gon datasets. Dashed blue – Mean non-orthogonal corners per dataset

As in the smaller polygon datasets RSS shows uniform performance as the number of non-orthogonal corners increases. In 12-gons 85,25% of the cases terminate with less than 12 diagonals, yet this number also decreases as the number of polygon sides increases, with 70,66% for 14-gons and 66,82% for 16-gons. This implies that RSS performance is also dependent on the size of n, with a possible correlation with the size of the non-convex sequences of corners.

Figure 7-14 shows the standard deviation of internal angle error by case for each algorithm version and n-gon dataset. The results show that RSS is more precise than RS4 or RS5, and that RS5 is marginally better than the former. For rooms with 6 sides, such as those that were surveyed in the Usability Testing experiment, all algorithms show a Standard Deviation of internal angles smaller than 1 degree in 96,5%, 96,8% and 98,7% of the cases. As the number of sides increases the angular precision reduces significantly for RS4 and RS5, with 62% and 66,6% polygons with less than 1 degree error for 16-gons respectively. RSS precision reduces marginally as the complexity of the polygon increases.

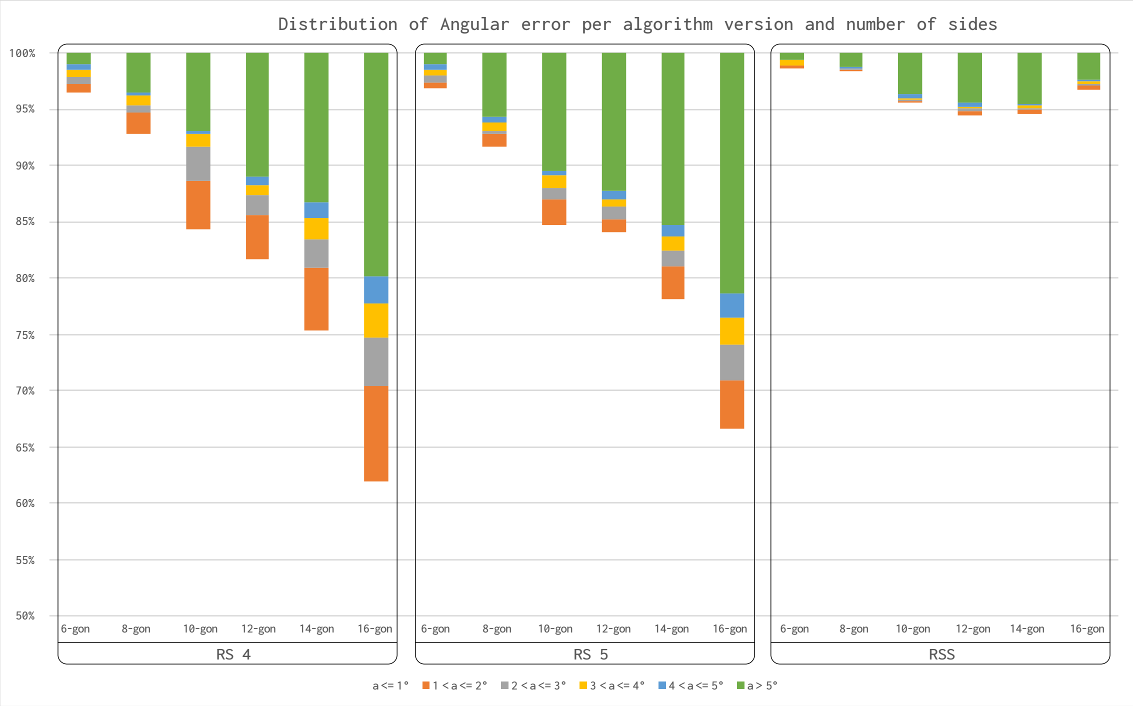


Figure 7-14: Distribution of internal angle error by case per algorithm version and dataset

Figure 7-15 shows the distribution of goal-output polygon similarity metrics for 16-gons computed with the Turning Function. Like with the previous metrics, RS4 and RS5, perform worse than RSS. Yet, all algorithms show a small subset of cases with little similarity.

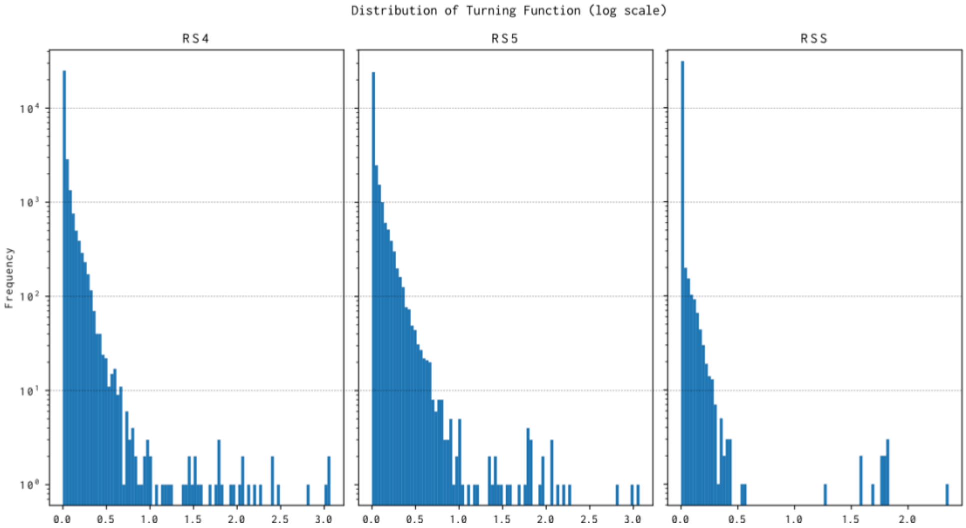


Figure 7-15: Distribution of Turning Function metrics (log scale)

Despite RSS good statistical performance, it is important to analyze the underlying cause of the angular error since in certain instances it has a non-negligible impact on the shape of the plan. Also, improving the precision of RSS can also improve the RS4 and RS5. Figure 7-16 presents one case with bad results angular-wise and in terms of similarity for 16-gons with RSS, which is representative of the causes of error in all the results with turning function worse than 0,4.

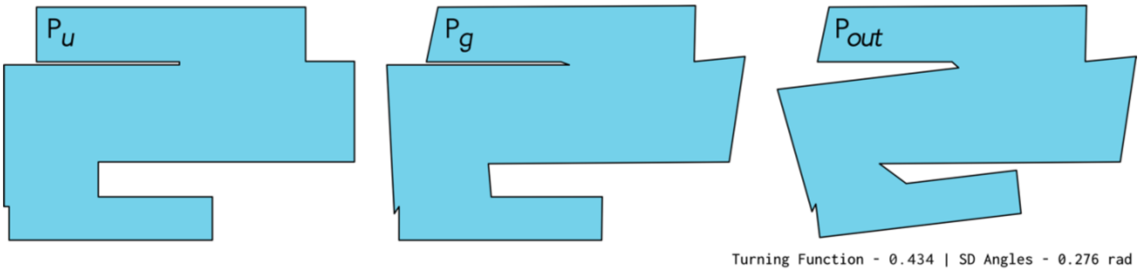


Figure 7-16: Case with large angular error and low similarity. Pu – 16-ogon morphology, Pg – 16-gon goal, Pout - result

The triangulation process requested 23 diagonals, 6 where not provided since these are not diagonals of Pg, hence the triangulation was completed with 17 diagonals. Figure 7-17 (top) shows the sequence of requested diagonals with the respective triangulated corners and the last requested diagonal is marked in red.

Analyzing the transformation stepwise we can see that the first nine diagonals, L_d1 to L_d9, are Case1 Triangulations. After having triangulated all convex corners, RSS defaults to requesting the longest diagonals, which may not contribute to triangulate any corner, as is the case with L_d10 to L_d13, and L_d16. L_d15 is a Case3 Pattern which triangulates corner 15 and allows the reuse of L_d14 to triangulate corner 1. Thus, implementing a detection procedure for Case3 patterns can improve the algorithm performance in non-convex corners reducing the number of requested diagonals.

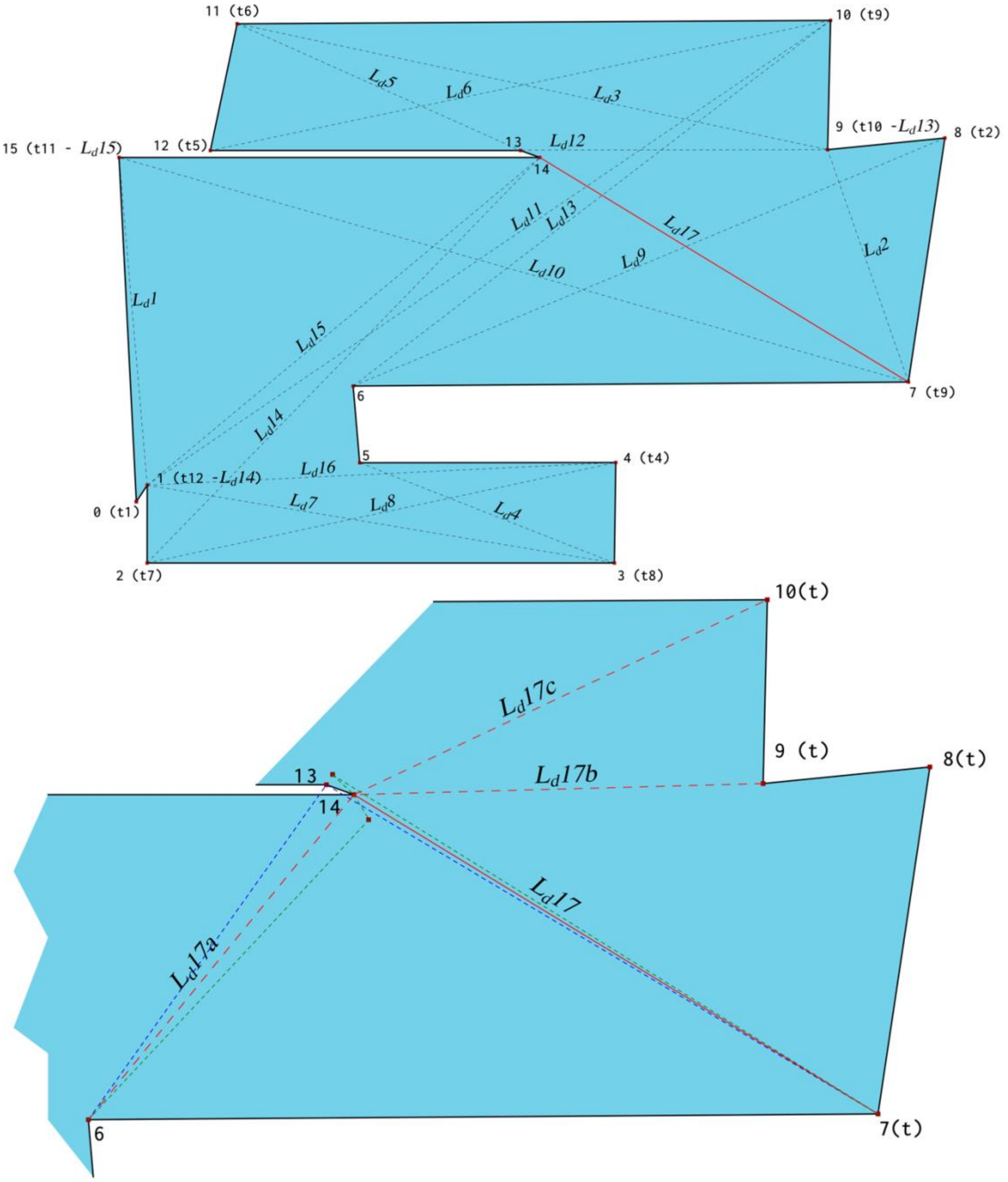


Figure 7-17: (Top) Triangulation sequence. (Bottom) Last executed triangulation and possible alternatives. Dashed blue goal triangulation, Dashed green wrong alternative.

L_d17 (Figure 7-17 top) is another example of a Case 3 pattern that was used to triangulate corner 13, in blue is the goal triangulation, in green the wrong one that was selected (Figure 7-17 bottom). Both orientations of the triangle maintain the corner type as non-convex in 13 and could thus be valid triangulations. Determining if corner 13 is visible from corner 7 could provide the solution, but the negation of visibility is ambiguous since it can also signify that there is an obstacle. Hence the corner cannot be triangulated with L_d17 without further user requests.

L_d17a, L_d17b, and L_d17c are alternative diagonals that will triangulate corner 13, yet are decidable, since one of the triangle orientations will flip the order of the corners creating a self-intersecting polygon. To check which orientation is wrong we only need to check if corner 13 turns left after being triangulated. It follows that we can detect if a triangulation is not decidable when both alternative triangle orientations keep the turn at the corner. Yet can we know beforehand if a certain diagonal will be decidable?

Note that the polygonal chain from corner 6 to 13 is rigid (Figure 7-17 top), since all corners from 7 to 12 have been triangulated, i.e., the angles between both edges incident to each corner have been determined. Triangulating corner 13 will make the position of corner 14 rigid relative to the triangulated polygonal chain. As such, any triangulation of corner 13 will only keep the corner type if corner 14 lies to right of the half-plane defined by the edge from 12 to 13. Consequently, any diagonal with one of its points in the left half-plane will be decidable, since one of the alternative triangulations will necessarily change the corner type at 13.

Let k be the corner to triangulate, j and i the endpoints of the diagonal such that $i < j$ and i is rigid. If i is left of the directed line from $k - 1$ to k, then there is no diagonal $|\overrightarrow{ij}|$ that will cause k to become invisible to i without changing the corner type at k.

Applying the above condition to our case we see that L_d17b, and L_d17c fulfill it while L_d17 and L_d17a do not. In the diagonal sorting we can prioritize the former two diagonals over the latter two, but not remove them since there may be instances where there is no other alternative diagonal.

The triangulation error described above, causes an angular error of 21.98° which propagates to the triangulation of the last 3 corners. L_d17 is the last requested diagonal but corners 14, 5 and 6, and hence the polygon, are not triangulated. RSS determines that some previously provided diagonals, L_d11 and L_d10 can be used to triangulate corner 14. The diagonal with the lowest index is selected, L_d11. Next, corner 6 is triangulated reusing diagonal L_d4. While these triangulations are valid it is instructive to compare other alternative options using the already described algorithms. Figure 7-18 compares the RSS results with, from left to right, Pattern000, L_d11 and Pattern00, L_d10 and Pattern00.

Using either Pattern00 or Pattern000 reduces both the angular error and increases similarity, with Pattern000 achieving the best results overall. Using L_d10 , with a larger internal angle β, instead of L_d11 reduces the angular error on corner 14 and allows significantly better results with Pattern00. Thus, when selecting between several diagonals to reuse these should be sorted by this metric.

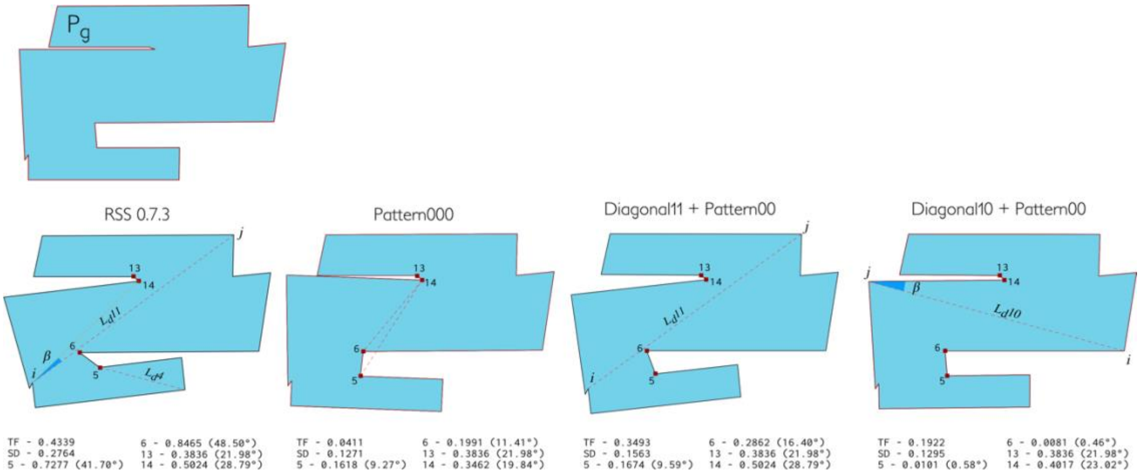


Figure 7-18: Comparison of different triangulation approaches

7.1.2.3 Discussion

The results from these experiments demonstrate that the error introduced by the iterative triangulation algorithms in surveying 6-gons is less than 1° in 96,5% of the cases for RS4. Hence, for simpler rooms it is true that angular error will mostly be caused by user measurement imprecision. Yet, this value drops significantly with RS4 and RS5 as the number of rooms sides increases. RSS performs significantly better in terms of precision which demonstrates assuming orthogonality takes a significant toll on precision. The results also reveal there is still some room for improvement in the triangulation process to address some edge cases, which could benefit all algorithms.

RS5 is statistically better than RS4, both regarding requested diagonals and precision, which is unlikely to change with any of the discussed improvements. With the current implementations, using RS5 to minimize the number of requested diagonals is only justifiable if the rooms are expected to have at most 3 or 4 non-orthogonal corners. Yet, the results might change if a Case 3 Triangulation detection is introduced.

7.2 Testing System

Considering the disruption caused by COVID-19 (2020 to 2022), the DigitalFUTURES yearly conference in 2020 was shifted to an online free event mixing workshops and talks organized for a world audience. The workshop "Context-aware Mass Customization Construction System" (*Sistema Construtivo Contextual Personalizável*)[34] was one of those workshops. It was held online to participating students over the ZOOM platform and livestreamed to Youtube for auditing students. The workshop lasted for 5 days, each day had 7-hour sessions, split into three parts: masterclass, individual/teamwork, and design review.

The objective of this workshop was to test the usefulness of the generic grammar and survey-to-production workflow for meta-designers to develop demountable MCC systems that can be deployed in online configurators for generic clients. The presentations to the students covered the generic grammar, the assessment criteria, the workflows, and tools described in previous chapters. They were shown examples of partition walls and construction systems developed under the tenets of this research and by other researchers. Each participating student was challenged to develop their own construction system of partition walls for building renovation individually, but they were also free to join in groups if they so desired.

The specific questions we were seeking to address are:

- How useful is the generic grammar and the survey-to-production workflow for meta-designers to develop customizable and disassemble-able partition wall construction systems for MCC?
- How well do each system responds to the proposed framework of criteria for the design of customizable and disassemble-able partition wall systems?

The first question deals with generality of the proposed generic grammar, which should ideally enable a wide range of different solutions to emerge. Usefulness is measured by student perceived value and difficulty, the completion of design tasks and evaluation of the designed outcomes. The second question seeks to address the effectiveness of the generic grammar in enabling the desired design outcomes. Naturally, the medium of teaching, the researchers' effectiveness in communicating the ideas and the background of the group of students will have an influence on what is achieved. So, the analysis of the results must be done individually and on average.

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[34] The workshop was taught in Portuguese

7.2.1 Participants

The workshop started with 10 participating students but only 7 of them made it to the end. The students were mainly from Brazil, except for one student from Portugal. The participants were all either architects or students of architecture. There were three University teachers with PhD level, four practicing architects with Master level, one PhD student and two Master students.

At the beginning of the workshop, the students were asked to fill a short questionnaire to assess their experience with the subject matter of the workshop. They were asked to self-assess their experience with Grasshopper (Question 1) and Digital Fabrication (Question 4) on a Likert scale, with one being unexperienced and five highly experienced.

Three further questions were asked: whether they had already developed parametric models to be used by others (Question 2); whether they had already published parametric models on online configurator platforms such as ShapeDiver or Paramate (Question 3); and whether they agreed with the assertion that digital design and fabrication tools may be used to implement customizable construction systems for building renovation online for generic users (Question 5).

The third question was on a Likert scale, while the other two were open to yes/no answers. Figure 7-19 summarizes the group experience self-assessment before the workshop with Grasshopper (Q1) and with digital fabrication (Q4). The mean on Q1 was low experience and on Q4 was average experience. None of the students had previously uploaded any model to an online platform (Q3), but some of them had already created models for others to use (Q2) (Figure 7-20). Most participants strongly agreed with the assertion in Q5 and Figure 7-20 demonstrates that there is a correlation between the participant experience with digital design and fabrication and the belief on the possibility expressed by Q5.

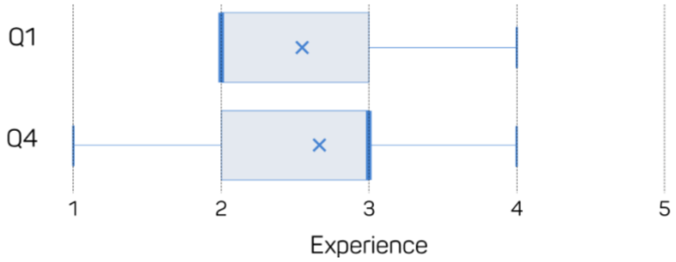


Figure 7-19: Experience self-assessment with Grasshopper (Q1) and Digital Fabrication (Q4)

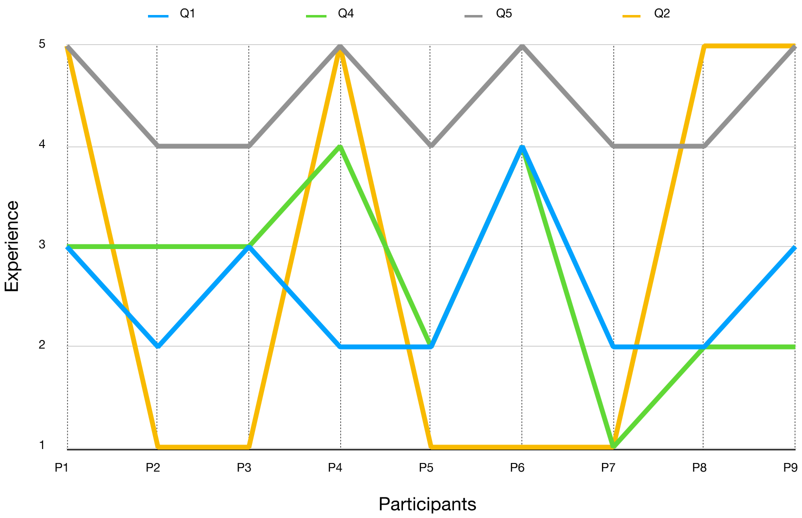
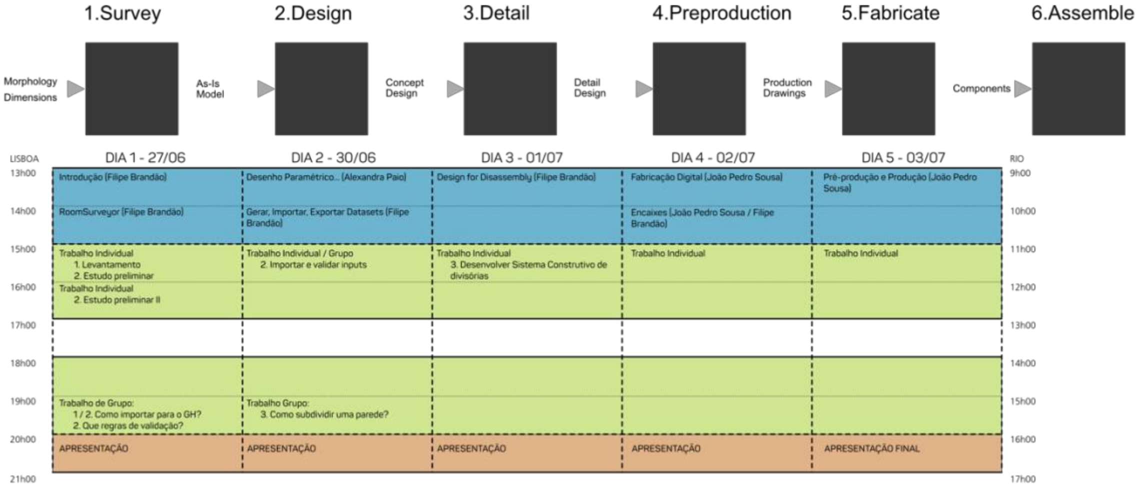


Figure 7-20: Correlation between experience self-assessment [Q1, Q2, Q4] and agreement with the assertion of Q5

7.2.2 Workshop outline

Each day of the workshop was dedicated to one of five first the steps of the survey-to-production workflow: Survey, Design, Detail, Pre-production, Fabricate (Figure 7-21).



LISBOA	DIA 1 - 27/06	DIA 2 - 30/06	DIA 3 - 01/07	DIA 4 - 02/07	DIA 5 - 03/07	RIO
13h00	Introdução (Filipe Brandão)	Desenho Paramétrico... (Alexandra Paio)	Design for Disassembly (Filipe Brandão)	Fabricação Digital (João Pedro Sousa)	Pré-produção e Produção (João Pedro Sousa)	9h00
14h00	RoomSurveyor (Filipe Brandão)	Gerar, Importar, Exportar Datasets (Filipe Brandão)		Encaixes (João Pedro Sousa / Filipe Brandão)		10h00
15h00	Trabalho Individual 1. Levantamento 2. Estudo preliminar	Trabalho Individual / Grupo 2. Importar e validar inputs	Trabalho Individual 3. Desenvolver Sistema Construtivo de divisórias	Trabalho Individual	Trabalho Individual	11h00
16h00	Trabalho Individual 2. Estudo preliminar II					12h00
17h00						13h00
18h00						14h00
19h00	Trabalho de Grupo: 1 / 2. Como importar para o GH? 2. Que regras de validação?	Trabalho Grupo: 3. Como subdividir uma parede?				15h00
20h00	APRESENTAÇÃO	APRESENTAÇÃO	APRESENTAÇÃO	APRESENTAÇÃO	APRESENTAÇÃO FINAL	16h00
21h00						17h00

Figure 7-21: Workshop structure and relation with survey-to-production workflow

On day 1 an introduction to the subject was provided, the survey-to-production workflow presented with a stronger detail on RoomSurveyor plugin and the low-key survey workflow. Participants were requested to survey one space and propose a subdivision of that space – a concept design. They were then asked to share the survey with the other participants, so all could propose subdivisions for each of the surveyed spaces. At the end of this process, they were asked to meet and discuss: (1) adequate rules to validate the concept design; and (2) the necessary inputs for their Grasshopper parametric models.

The objective of the first exercise was to make the students experiment the role of the instance-designer of their construction system and be confronted with other designers' points-of-view. Our expectation was that this process would cause them to realize the differences between instance-designer and meta-designer mindsets and make them self-aware of their stance. Hopefully, the need to transition from the traditional architectural mindset of designing the instance to the mindset of system design would become evident.

The presentations of the second day focused on design strategies for meta-designers: such as designing with ranges in mind; validating inputs with metric, geometric, proportion or topological rules; using datasets to test design assumptions; relate parametric hierarchies with construction hierarchies. Some examples of how to implement the design strategies were shown and the participants were challenged to develop specific algorithms within a parametric model to import and validate surveys and concept designs into Grasshopper with the proposed strategies (Figure 7-22). To develop their individual task, they had to collaborate with the other students to determine the type of inputs each of their algorithms would receive. At the end of the day, they were asked to propose subdivision rules for the partition walls that were imported and validated by the parametric model.

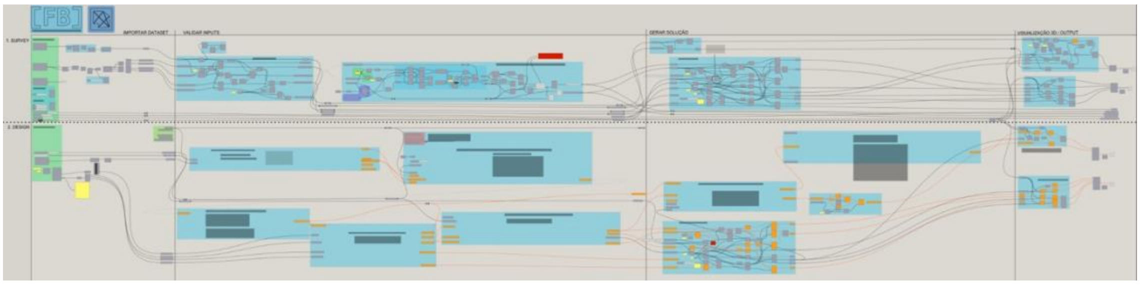


Figure 7-22: Day 2 student exercise – Survey and Design workflows

The masterclass of the third day focused on the context of building renovation, on criteria for designing demountable construction systems and on generic subdivision methods for partition walls. Some partition wall construction systems, developed in the context of this thesis, were presented to the participants. A parametric model to assist the generation of partition walls was provided and strategies to model modular components were described (Figure 7-23).

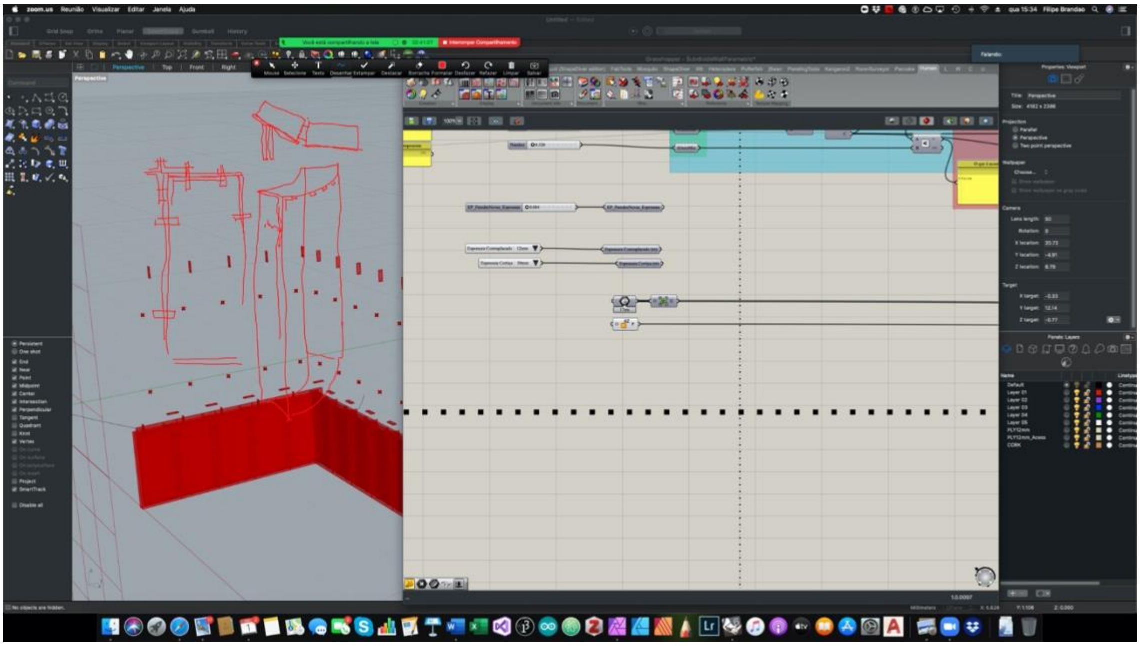
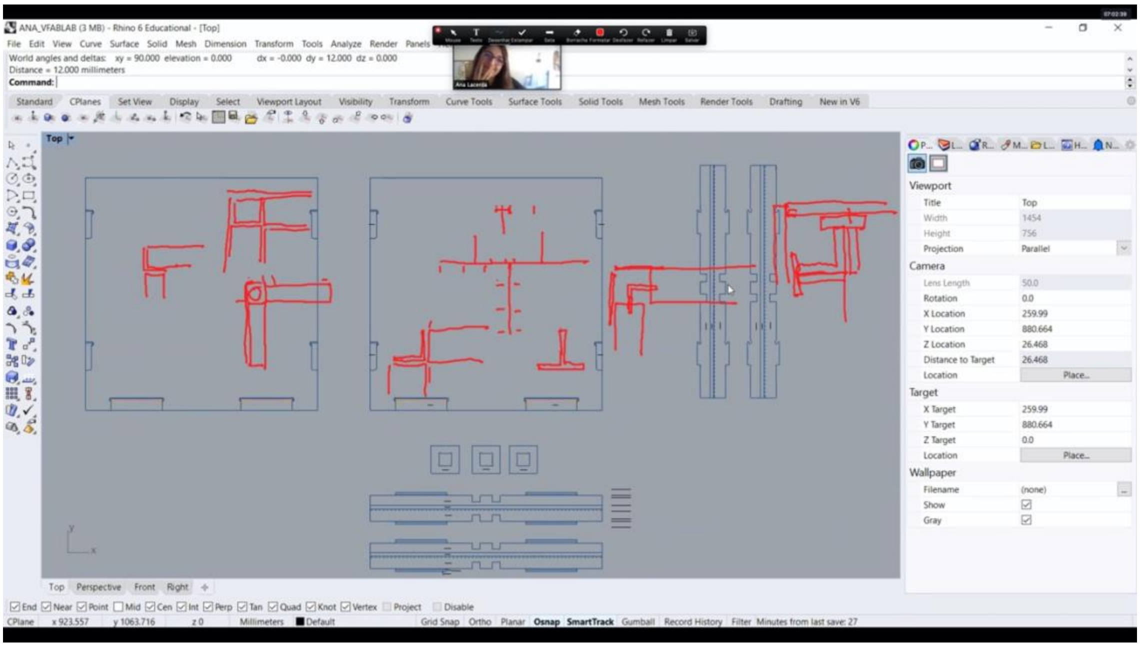


Figure 7-23: Parametric model for generating partition walls in use.

On the fourth day, the participants were introduced to digital fabrication processes and tools with a particular focus on CNC fabricated joints. Examples of friction-fit, snap-fit and t-slot joints, as well as construction systems designed with these joints, were presented to the students. Their advantages and shortcomings were discussed together with strategies to model them and prepare the pre-production files for digital fabrication.

On the last day, participants were walked through all the steps required to produce a protype of one of their systems: from importing the production files, to the CAM software, to the assembly of the components.

From the third day onwards, participants focused on developing their own mass-customizable and demountable construction systems for building renovation. The challenge was to develop a demountable partition wall construction system, built from CNC cut flat materials such as plywood or insulation cork board (ICB). The specific design tasks included: (1) define a wall dimensional and functional subdivision strategy; (2) define each of the system components in terms of their materials, functions, and assembly sequence; (3) define an assembly sequence for the system components – how do they connect to make a wall; and (4) define solutions for interface conditions with wall, floor, and ceiling (Figure 7-24).



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World angles and deltas:   xy = 90.000  elevation = 0.000        dx = -0.000  dy = 12.000  dz = 0.000
Distance = 12.000 millimeters
Command:
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Viewport

Title	Top
Width	1454
Height	756
Projection	Parallel

Camera

Lens Length	50.0
Rotation	0.0
X Location	259.99
Y Location	880.664
Z Location	26.468
Distance to Target	26.468
Location	Place...

Target

X Target	259.99
Y Target	880.664
Z Target	0.0
Location	Place...

Wallpaper

Filename	(none)
Show	☑
Gray	☑

☑ End ☑ Near ☑ Point ☐ Mid ☑ Cen ☑ Int ☑ Perp ☑ Tan ☑ Quad ☑ Knot ☑ Vertex ☐ Project ☐ Disable

```
CPlane   x 923.557   y 1063.716   z 0   Millimeters   Default   Grid Snap  Ortho  Planar  Osnap  SmartTrack  Gumball  Record History  Filter  Minutes from last save: 27
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Figure 7-24: Tutoring author of System B

7.2.3 Workflow assessment

During the first day, all students were able to survey a room using the plugin, propose some spatial subdivisions of that space, and some design validation rules (Figure 7-25). Most of the rules proposed by the students were deeply related with their sociocultural and geographical background as well as with their training as architects. As an example, some rules were related with the building orientation, while other rules were related with the spatial relation of spaces. As the students attempted to define an agreed ruleset for the construction system, they quickly concluded that it could not contain rules related with building orientation or space use patterns.

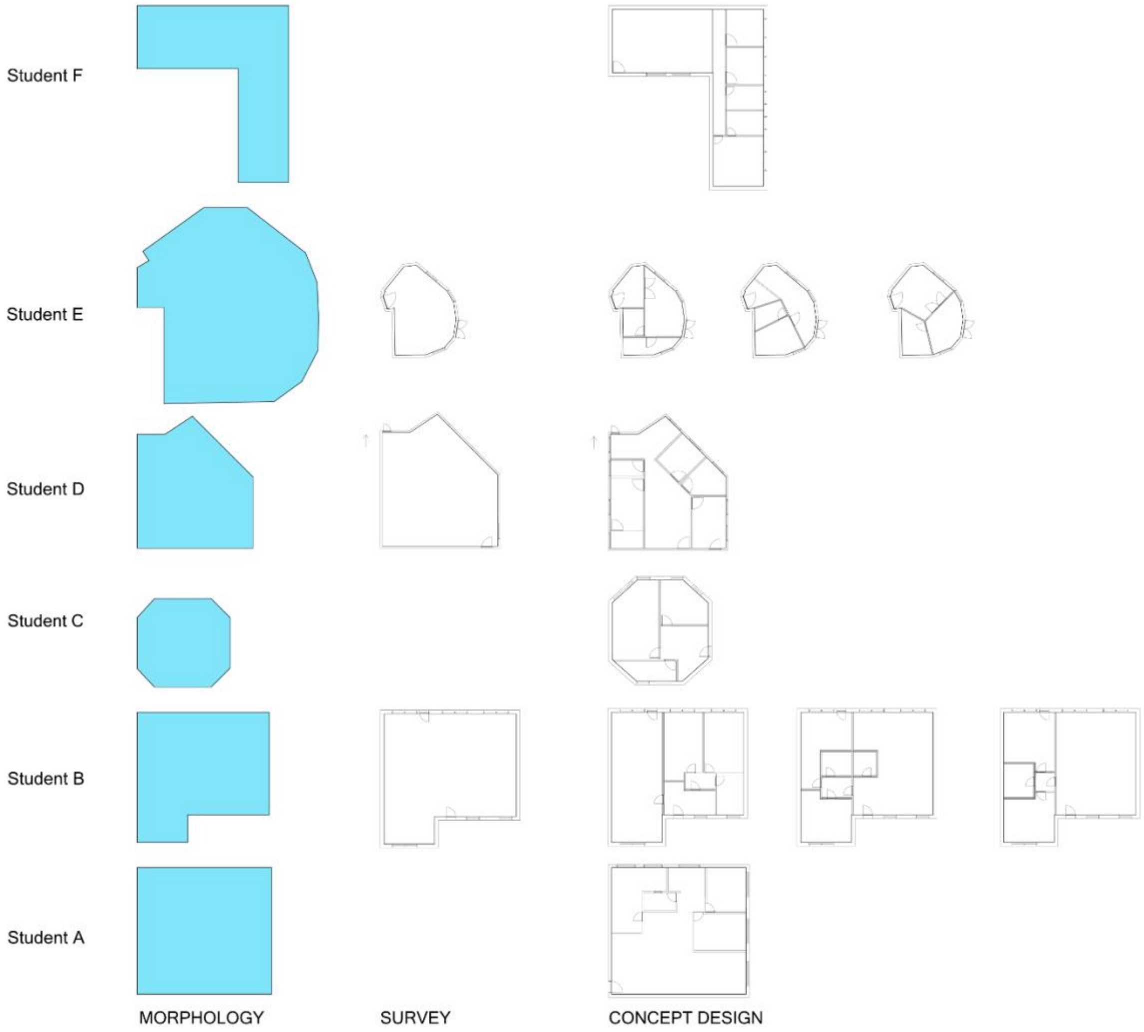

Figure 7-25: Survey morphology to existing space plan and possible spatial subdivision

None of the students was able to complete their task of developing one of the algorithms in the proposed workflow, during the second day, and only one was able to state the complete set of operations involved in the assigned task. This result is not unexpected, since their experience with Grasshopper was on average low and the available time to complete the task was just 4 hours.

The students developed six partition wall construction systems which from hence on we name system A, B, C, D, E and F (Figure 7-26). Except for system D, which was developed by two students, all other systems were the result of individual work over the course of three days.

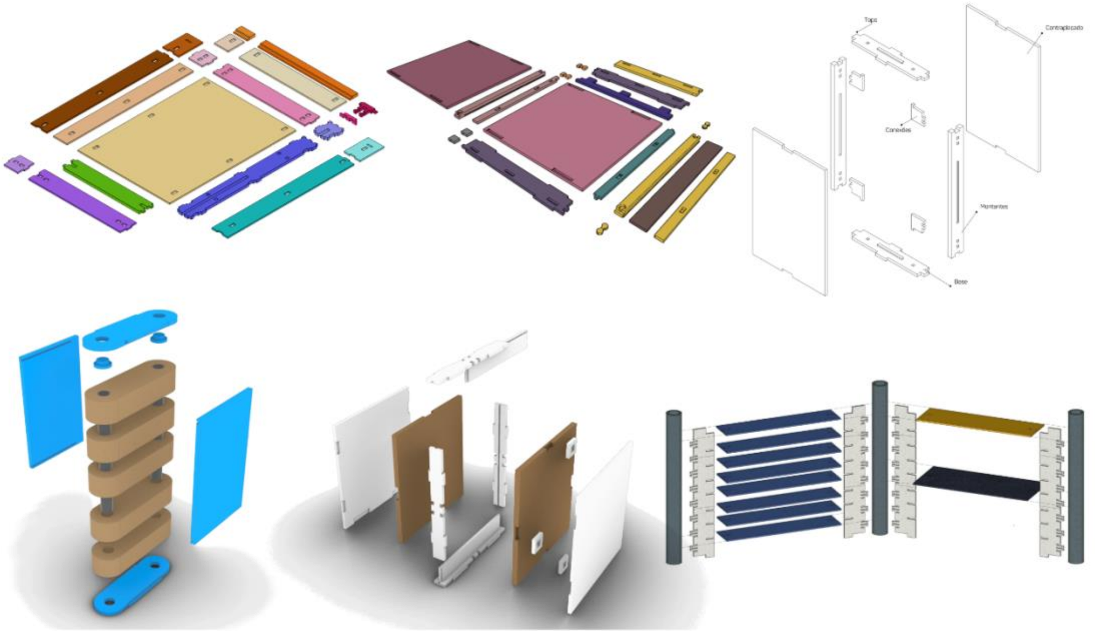

Figure 7-26: Bottom row from left to right - System A component, System B component, System C parts; Top row from left to right – System D parts, System E parts, System F component parts.

Another questionnaire was performed at the end of the workshop, to which five out of seven students replied. The students were again requested to self-assess their experience with Grasshopper (Question 2) and Digital Fabrication (Question 3) on a Likert scale. Similarly, the question about their agreement with the assertion that digital design and fabrication tools may be used to implement customizable construction systems for building renovation online for generic users was repeated (Question 1). The remaining questions were on the relevance of the proposed workflow for each of the student's future work (Question 4), on the usefulness of the tools and workflow for the development of the proposed task globally (Question 5) and for each of the steps proposed by the workflow (Question 6). Lastly, Question 7 focused on how easily each of these steps were accomplished. All the previously mentioned questions were on a Likert scale. Three other questions were asked, all with open answer, about further aspects that the workflow should consider (Question 8), if they missed some tools (Question 9) and lastly if they wished to leave any further comment (Question 10).

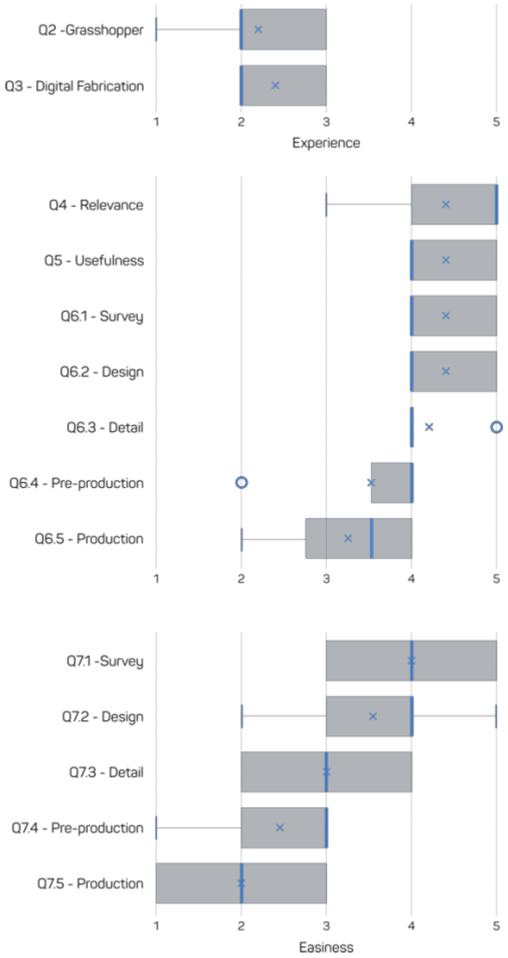

Figure 7-27: Top to bottom) - Grasshopper and Digital Fabrication experience self-assessment; Q4 - relevance of workflow and tools; Q5 and Q6- Usefulness of workflow and tools globally and step-by-step; Q7 – Perceived difficulty of each step

The students self-assessed previous experience with digital design and fabrication tools reduced at the end of the workshop, as can be seen in Figure 7-27.The reduction was slightly higher in digital fabrication experience. This correlates with the higher perceived difficulty with the pre-production and production steps of the workflow, identified by the students in their reply to Question 7. On the other hand, although on average the experience with grasshopper is assessed as lower than with digital fabrication, the first two stages of the workflow were found to be easier. Possible reasons are: (1) students are more proficient in design tasks; (2) the proposed tools for the first stages are better; (3) the duration of the workshop was not enough to allow them to develop each of the steps with equal depth. While we cannot exclude (1) and (3) might have influenced the replies, the answers to question 6 indicate that likely (2) is the main reason.

7.2.4 System Design Evaluation

All the systems presented by the students at the end of the fifth day had viable solutions for the standard modular wall components (type A components), with a clear component sub-assembly logic. The students were able to say which materials were used, what functions they performed within the component and how all the parts were assembled into a component. All systems' type A components were statically feasible, except for system D which missed the interlocking of the frame parts on the top left corner. Some of the parts of System D and E cannot be fabricated with a 3-axis CNC without rotating them on the table.

While not all systems effectively solved all the end-wall and interface conditions, all students correctly identified in their systems the functions of each of the components relative to their position on the wall. The authors of System D and E explicitly defined minimum and maximum dimensions for their system components as well as functional subdivisions, while the author of System F only defined the functional subdivisions. All other systems have components of one functional type and their authors did not fully define their ranges of dimensional variation.

In terms of component assembly into a complete wall, while all students provided a reasonable logic and assembly order, only the designs of system A, B and C were free of issues. System E is over constrained, the components of the first row can be assembled but not the second row, while systems D and F had issues with the assembly of the last or first components of the wall.

Except for System A, which only defined the connection with the floor, and System C, which conceptually could make do with only the floor detail, all other systems clearly defined solutions for wall, floor, and ceiling interfaces, yet, as previously mentioned not all are feasible. Furthermore, only System D defines a solution for tolerance control at all the system boundaries, System A and B only do so at the floor and ceiling interface.

At the end of the 4th day, Systems A and B had a component design that could be manufactured with a few small adjustments (Figure 7-28). A component of System A was prototyped on VFABLAB on the 5th day of the workshop. A component System B was also ready to be prototyped at the end of the 4th day but it was only manufactured after the end of the workshop for lack of time.

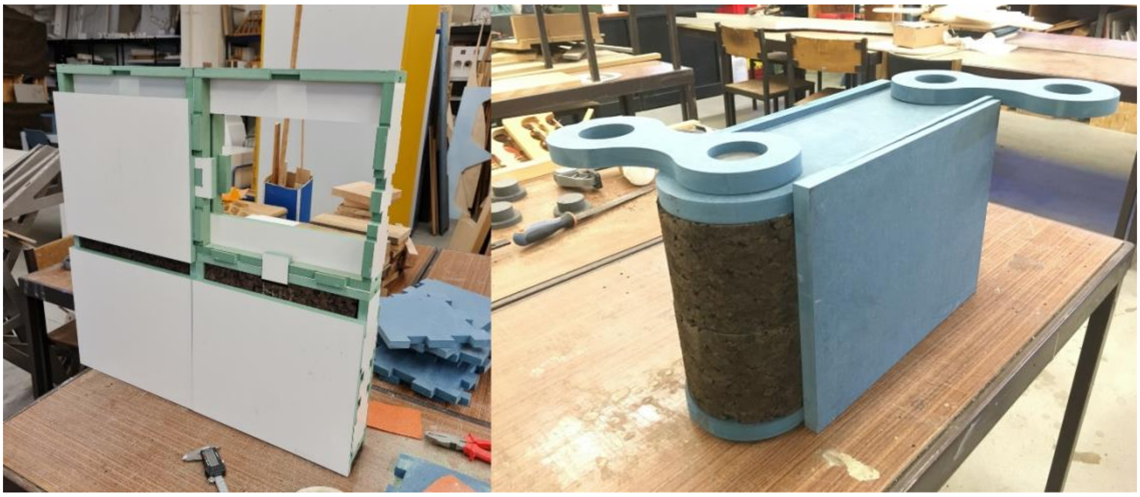

Figure 7-28: Prototypes of 4 components of System B (left) and a component of System A (right)

The authors of systems B, D, E and F developed component designs for simpler straight walls, with variety of wall subdivision strategies. The proposed survey-to-production workflow is evidently applicable these systems. The author of System A intended to develop a construction solution that could be applied to NURBS curves, generated from the intersection of user defined functional areas. The envisioned method to generate the walls would be indirect, changing the wall input in the proposed workflow with an input to generate the desired areas.

System C is based on modular shelves elements that can be used to create a space subdivision. Each module may connect with at most 3 other modules at the extremities, in a total of 20 possible patterns of connection of 1, 2 or 3 modules. Each module is comprised of cylindric column, a configurable number of shelves, and a vertical slat that connects the shelves to the support column. An interactive workflow is eminently applicable to this type of system, where each new state is contingent on the previous configuration state. In fact, the system requires a more constrained version of the proposed survey-to-production workflow, where angles and wall lengths are constrained to specific lengths.

All authors were able to design systems with component sizes that can enter the space through an existing door. Table 7-4 presents a summary of the main properties of each of the systems. To evaluate the systems regarding the proposed criteria in Chapter 4, we apply their designs to a partition wall with 3 x 3m, which is the minimum length recommended for technical assessment and was used to evaluate all the systems presented in Chapter 6.

Not all systems have preassembled components, in System C and E all parts are sent to be assembled onsite, although in System E there are opportunities for a small degree of pre-assembly. Consequently, in C and E the number of components to assemble on site is the total number of parts. At the system level, System B has the lowest number of different component functional types to assemble on site, and C and D the highest, both with 11 (Table 7-4). When the functional types are combined with the specific dimensional subdivision for the selected case study, the number of different components increase to 7 for both A and B systems.

Table 7-4: Comparison of system properties

	Subdivision type		Assembly Sequence			Number of Functional Types			Component Joining	Pre-assembled?
	Horizontal	Vertical	Horizontal	Vertical	Type	Components	Interfaces	Connectors		
SYSTEM A	Integer	Integer	Bidir	Unidir	Type II	1	2	1	Third component	Y
SYSTEM B	Integer	Integer	Local	Local	Type V	1	1	1	Third component	Y
SYSTEM C	Integer	Integer	Bidir	Unidir	Type II	2	1	1	Interference	N
SYSTEM D	Metric	Metric	Unidir	Unidir	Type I	4	4	3	Interference / Third	Y
SYSTEM E	Metric	Metric	Unidir	Unidir	Type I	3	2	2	Double Interference	Maybe
SYSTEM F	Metric	Metric	Bidir	Unidir	Type II	4	2	0	Interference	Y

Table 7-5 summarizes the results of the analysis of the systems developed by the students when applied to a 3x3m wall. System B achieves the best results in most criteria and provides interesting improvements over ORW v4: namely aligning the position of the internal structure with edges of the component, achieving functional independence in the panel, and improving the separability of the component connector. These improvements have several negative consequences. The number of connectors is doubled which increases the number of components to be assembled onsite (which results in lower Simplicity). Although disassembly sequences can be local the number of disassembly dependencies doubles. There is no solution for the interface with the existing walls. Lastly, integrating services is significantly complicated by the position of the frame reinforcement.

Table 7-5: Evaluation of the developed systems by the proposed criteria

Criteria		Subcriteria	Method of evaluation	System A	System B	System C	System D	System E	System F
Environmental	**EIM**	**Independence - material**	% of independent parts per system	**1**	**1**	**1**	**1**	**1**	**1**
	EIF	**Independence - functional**	% of parts with covariant functions per system	**0,86**	**1**	**1**	**1**	**0,93**	**0,80**
Assembleability	**AS**	**Simplicity**		**0,070**	**0,048**	**0,076**	**0,042**	**0,028**	**0,041**
			Number of operations (1/n)	0,015	0,012	0,040	0,008	0,005	0,023
			Number of different operations (1/n)	0,125	0,083	0,111	0,077	0,050	0,059
	AP	**Praticality**		**0,8**	**0,92**	**0,78**	**0,65**	**0,65**	**0,72**
			Assembly/Dissassembly Sequences (Type I to V)	0,4	1	0,4	0,2	0,2	0,4
			Tools	1	0,75	1	0,75	0,75	0,75
			Weight per component (Range 15-75kg)	1	1	1	1,00	1	1
	AC	**Comunication**		0,5	0,6	0,5	0,4	0,5	0,6
Flexibility	**FG**	**Geometric flexibility**	Levels (Type I to V)	**0,6**	**0,2**	**0,2**	**0,2**	**0,2**	**0,2**
	FS	**Services integration**	Levels (Type I to V)	**0**	**0,4**	**0**	**0,6**	**0,2**	**0,6**
	FMS	**Modularity - Separability**	Levels (Type I to Type X)	**0,68**	**0,82**	**0,70**	**0,74**	**0,70**	**0,70**
	FMC	**Modularity - Combinability**		**0,195**	**0,195**	**0,320**	**0,042**	**0,085**	**0,153**
			Connection types (1/n)	0,25	0,25	0,5	0,008	0,13	0,14
			Component types (1/n)	0,14	0,14	0,14	0,077	0,04	0,1667
	FP	**Personalization**		**0,55**	**0,65**	**0,65**	**0,50**	**0,40**	**0,40**
			Applicability of joining solutions	0,7	0,7	0,7	0,4	0,4	0,4
			Applicability of solution to renovation	0,4	0,6	0,6	0,6	0,4	0,4

System A and C achieve higher simplicity than System B but do so by the reduction of the number of interfaces of the system with the boundaries. System C only has interfaces with the floor and System A with the ceiling and floor.

In conclusion, all the students could develop different systems that on average present improvements in Simplicity, Functional Independence, Practicality, and Modularity criteria, when compared to the analyzed cases in the literature. Conversely, they present on average worse results in Personalization, Geometric Flexibility and Services Integration. Several difficulties where noted, particularly with correctly planning assembly sequences that consider all interface constraints and dealing with the limitations of the selected digital fabrication system. The latter difficulty may be related with workshop medium while the former supports the student feedback that the pre-production and production steps are more difficult to perceive.

CONCLUSION AND FUTURE WORK

This section provides a general review of the research conducted during this thesis, the conclusions than have been reached and the limitations of the present work. It begins recalling the motivations and contributions highlighted in the Introduction, ensuing with the methodology, the research and specific conclusions that have led to those contributions. It finishes with some suggestions of threads for future research.

Conclusions and recommendations

As described in the introduction to this thesis, there are latent opportunities to use digital design and fabrication to design disassemble-able MCC systems for the context of building renovation by generic users. For architects this is an opportunity to extend their practices to serve generic clients by leveraging configurator platforms.

The motivations that led this thesis have resulted in specific contributions that are summarized bellow:

Contribution 1 –Theoretical/Practical contribution of a low-key survey-to-production workflow to develop configurators of partition wall systems for building renovation of interior spaces. The workflow is aimed for meta-designers but can also be valuable to other stakeholders particularly those involved in production and construction.

Contribution 2 – Theoretical contribution towards the definition of a rigorous set of design criteria for designing open and disassemble-able digitally fabricated partition wall construction systems for open building renovation. The analysis of the designs considering the criteria is a contribution to future research aiming to increase reusability of building systems.

Contribution 3 – Theoretical contribution in the form of a generic grammar condensing a generalizable set of design patterns, subdivision rules and modularization strategies, for digitally fabricated partition wall systems. This contribution had a practical part in the developed partition wall systems, which illustrate the grammar and are examples of systems for further design iteration, and the T-slot joint which adds to the range of available CNC fabricated joint details for partition wall construction systems. These contributions have practical applications for developing more specific disassemble-able and mass customizable partition wall construction systems by architects, as demonstrated by the results of the work described in Chapter 7, and in the development of subdivision algorithms for each of the identified patterns that can be used to populate the partition walls with specific systems components.

Contribution 4 – The iterative triangulation algorithms described in this thesis are theoretical contribution which provides a rigorous framework for developing interactive algorithms for semi-automated survey of interior spaces by generic users. RoomSurvey algorithms are practical implementations of the described algorithms in a Grasshopper plugin, and two JavaScript apps which can be used to build low-key interactive survey workflows for online configurators. The resulting surveys are parametrical models of the existing spaces, and hence updatable, that can be used in design-to-production workflows that depend on the geometrical context.

To achieve the enumerated contributions towards Open ReWall Survey-to-Production Workflow for Building Renovation the described research was focused on the areas of design for generic users, mass customized construction and DfD.

In the theoretical framework it was established that building renovation is a complex, emergent process with diverse stakeholders and increasing relevance in industrialized countries, that spans over a diverse and growing ecosystem of ageing buildings, in which the participation of architects is frequently not required or feasible. The design and construction in building renovation require higher labor, technical and contextual knowledge, both in design and construction, and is less prone to standardization. Renovating buildings is widely seen as more sustainable approach that demolishing and rebuilding, and the renovation of interior spaces, within which partition walls, has a high impact in waste generation and resource consumption. The above arguments fundament an open building renovation approach to the design and construction of buildings and their iterations over their life-cycle, in which DfD is the crucial component in enabling the design of systems for increased reusability.

At the root of the open building is the idea that users of the buildings should be involved in the renovation process. Similar ideas have been explored since the sixties, starting with authors such as Nicholas Negroponte and Yona Friedman, which proposed employing computer means to guide generic users in designing. These ideas have evolved over the years into MCC which is argued to be a systematic form for the distribution of control over design and fabrication of buildings.

Chapter 2 reviews the fundamental characteristics of the MC concept, the levels of user control and customization and their relationship with system properties, e.g., modularity and interfaces, and the enablers, e.g., configurators, that allow its implementation in practice. The MC concept is firmly related with a process of finding an alignment between design and fabrication potential with the specific context of application and user's needs. The MC concept is contrasted with PF which lead to the intuition that although they depart from opposing views regarding production control, they share tools and methods to achieve design democratization. This intuition is examined with the use of a mapping methodology contrasting concepts and paradigmatic cases from theory and practice of MC and PF to the AEC industry. The results of the exercise (Figure 2-9) revealed that Visionary MC is the space where design control between architects and users is effectively traded and is thus the ultimate frontier for MCC to involve the user in the design process.

In Chapter 3 the review is deepened on the tools and methods that have been proposed to implement configurators and to establish seamless design-to-production workflows for generic users. The application of the concept of configurators to the specific case of building renovation exposes a gap in simple survey methods to collect the geometrical context for a design. Similarly, the application of the mapping methodology to these tools and methods reveals that interactive methods of design may be better suited to provide Visionary MC level design control to generic users. Also, although MCC was found to be an appropriate fit to the non-standard challenges of building renovation, the studied examples of cost-effective digitally fabricated systems failed to address the best practices of DfD, particularly regarding the reusability of parts and components, and the complexity of systems. Most of the proposed systems were also found to be closed, or require dramatical changes to the stakeholder roles in AEC, features which have historically led to failure of adoption (Habraken, 2003). An open approach of incremental innovation of building systems is posited as an alternative, implemented by the means of a workflow.

In Part II of this thesis, we address the challenges raised in preceding part using a systemic approach. In Chapter 4, criteria, requirements, and guidelines from different fields, i.e., building renovation, DfD and MC, partition wall design, are examined, compared, and reconciled. The analysis results in a consistent set of criteria and methods of assessment for the developing disassemble-able digital fabricated partition wall systems (Table 4-7), and which were validated with expert interviews. Paradigmatic examples of cost-effective digitally fabricated systems from the literature were analyzed with the proposed criteria (Table 4-10). Opportunities for research were revealed particularly in the criteria of Modularity (FMS, FMC), Simplicity (AS), Practicality (AP) and Functional Independence (EIF). This led us to question if there were specific design patterns that make systems more reusable. The proposed set of criteria combined with the analyzed cases from literature, and the evaluation of the partition wall systems developed during this thesis (Table 5-11) and those developed by the students (Table 7-5) are the core of contribution 2.

In Chapter 5, we analyzed paradigmatic and emerging workflows amongst computational designers and proponents of design-to-production systems and how these may be reconciled with practice. We reflect on the emerging figure of the meta-designer and on how it has contributed to connect the dots by developing custom workflows which are then generalized into open-source plugins. These ad-hoc contributions have coalesced providing opportunities for complete design-to-production workflows. Several alternative configurator platforms to deploy these workflows to online configurators for generic clients were analyzed (Table 5-1, Table 5-2, Table 5-3). To address the as-is surveys for generic clients gap in design-to-production workflows we compared and conducted user testing of several methods of survey with semi-automated workflows available in mobile apps for generic clients (Figure 5-12). We found these methods to be insufficiently precise for design-to-production workflows (Figure 5-16, Figure 5-19) and that non-expert users had significant difficulties using them (Table 5-9, Figure 5-22).

The last section of Chapter 5 describes design methods and patterns architects may use to tackle the design of partition wall systems for open building renovation. The generic grammar is the result of the reflection on the iterative design cycles of partition walls. It describes key patterns that can be followed to increase system, component, and part reusability, identifying types of internal and external interfaces, typical solutions and their impact on component reusability and modularity. It describes the development of a new type of digitally fabricated joint - the T-Slot joint - that can be used to address the specific need of partition walls of reduced number of exposed joints. These elements are the core of contribution 3 of this thesis.

In Chapter 6 we argue that extending MCC systems to building renovation requires extending Duarte's conceptual model by adding a survey system (Figure 6-1 and Figure 6-6). This finding coupled with the described results of Part I and II led to the proposed low-key survey-to-production workflow for open building renovation (Figure 6-2). The workflow demonstrates a step-by-step process of how architects and/or meta-designers may extend their practices with survey-to-fabrication systems for generic clients, following a familiar modular pattern of AEC design and production stages: survey, concept design, detail design, pre-production, production, and assembly. Since the viability of developing design-to-production workflows has been demonstrated in the literature, the survey system is considered the key to unlock the possibility of developing survey-to-production workflows for building renovation of interior spaces. The remaining steps of the full workflow are described in An Interactive Design-to-Production Workflow. All workflows are similarly divided into input, validation, generation, and output stages.

In An Interactive Survey Workflow we describe iterative triangulation and diagonal sorting algorithms inspired by the empiric surveying methods used by building experts to automate the drawing of the space plan. The algorithms are used to implement a semi-automated interactive survey workflow (Figure 6-7, Figure 6-8) that takes the room morphology and the side lengths as initial inputs. It then requests diagonals if needed to triangulate the polygon. Several versions of this interactive workflow were developed, RS4 (Figure 6-20), RS5 (Figure 6-21) and RS Strict (Figure 6-22), and implemented in a Grasshopper plugin called RoomSurveyor. The plugin was integrated with the ShapeDiver configurator platform to enable the possibility of developing interactive survey-to-production configurators and several example applications were produced to demonstrate the use of the plugin in practice. To validate the envisioned low-key survey workflow two experiments were conducted: a usability testing with expert and non-expert instance-designers, an experimental performance test with random data to profile the behavior of the algorithm in wider range of cases. The usability experiment clearly demonstrated the validity of the approach with non-expert instance-designers achieving on average better results than experts. Although the results were successful there was one case of an instance-designer who was not capable of sketching the room morphology. The limited size of the experiment does not allow conclusions on the incidence of users that might face similar difficulties.

The experimental tests with random data have demonstrated some intuitions regarding the properties of the algorithms and their predicted behavior in rooms with more sides. It was concluded that RS5 on average performs best in rooms with at most 3 non-orthogonal corners, while RSS is more precise at the cost of at least requesting more diagonals. In general, the algorithms were found to be more precise than the best performant user in the user testing experiment. These results fundament the conclusion that non-expert users can survey spaces with sufficient precision for concept design stages with the proposed low-key workflow.

The last step of the current thesis was to test if architects can design cost-effective digitally fabricated system based on the proposed generic grammar, criteria, and survey-to-production workflow. This validation was achieved through the experiment described in Testing System, an international online workshop where each participating student developed their own partition wall system.

Future work

Although the results of the tests have demonstrated that the Room Survey algorithm is sufficiently precise in practical use cases there are opportunities for improvement as shown by the results of the experimental tests. Several possible improvements have been identified which can lead to an increase in the precision of the survey process for an even larger number of cases, particularly with the RSS algorithmic approach. Different sorting heuristics were also identified which could lead to significantly reduce the number of requested diagonals for rooms with higher number of sides.

On a higher level, low-key methods such as the one developed here are difficult to extend to the third dimension, as even handling a simple cuboid can require many diagonals. As the adoption of LIDAR sensors in mobile platforms increases and their accuracy and range improve, together with better reconstruction algorithms and increasing computational power, the relevance and adoption of these methods will increase. Currently, besides the limitations in automated Scan-to-BIM, there are also limitations in the use of these sensors on the web and a lack of configurator platforms that can leverage these types of sensors from mobile phones.

Recent advances in the integration of AI with photogrammetry also constitute promising alternative approaches to the collection of building surveys by generic users. The challenges remain the computational cost of training and running those systems as open-source alternatives and the difficulty to integrate them with computational design tools.

There are still many opportunities for improvement of customizable and disassemble-able partition wall systems with digital fabrication regarding the identified criteria. Future work should concentrate on eliminating dependencies between the insulation infill and the connectors while also focusing on increasing the functional independence of the structure and the panels of the wall systems. Removing the gap between component-to-component structure could directly contribute to reduce the number of components to assemble onsite. Yet, this should be achieved without compromising the interface tolerance dimensional control on all interfaces.

Regarding the workflow, the findings described in Testing System suggest that developing or identifying specific tools to reduce the complexity of designing complex assemblies with integrated joints could make the process more accessible.

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ANNEXES

ANNEX A – Interview with António Carlos Fernandes Rodrigues

António Carlos Fernando Rodrigues is the CEO of Grupo Casais. Grupo Casais is a large construction conglomerate with headquarters in Braga and is present in several countries around the world. Besides construction, its activities include industrial carpentry, material construction distribution and sale, real-estate, and others.

The interview was conducted by the author on February 2nd, 2018 on Grupo Casais headquarters in Braga.

1) A reabilitação tem ganho uma relevância crescente no panorama nacional. Quais são as maiores dificuldades com que os engenheiros se deparam nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação?

A.C: No caso da reabilitação, há que ajustar muitas das partes do trabalho localmente, e acho que a maior parte das equipas não estão preparadas, e começa logo pelo próprio dono da obra. Eu vejo hoje em dia muita insatisfação com o cumprimento dos prazos e acho que é a falta de reconhecimento que a obra de reabilitação é uma obra que requer esse trabalho em obra. E a rigidez contratual da forma como se fazem os projetos, como se fazem a inserção de fiscalizações, e depois a própria rigidez contratual da obra faz com que essa flexibilidade necessária em obra para fazer o ajustamento nem até do ponto administrativo existe, ou seja, mesmo que tenhamos as competências para em obra fazermos as interações e ajustes esbarramos muitas vezes em processos administrativos porque o contrato obriga a colocar um A ou B, ou seja isto é incompatível com a necessidade, já que às vezes são obras pequenas, de fazer alteração. Se numa obra normal quando existe uma dúvida isto tem um impacto maior, numa obra de reabilitação são muitas, mas pequenas e que requerem uma reação rápida, da parte dos técnicos e do cliente. Da parte dos técnicos é preciso estarem preparados, e começam agora a estar mais preparados, têm mais formação, mas começa mais pelo dono da obra, o dono da obra tem que adotar um modelo contratual diferente e mais flexível, e os próprios projetistas também têm que aceitar no fundo um modelo, que se calhar até nem têm que entrar tanto no detalhe numa fase de projeto, têm é que deixar as ferramentas para depois em obra fazer o ajuste.

F.B.: O próprio projeto de reabilitação, tendo em conta os tipos de levantamentos que se fazem e a informação que existe na fase inicial do projeto, provavelmente encontram muita coisa em obra que não seria possível prever no projeto?

A.C.: Sim, há-de haver sempre muita coisa que vai estar escondida, que só quando se fizer o trabalho, ou seja, não vale a pena o investimento quase comum, chega-se a um determinado patamar a otimização em tempo investido já não é muita e as surpresas vão estar lá na mesma.

F.B.: Claro, então dirias a esse nível um modelo que integrasse o empreiteiro e o arquiteto, faria sentido?

A.C.: Faz sentido. Muito mais sentido.

F.B.: Eventualmente, até o arquiteto, o cliente, e o empreiteiro.

A.C.: Sim, sim.

2) Alguns autores sugerem que a tendência de crescimento da reabilitação em detrimento da construção nova se mantenha, levando a que Portugal se aproxime da média europeia. Partilham desta opinião?

A.C.: Sim partilho desta opinião. Já não temos um crescimento da população. Seria um desperdício se do ponto de vista administrativo se permitisse fazer construção nova quando temos já tanto património edificado em relação à população existente. E depois também estamos agora um bocadinho com a dinâmica das cidades, as pessoas gostam de viver na cidade, mais que construir na periferia, enquanto houver saldo de ocupação na cidade, e isso vê-se com os exemplos de Porto e Lisboa, que ainda há muita coisa por reabilitar.

F:B.: Voltando um pouco à questão anterior, nela referiu que são muitas obras muito pequenas, isto também é um problema do ponto de vista da organização, do ponto de vista de mão-de-obra?...

A.C.: Sim, agora bateu um pouco no ponto crítico que é a questão de falta de recursos humanos, tendo acabado também a mão-de-obra barata, por isso estamos condenados a ter que encontrar processos industrializados e processos mais produtivos.

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil standardização, necessitando além disso de mais mão-de-obra do que a construção nova. Tal parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

A.C.: Eu acho que a tecnologia é que vai permitir isso neste tipo de projeto, se conseguirmos encontrar modelos digitais que permitam de uma forma muito simples fazer rapidamente a tradução do que se encontra na obra para o meio de produção, no fundo baixamos o custo da prototipagem, ou seja, deixa de ser protótipo e passa a ser um mero input como outro qualquer e tanto custa fabricar standard como fora de medida. O que se chama de reabilitação é esse ajustamento à realidade local, mas se isso fizer parte do processo passa a ser normal. Este modelo de digitalização vai trazer alguma economia para o processo.

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se continuam a utilizar componentes sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

A.C.: A indústria tem que proporcionar soluções que respondam a esse tipo de características de sistemas, e o próprio treino de quem executa. Nós continuamos a ter muito o hábito do tijolo, do pladur, etc., enquanto nos países no norte da europa já se utiliza mais as madeiras, os CLT’s, etc., eles têm indústria, também não têm tijolo, por isso acabam por ter outro incentivo para utilizar a madeira, e a mão-de-obra de quem executa já está mais treinada para executar com esse tipo de soluções. Por isso é que eu em Portugal o desafio é a adaptação, é a formação, a informação, e ainda não estamos a fazer muito em formação para utilizarmos outros tipos de sistemas que não os tradicionais, e a indústria para começarmos a produzir outros tipos de sistemas ainda tem que se desenvolver.

F.B.: Isto não poderá passar por outra coisa.... o que tiramos da obra só tem valor quando podermos tirar da obra e recolocar noutro sítio?

A.C.: Sim, por exemplo, quando falo na madeira, esta é tida como solução sustentável porque se pode regenerar ou reflorestar e dependendo do tipo de elementos também se consegue reaproveitar. Isso está muito na agenda na europa, a utilização de sistemas com madeira em particular, porque permitem essa reutilização. Quando falamos em tijolo, estamos a falar depois dos RCD (Resíduos de Construção e Demolição) que quando muito vão para inertes, mesmo a valorização potencial de uma parede reciclada, tem valor muito baixo porque transformamos uma parede em agregado.

F.B.: Claro, na verdade é um “*down cycling*”...

A.C.: E mesmo esse agregado acaba por não ter saída no mercado. Nós já tivemos esse negócio. E o agregado natural não é como na Holanda onde não há pedra para explorar, aqui não falta, temos muitas pedreiras, e o agregado natural aqui acaba por ser mais barato.

5) Considera que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

A.C.: Sim, até porque o ciclo de utilização é diferente, podemos ter um edifício que dura, e a reabilitação é exemplo disso, são muitas das vezes edifícios que sofrem apenas uma remodelação de interior que já lá estão há cem anos e vão continuar, mas o que muda é o interior porque as modas, as necessidades, a utilização essa altera-se com um ciclo muito mais rápido. Por isso deve ser feita essa separação entre o ciclo de vida e o tipo de soluções utilizados para o invólucro, e depois o interior, claramente são diferentes.

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o

desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concorda com essa a afirmação?

A.C.: Sim, a digitalização como já falámos anteriormente, permite fazer aqui o elo de ligação, ou seja, o modelo passa a ser algo que já está ligado à máquina que produz, ajustando um deles um está informado o outro também está informado, por isso encurtamos aqui o ciclo. Se olharmos para o método tradicional, que ainda hoje acontece, alguém tem que entrar num departamento comercial, orçamenta, vai de volta, itera, chega um preço, só depois vai para o CNC, programa, tudo isto estando integrado...

F.B.: Pois e permitiria o que falava há pouco, ter um desenho em projeto mais simples, na medida em que se dedica menos tempo a desenhar o pormenor da solução, simplesmente se especificou o sistema, que é depois ajustado à realidade na obra. Verifica-se que na obra é mais pequeno e é possível ajustar os parâmetros sem ter que redesenhar....

A.C.: Sim, mesmo na forma de chegar a um custeio da solução. Eu recordo-me que quando há vinte anos fazíamos um cálculo tínhamos que deixar o computador a noite toda para chegar a uma solução. Agora não, a computação é tão rápida que conseguimos colocar mais informação, mais dados, eu quase que diria que estamos muito perto de fazer o projeto e o orçamento tudo ao mesmo tempo...

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

A.C.: Tem de haver algum standard para se conseguir tirar proveito do treino e da adaptação da mão-de-obra, porque já vi bons sistemas, mas o problema é a barreira à entrada, as pessoas começarem a utilizar, verem o benefício e depois através da repetição verem que é mais vantajoso. Agora essa barreira de entrada é tirar as pessoas de um processo para o outro, esse acho que é um dos maiores desafios.

F.B.: Mas através da simplificação do processo construtivo seria um caminho?

Resposta: sim, eu acho que cada vez mais hoje em dia, com estas soluções em conseguir fazer-se tudo em 3D, BIM, etc., na verdade estamo-nos a aproximar de uma forma de transmissão de conhecimento mais intuitiva do que aquela que como engenheiros e arquitetos aprendemos, que é fazer desenhos em 2D que só engenheiros e arquitetos interpretam ...

F.B.: É verdade, a forma como se comunica com as pessoas é determinante... por exemplo, o IKEA é um bom exemplo de uma forma de comunicar, utiliza desenhos tridimensionais representados em 2D mas muito mais fáceis de interpretar do que plantas cortes e alçados...

8) Os sistemas de divisórias desmontáveis são considerados à-priori mais flexíveis. No entanto, que critérios devem ser tidos em conta para o desenvolvimento de um sistema construtivo de divisórias desmontáveis para que ele seja realmente flexível?

A.C.: Eu acho que a questão volta ao processo de desenho inicial, porque por exemplo, quando alguém encomenda uma cozinha, e mesmo tendo o arquiteto desenhado, chega o fornecedor e diz:" -Não, vai ter que ajustar são mais 10cm deste lado..." Porque no fundo ele faz uma adaptação aos módulos, ele já tem aquilo modelado, e faz essa modelação. Ou seja, o encontrar uma métrica, uma modularidade no sistema que permita uma personalização tipo "Lego".

F.B.: Haver um equilíbrio entre a personalização e a modularidade para ter alguma eficácia industrial, e a cozinha é um bom exemplo.

9) Os requisitos regulamentares para uma parede divisória são relativamente baixos quando esta compartimenta espaços interiores. A ETAG03 define os requisitos de estabilidade, mas não estão definidas na regulamentação nacional exigências especificas para o comportamento acústico ou térmico. Tendo em conta o objetivo do presente trabalho que critérios de performance devem ser cumpridos pela divisória a desenvolver?

A.C.: Eu acho que essencialmente o acústico e o mecânico, e mesmo o mecânico não sendo uma função estrutural, até para se quisermos olhar para o tempo de vida do invólucro e do interior, se for estrutural já não podemos mexer nela, será muito difícil depois alterar.

Se não for estrutural, que eu acho que deve ser o caso, tem de ter uma resistência mecânica.

F.B.: O ETAG?? Define 3 testes: O primeiro é atirar um saco de 50kg que está pendurado por um cabo contra uma parede, é um corpo mole, está cheio de areia. O segundo é uma bola de aço de 1Kg que é lançada contra a parede. Com isto quer-se verificar o dano que é causado à parede com a bola. E o terceiro consiste em montar uma prateleira a uma determinada cota e depois colocar um peso na ponta da prateleira, uma carga, e verificar qual é a deformação da parede. Isto são uns testes mecânicos da ETAG.

Portanto, a nível acústico, não está definido nada, nem na legislação, não existe referência nenhuma, também não existe nada a nível térmico, mas estamos a falar da compartimentação de espaços interiores, e há a questão do fogo....

A.C.: No interior, há a questão do contributo para a massa para a inércia total...

F.B: A inércia térmica, portanto...

A.C.: A quem diga que ter paredes de pladur é o mesmo que não ter nada, porque não contribui para a inércia térmica do espaço. Num clima como o nosso ajuda se houver alguma inércia, caso contrário isso tem que ser depois compensado com ar-condicionado que é aquilo que reage mais rapidamente.

10) O custo de um sistema ou componente construtivo é fundamental para determinar a sua viabilidade, no entanto sendo este um sistema desmontável devem ser considerados outros custos? Que tipo de custos?

A.C.: Estás a falar numa perspetiva global? Numa fase de desenvolvimento ou numa fase de execução deste tipo de trabalhos?

F.B.: Na execução deste tipo de trabalho eu vejo dois tipos de custos. Há o custo da produção propriamente dita, os materiais, etc., o transporte e a entrega ao cliente. Neste caso não faz sentido considerar a mão-de-obra a não ser na questão do tempo – saber se de facto demora mais ou menos do que um processo comparável – mas não faz sentido incluir o custo da mão de obra porque sendo à partida um utilizador a montar esse custo não existe ou na verdade não é contabilizado, que é um bocado o que acontece com o IKEA. Agora, poderá haver outros custos. Se o sistema é desmontável e o utilizo para reorganizar o meu espaço há porventura um custo de alteração, que poderá ou não fazer sentido considerar. Depois há o custo da manutenção, que é preciso saber se é mais ou menos frequente que os outros sistemas.

Todos os outros sistemas precisam de manutenção, portanto poderia até considerar-se que são equiparáveis.

A.C.: Eu não identifico nenhum acréscimo de custo, ou seja, uma manutenção não há-de ser diferente de uma solução tradicional, no fundo, o ter que fazer a solução propriamente dita ou industrializável isso está no custo da própria produção, como está também na produção do tijolo, mais mão-de-obra para montar, ou seja eu acredito que até um efeito de escala numa produção industrial faz com que haja uma redução de custo.

F.B. Sim, é um facto. Mas até isso, do ponto de vista do contexto em que estamos a desenvolver este sistema, é relativamente problemático porque estou a utilizar ferramentas relativamente "informais". É uma CNC, é certo, mas é uma CNC num contexto universitário e há muitas coisas que se estão a fazer que podem ser otimizadas utilizando outro tipo de máquinas que são muito mais rápidas ou até CNC que são muito mais rápidas do que as que tenho acesso. Portanto é sempre limitado o tipo de custo a que vamos chegar. Não é um custo de mercado certamente porque uma coisa é o que o tempo de máquina custa para estudantes outra coisa é o que uma máquina numa produção custa. Portanto há todas essas limitações. Depois há ainda a questão dos materiais, o valor a que eu os consigo adquirir não é o mesmo que uma indústria consegue a partir do momento em que a produção adquire uma escala.

A.C.: Mas olhando numa perspetiva de velocidade de cruzeiro, só tende a ter um benefício em relação à solução tradicional. Se além disso olhares para o ciclo de vida, tens aí outro benefício, o produto da desmontagem deixa de ser um residio para ser um material reutilizável. E ainda a questão da mão-de-obra, que eu parto do princípio de que tudo que sejam sistemas montáveis que acabam por ser mais produtivos e mais baratos em termos da componente da mão-de-obra.

Lista de critérios.

A.C.: Acho que os parâmetros estão bem. Tem é que se fazer uma análise das soluções tradicionais para depois fazer uma comparação. Mas acho que são critérios bons para acompanhar o desenvolvimento, mas há-de chegar uma altura em que há "tradeoffs", ou seja, para melhorar um critério terá que se abdicar de outro.

ANNEX B – Interview with Brimet Silva

Brimet Silva is a Portuguese architect and designer, co-founder and CEO of DigitaLab, a creative laboratory for research oriented towards advanced digital technologies. He is an authorized rhino trainer by McNeel Europe, and he is Co-founder and director of Rhino3Dportugal. The interview was conducted on May 16th, 2018 at DigitaLab offices in Oliva Factory, São João da Madeira.

11) A construção personalizada em série (ou Mass Customized Construction) é um paradigma que vêm sendo discutido há quase 20 anos. No entanto, as suas implementações na prática são ainda muito limitadas do ponto de vista da liberdade (escolhas, desenho, configurações) que é posta nas mãos dos clientes. Tendo em conta a tua experiência no desenvolvimento de sistemas design-to-production para arquitetura, quais são as razões/dificuldades que têm limitado a adoção deste paradigma na prática?

B.S.: Falas de arquitectura, não é?

F.B.: Sobretudo de arquitectura, mas também dos componentes para a arquitetura...

B.S. Isso para nós é absolutamente impressionante. Eu acho que te posso dar aqui três ou quatro exemplos. Dois ou três de arquitetura e um de design, e são muito curiosos. Vou começar pelo GenCork que vai mais ou encontro daquilo que estás a trabalhar.

Repara que o nosso bestseller é generativo. Eu fui pressionado pela Sofalca, pressionado no bom sentido, como estratégia de ter algo modular, que se repete, e isso obrigou-nos a desenvolver o conceito de generativo à-priori ou à-posteriori. O que é que isto quer dizer? À-priori é quando é feito pelo programador, é feito pela DigitaLab, à-posteriori é quando é feito pelo cliente. O que é que isto quer dizer? Nós tínhamos que ter uma cota de 30 a 40% de padrões que iriam ser generativos sim, para se manterem fiéis à marca, mas à-posterior, significa que o cliente poderia rodar, ampliar, etc, poderia customizar, mas continuava a ser generativo no verdadeiro sentido da palavra. Porque as pessoas falam do generativo como uma coisa muito abstrata, mas para mim o generativo é uma coisa básica que é tu conseguires criar alguma coisa, e o design generativo é um processo de criação. Vai daí, nós gostamos muito de ligar a parte computacional, e a verdade é que nós tivemos muita sorte com o GenCork porque nós somos muito fiéis, porque tu tens o que é personalizado por nós à-priori, e digo-te é o nosso bestseller, as pessoas dão-nos a parede e nós customizamos - aberturas, rasgos, etc. -, simulamos, enviamos, e eles dizem “perfeito pode avançar”. E depois temos os generativos à-posteriori...

F.B. Sim, eu por acaso estou curioso com isso. Esse [generativo à-posterior] é o conceito de customização em massa, mas não existe um site onde possas ir e customizar...

B.S.: Mas o generativo à-posteriori não...não há um site, ou um texto que diga o que é o generativo à-posteriori, nós é que sentimos a necessidade de criar um generativo à-posteriori. É quase tu deixares a parte de execução e produção indeterminada...

F.B. O desenho, a configuração...

B.S.:... a configuração final, não na totalidade, imaginemos que tu tens um padrão por exemplo o Vector Fields, e tu deixas uma linhas de combinação em que o cliente chega e diz “Ok, mas agora eu quero fazer à minha maneira, usando este jogo, esta peça, mas quero...”. Ele está a personalizar!

F.B.: Exatamente, isso é que é customização em massa.

B.S.:...isso é que é customização em massa. Agora, voltando um pouco à história da customização, ouvi uma conferência brutal do Gramazio Kohler, que tu deves ter visto também, que eles falavam da customização de uma mesa com um telemóvel.

F.B. Sim, eu conheço...

B.S.: É um clássico, não é?...que falhou! Foi um fiasco!

F.B.: Também era um bocado louca a mesa que era gerada ...

B.S.: Mas tens outros exemplos, sobretudo no mobiliário, que nunca resultou com muita pena minha. E isso obriga-nos a pensar o que é que pode ser a customização. A nível do GenCork posso dizer que a customização é um sucesso. Existe.

F.B.: Mas feita por vocês, não é?

B.S.: Mas feita por nós. Ou seja, estamos a dizer que não é uma plataforma online, é um WebGL que está a customizar e controlar. Se tu perguntas, achas que isso é plausível no futuro. Eu acho que é plausível no futuro, a curto prazo não me parece, mas a longo prazo pode ser possível. Essa lógica de co-criação, em que o utilizador ou o cliente fazem parte do processo, eu acho que é possível a longo prazo, mas estamos longe disso. Porque não é a customização da Adidas, como dizias, em que pões uma cor, eu acho que a ideia é genial, mas...e tu tens essa experiência, os prazos são tão apertados que a ideia da customização..., ou tu tens a sorte de ter um cliente que te diz "OK, vou usar software e vou customizar" mas ...nunca resultou. Eu lembro-me de um projeto de mobiliário que tinha essa lógica. Arrancou com uma força desalmada e já está a morrer aos poucos. Eles acabam por perceber que vocês querem a mesa de 70x100cm, ou 100x100cm, ou 70x150cm e não se querem estar a chatear para estar a customizar mais ou menos um centímetro. Ou tu tens um sistema tão bem desenhado que tu mudas um parâmetro e ele automaticamente te redesenha, ou então tu tens uma customização limitada, onde os parâmetros já estão limitados à priori: Cor, acabamento, etc. Aí entra outra experiência que estamos a ter agora. Estamos a desenvolver uma linha de vidros generativo com uma empresa da Marinha Grande. E é customizavel? É, mas o molde não é customizavel. O que é que tu podes customizar? Podes customizar intensidade de luz, óbvio – é só controlar a lâmpada, acabamento – se é texturado ou não, se é com cor, mas mesmo aí nós fomos pressionados pela indústria dizendo "Não, vocês não vão abrir o espectro. Vocês têm que escolher seis cores e o cliente escolhe destas seis cores". Ou seja, mesmo essa customização que tem que existir, acredito que tem que existir, mas com limitação. Que é exatamente o que acontece no software que tens online, os parâmetros que estão controlados, tens mínimos e máximos. Tens que balizar. Se não balizares o software entra em colapso.

F.B.: Sim, mas mesmo que não entre é uma questão de qualidade do teu controlo sobre o projeto...

B.S.: Fora daí já não é o teu projeto. Já estás a levar o projeto para um patamar extraordinário, no sentido de fora do normal ou ordinário. Acho que isso é muito curioso perceber, nós na DigitaLab estamos a trabalhar com essa ideia da customização levada ao extremo. Nós começamos com cortiça, mas que toca agora na arquitetura é o que mais te interessa, nós estamos com três materiais relacionados com arquitetura: cortiça, chapas metálicas e betão leve.

F.B.: Reforçado com fibras?

B.S.: Sobretudo para pavimentos e revestimentos. Todos eles vão ter um ADN muito perto da GenCork. E com casos de estudo. Nós estamos a conseguir implementar estas lógicas diretamente na arquitetura.

F.B. No Betão estás a trabalhar com quem, com a AMOP?

B.S.: Sim, com a AMOP. Nós começamos a trabalhar com a AMOP há uns sete anos atrás. E na altura, acho que eles tinham alguns problemas de valorização. São excelentes profissionais, têm um know-how muito forte, mas falta-lhes alguma estratégia.

B.S.: ...sobretudo a ideia de aplicação. Nós começamos a trabalhar com o GenCork para interiores. Nos moldes que estamos a fazer para exteriores já estamos a usar a cortiça com padrões generativos, já estamos a assumir que a cortiça pode estar no exterior com os nossos padrões.

E a ideia de customização, se tu perguntares “Imaginemos que agora vocês lançam o vosso projeto de um módulo de habitação modular”. Podes dizer que isto não é nada de novo, claro que não. Habitação modular já não é novidade, é uma mesa, um produto. E da mesma maneira que não há só uma mesa no mundo, só um design de uma mesa no mundo, não há apenas um tipo de cadeira, um tipo de sofá, o que aconteceu é que as marcas que os arquitetos têm podem começar a ter um produto, cada atelier pode ter o seu produto. Então se um designer pode vender uma mesa porque é que não posso vender uma casa modular? E porque é que a minha casa modular há-de ser melhor do que a tua? O que não faltam aí são resmas de casas modulares. A casa modular já não é uma novidade, a novidade é o tipo de valorização que podes fazer numa casa modular. Da mesma maneira que os Eames começaram a usar o plástico no design, na altura era uma novidade, e agora a quantidade de cadeiras...aliás nós estamos sentados nas cadeiras dos Form us with Love que é de plástico reciclado do IKEA. Então tu começas a perceber que já não é o que é que estás a fazer, mas como é que estás a fazer. O que é que eu posso acrescentar, que tipo de vivência que eu posso acrescentar numa habitação modular. E isso é muito importante porque a habitação modular já te obriga a customizar, a nível de escalas, de intersecções, se é um T1, um T2, e tu podes customizar isso, que tipo de acabamentos. Se calhar nessa lógica é muito mais fácil trabalhares a arquitetura enquanto produto. E a arquitetura enquanto produto depende da escala. Quando recuas, SMLXL, dificilmente consegues customizar o XL...

F.B.: É por natureza customizado, ocorre tão poucas vezes que não dá...

B.S.: Mas tu podes customizar o S. Até o M com alguma sorte podes. Mas se nós conseguirmos customizar o S, a nível da forma, a nível do conteúdo, a nível da organização espacial, a nível da matéria, isso pode ser porreiro. Imagina que o cliente diz “Ok Brimet! Eu quero o vosso módulo, mas com interior em madeira, mas o revestimento quero com AMOP e não quero com o GenCork.” Pode, claro que sim, está tudo parametrizado. Entendes? Eu acredito que estamos a caminhar tranquilamente [para isso], porque já o estamos a fazer. A grande questão aqui é quem faz essa customização. É online? É offline? O online acho que estamos longe.

F.B.: Alias, porque há questões muito complicadas. Ou seja, o que estás a descrever, essas possibilidades de customização são essencialmente o trabalho do arquiteto. Porque a partir do momento que alteras sistemas construtivos, tens que resolver questões mais complexas, terias que ter um modelo computacional muito mais sofisticado. E eu acho que esse é um passo que até agora ninguém deu. Substituir o trabalho do arquiteto, mesmo, isso ainda ninguém substituiu, nem acho que seja possível a curto prazo.

B.S.: ...nós estamos a fazer a nossa monografia. Tu dizes “fazer uma monografia com 5 anos, isto é ridículo”. Mas nós sentimos essa necessidade por causa da mudança de escala, nós queremos fechar um ciclo e começar o outro. Nós queremos fazer a nossa monografia não para dizer que somos prematuros, mas porque sentimos que o atelier estava a mudar. E tu queres fechar um ciclo para abrir outro, para dizer “nós somos a DigitaLab daqui a aqui, daqui para frente somos uma DigitaLab diferente”. E uma das coisas que me apercebi, quando estava a pensar a monografia e na proteção do arquiteto nesta gestão. Tu começas a perceber que nós estamos “in between”, e o tema central é mesmo esse. Nós somos muito digitais no discurso, mas somos muito analógicos ao mesmo tempo. E somos muito “underdog”, porque estamos a fazer muita coisa que a maior parte das pessoas nem se apercebe, e a densidade das coisas, não publicamos nem comunicamos nem um terço.

Falo disto para te dizer o seguinte, eu sou muito tradicional, em que sentido, nós usamos processos digitais, mas não damos liberdade ao cliente. Ele faz parte do sistema, faz parte do processo, mas o trabalho computacional é muito racional. Ou seja, a ideia do “random”, podemos usar para “form-finding” mas mesmo aí tu estás a balizar muito bem os “inputs” e o “range”. A verdade é que o trabalho é super humano. O código, o script é das coisas mais humanas que existem quando é gerado por um humano. É um desafio muito grande da tua inteligência. Como é que tu consegues controlar o output baseado nos teus inputs. Seja um input estrutural, seja um input baseado no local, tudo isso é muito forte. Se me perguntares – “Brimet, tu vês daqui – como acontece com os Nervous Systems do MIT que têm o know-how que nós não temos – vês daqui a algum tempo as pessoas a personalizarem habitação ou tudo digitalmente?” Eu acredito que a coisa possa existir, mas como tu disseste e bem, se analisares a fundo são pouquíssimos os casos de sucesso. Porque é que isso acontece? Porque por um lado ainda não resolvemos dar esse pulo, porque precisamos de ter isto: convidar o cliente, mostrar o nosso script, em conversação...

F.B.: ...e depois otimizar tudo.

B.S.: ...isto para nós vale ouro.

F.B.: O que estás a dizer é que os parâmetros da análise não são performativos, ou seja, não é uma sequência de parâmetros que são aplicados mecanicamente e dão um resultado. São avaliações emotivas com outro tipo de análise...

B.S.: Embora a parte performativa faça parte do processo. Se tu fazes uma análise, uma otimização do teu processo ou do teu output, isso funciona como um ponto: “Não, mas eu tive a fazer uma análise solar ao espaço e teoricamente se nós tivermos a janela a esta distância com uma varanda X a quantidade de luz que nós conseguimos é muito maior do que ter ali, isso é óbvio. Então vamos fazer um cálculo se estiver a meio...” Isto pode funcionar como argumento, no verdadeiro sentido computacional, como parâmetro para tu dizeres ao cliente.

F.B.:...olhe assim é melhor, porque... Mas é curioso referires isso porque há um tipo de argumento que um cliente nunca rebate, é o argumento técnico. Se dizes “isto é ilegal” ou “isto não é possível”, ele não discute, mas se disseres “isto é feio”, ele vai discutir.

B.S.: Sintetizando a minha resposta à tua pergunta. Nós usámos a customização? Sim, como customização interna onde as relações humanas são muito importantes, entre o cliente e o criativo. Se tu me perguntares sobre o que é customização no nosso “workflow”, existe à-priori e à-posteriori. À-priori é controlado por nós, à-posteriori é controlado pelo cliente, mas mesmo assim nós desenvolvemos o à-posteriori e ele termina o processo. Por último, numa lógica mais visionária, se é possível criar interfaces online onde essa customização é feita em “real time”, claro que é possível, a tecnologia existe. É contratares o programador e passares as premissas, e os “inputs”, e o “script”. Já existe online, é super fácil de fazer. Agora já há “mainstream”? É preciso andar um bocadinho para chegar a um patamar... repara o seguinte, quantos anos têm o design generativo?

Como hoje o conhecemos, não tem assim muito. Diria 15, 20 anos talvez, se calhar um bocadinho mais.

Ok. Partindo do pressuposto que o BIM começa em 63 com o Sutherland, com o SketchPad, isso é o início da parametrização. Depois houve a descoberta da computerização, toda a gente começou a brincar com o Maya com o MelScript. Depois não aparece só o Grasshopper, aparece o uso da computação, que há muitas coisas feitas em C++, em C#, em VB, em AutoLisp. Depois as pessoas começaram a querem construir estas coisas. A Zaha Hadid esteve anos sem construir nada. Quando eu comecei a trabalhar com design generativo foi há 10 anos. Sabes o que me disseram? Daqui a 10 anos isso vai estar a bombar, vai ser uma coisa surreal. Continua a ser 0,0001! Eu tive em Milão há pouco tempo e falei com o Arturo Tedeschi, o tipo que escreveu o livro..., e tive também com o Ross Lovegrove lá na área de design. E o Ross Lovegrove apaixonado a dizer que adora a nossa geração porque nós temos um conhecimento que ele nunca terá, porque isto de programar e ter uma mente de programador é uma coisa que tem que começar com bastante antecedência. Senão, não consegues usar isso na prática, porque depois há esse período de maturação. O domínio da ferramenta para criar algo. E eles diziam essa coisa muito interessante, o Arturo Tedeschi dizia-me o mesmo. Eu conheci o Arturo Tedeschi no fórum do Grasshopper, quando existiam 200 ou 300 pessoas. Eu tive a sorte de estar no início do Grasshopper, porque não estava em Portugal, estava na Alemanha e tive aulas de Grasshopper, quando ainda não era Grasshopper, era “Explicit History”, com um dos colaboradores da Zaha Hadid que nos disse: “rapazes, vocês vão aprender a programar”. E eu “credo o que é isso?”. Para quem vinha de Coimbra, que era aquela escola que era uma extensão do Porto, uma filial pobre do Porto, para mim foi um soco no estômago. E repara no seguinte, aí foi uma grande mudança, eu demorei 5 anos a perceber como podia por isto em prática seja na indústria seja no .... Obviamente que foi bom ter a parte académica, consegui ter um discurso mais teórico sobre isto, e deu tempo para experimentar. Ou seja, a questão do tempo aqui é muito abstrata, conta-se pelos dedos da mão as pessoas que usam o design generativo de uma forma séria. Que é dizeres, este é o meu processo, e as pessoas viveram o espaço e estão a criar o espaço. É preciso ter um domínio muito grande, e é preciso que as pessoas estejam preparadas para viver isso. Para chegarmos a um mainstream da customização online, vai acontecer, acho que ainda é preciso algum tempo. Não sei como é que está, mas a Adidas, a Nike tem feito várias plataformas, mas depois isso são projetos que foram desaparecendo, porque industrialmente é muito difícil. A nível de arquitetura. Eu estive com o Sou Fujimoto agora em Milão, e foi brutal falar com ele e ele perceber: “ah pois, vocês exploram design generativo. Isso é muito interessante. Nós estamos a tentar implementar isto lá no atelier, porque apareceu-nos um estagiário. Isto realmente tem pano para mangas!”. O que eu senti, no estagiário, é que ele depois tem muita dificuldade em materializar. “Depois é chato” – dizia ele - “temos sempre que contratar a Arup e eles são muito caros (risos). Então acabamos sempre por abdicar.” Depois eles simplificam, porque é muito caro. O miúdo até tem boas ideias, mas depois não consegue levar o projeto até à materialização, porque empanca ou num ângulo ou ... e estar a pagar uma fortuna para contratar a Arup, leva-lhes os honorários todos. Estás a ver? Estamos em 2018! Leva muito tempo.

1) A reabilitação tem ganho uma relevância crescente no panorama nacional.

B.S.: Absolutamente.

F.B.: Já disseste que a reabilitação da pequena casa, do pequeno apartamento não vos interessa.

B.S.: Mas uma coisa muito importante. Se houvesse abertura desse tipo de clientes de experimentar outro tipo de coisas e não virem já com ideias pré-estabelecidas daquilo que querem para o espaço, nós poderíamos equacionar. O que sentimos é que não existe essa abertura...

F.B.: Eu digo-te que por experiência profissional isso acontece por duas razões. Mas a pergunta na verdade é: Quais são as maiores dificuldades com que os engenheiros se deparam nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação? Mas já respondendo ao que estavas a dizer. Na minha experiência pessoal reparo que o facto de o edifício já existir faz com que as pessoas tenham muito mais facilidade em conceber o que é que eles pretendem para o espaço. Por outro lado, tem alguma dificuldade em compreender alterações que vão muito para além daquilo que lá está.

B.S.: Absolutamente, repara no seguinte. Eu lembro-me de dois ateliers que são de certa forma bons exemplos nós na questão da importância do ADN, tirando a Zaha que agora já um pouco mais mainstream, os Future Systems e claramente uma das nossas maiores referências Diller + Scofidio. Eles estiveram anos a experimentar coisas e tentaram ser super fiéis à matriz do gabinete. Quando percebemos que o mercado nacional é baseado na reabilitação, tu tens que tomar decisões. Pode ser um caminho sem volta. Se tu vais na ótica mais tradicional da reabilitação. Das duas uma ou tu tens um arcaboiço e capacidade de discurso e tens budget para convencer as pessoas a experimentar. Mas repara nós somos um atelier pequeno, não temos qualquer força no panorama nacional. Ainda não conquistamos aquela coisa em que os clientes contratam a DigitaLab porque querem um projeto à DigitaLab. Isso aconteceu agora em Braga, mas nós não sentíamos que isso acontecia num projeto de reabilitação. Quando tens uma entrevista e há uma série de pré-conceitos, algo que já está pré-estabelecido – "ah porque vi no Pinterest, ah porque vi no Archdaily, ah porque vi no Designboom, ah porque vi no Dezeen, ah porque vi uma foto do meu colega, de um cliente que era espetacular e quero algo semelhante." Não há sequer abertura para experimentação. E quando tu sabes que na faculdade te explicam que a boa reabilitação é aquela que mexe o menos possível. Aí tu tens que perceber, não é o mundo que está errado, eu é que não me enquadro. Tens que ter a noção clara que aquilo que queres fazer não é possível ser feito na reabilitação, ou se é para ser feito na reabilitação tem que estar reunidas uma série de condicionantes, inclusive económico-financeira, porque aquilo que queres implementar não é barato de fazer. Porque em vez de ser cortado leva um padrão que leva não sei quantas horas de CNC e o cliente não quer gastar esse valor. Ou seja, ou tu levas a coisa para uma componente mais superficial, mais de maquilhagem, mas a nós interessa-nos uma coisa mais de fundo, mais estrutural. Da mesma maneira que tu crias uma gramática da forma para te gerar mobiliário, ou "furnitecture" dentro de um sistema, e isso começa a interessar-nos muito mais. Não há dúvidas que a reabilitação é o futuro a curto prazo, se calhar a longo prazo, concordo plenamente. Agora é perceber o que nos interessa enquanto atelier, aonde nós queremos entrar, em que áreas podemos entrar, e áreas que é quase um caminho de ida sem volta. Tu sabes que se entras na reabilitação, começas a fazer aquela linguagem, não consegues implementar os teus princípios, senão és um demagogo, aquilo que tu dizes não é aquilo que tu fazes. E as pessoas dizem "então andavas ali com um paleio sobre design generativo, e fabricação digital e depois fazes mais do mesmo?" Como é que tu explicas isto? Eu estava a dar-te os exemplos do Diller+Scofidio e dos Future Systems, que agora é só a Amanda Levete, exatamente por causa disto, os gajos demoraram anos a construir seja lá o que for.

F.B.: Mas também fizeram reabilitação. A ponte também é uma reabilitação.

Sem dúvida, a reabilitação está lá. O highline é uma reabilitação, mas todos os princípios que os Diller + Scofidio defendem, encontras no highline e é uma reabilitação, mas vê a escala. Eu posso estar enganado, mas se dessemos um apartamento no centro de Lisboa para o Diller +

Scofidio reabilitar, até podem conseguir porque eles têm nome, podem chegar lá e fazer uma coisa à imagem deles, mas só é possível quando tu tens nome....

Agora a reabilitação tem uma importância vital nas cidades. Se me falares de reabilitação de espaço público, aí interessa-nos porque aí há espaço para tu seres muito coerente. Porque o espaço público não tem que ser todo ele generativo, aí pode ser mais pontual. Aí a atitude pode ser muito mais pontual e muito mais experimental. E isso interessa-nos muito, mais o conceito de espaço publico generativo, o conceito de praça. Nós andámos a ler agora o Jan Gehl, que não tem nada a ver com generativo, mas muito a ver com a maneira como te relacionas com a cidade. E isso interessa-me, essa ideia de usar esses sistemas generativos em espaço urbano paramétrico que se vai reabilitando e regenerando. Se me falares de reabilitação, vemos muito mais a DigitaLab a encaminhar-se nesse sentido do que nos interiores, desses queremos afastar-nos. Mas agora vou dar-te um exemplo de interiores. Nós estamos a fazer agora uns escritórios e usamos uns sistemas generativos para fazer uma série de coisas. Foi tudo feito com scripts. Não deixa de ser reabilitação. Mas houve espaço, houve investimento e houve dinheiro para tu experimentares. E sem aquele compromisso "ei pá, vão dizer que eu sou um péssimo arquiteto. Que não tive sensibilidade em relação ao lugar. Que não tive sensibilidade em relação àquele pilarzinho de pedra." E quando tu não estás confortável com uma área de projeto, afastas-te.

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual...

B.S. : Eu acredito, mas isto é verídico, a boa reabilitação é cirúrgica.

F.B.: ... é por natureza de difícil standardização, porque cada caso é um caso, necessitando além disso de mais mão-de-obra do que a construção nova.

B.S.: Repara no seguinte, desculpa isto é mesmo importante porque é algo que nós vamos falando uns com os outros. Tu vês os nossos colegas a fazer muita reabilitação. E as pessoas estão sempre a perguntar, mas vocês não fazem reabilitação? É tanto trabalho! Porquê é que vocês não fazem reabilitação? Como se fosse a solução para os problemas do atelier. "Ah, não! Vocês têm que começar a fazer reabilitação." E as pessoas não conseguem perceber o que é tu definires o perfil, um ADN do atelier, e seguires esse ADN. E perceber que por vezes tens que deixar de fazer alguns projetos para seguir esse ADN. Imaginemos que vem agora a Vodafone e diz – "Faz um stand da Vodafone", eu digo – "eh pá, mas calma eu posso fazer o stand da Vodafone, mas como é que vai aparecer a Vodafone? vocês vão-me obrigar a pintar tudo de vermelho?" Estás a perceber? "Então, já não quero!". Deixa-me fazer stands de coisas completamente experimentais porque dão-me liberdade....

F.B.: Certo, na sequência do que já comentaste, o carater cirúrgico etc, vem a pergunta que tal parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

B.S.: É tudo uma questão de "boundaries", é tudo uma questão de limites. Se tu trabalhares nos limites, é muito mais complicado. Imagina o ovo, se tu queres trabalhar na gema ou na clara. Acho que o ovo esclarece muito bem. Tu sabes que se trabalhares na gema, tu tens uma vantagem é que a clara deixa a gema flutuar. Se trabalhares a gema é um núcleo, está a boiar na clara, é independente. A relação modular é muito mais livre. Tens que ter em linha de conta que a comunicação com a "boundary" da clara tem que existir, a nível estético ou não estético. Das duas uma, ou há uma relação direta a nível de complementaridade ou há um desafio. Falamos de João Medes Ribeiro, é um tipo que faz reabilitações incríveis. Dentro da lógica minimal, o tipo trabalha muito bem a clara e a gema. O tipo é muito inteligente nesse sentido, pode-te por um módulo técnico, super minimal, que nem é nada de extraordinário, mas que coze, ou pode dar-te um módulo técnico que é todo espelhado, ou então pode sistema construtivo qualquer em que complementa o espaço. Aí acredito que consigas aplicar a componente mais industrial. Agora, se tu trabalhas na "boundary", é muito mais difícil porque métrica será sempre volátil. E não pode ser um volátil de dois metros, tem que ser um volátil de 50 ou 30 cm porque as variações são muito grandes. Seja em parede, seja em mobiliário, seja no que for. É como tu dizes, é tão cirúrgico. Tu vês as cozinhas antigas...

Claro que é compatível, mas tens é que perceber em qual camada é que estás a trabalhar. Se é na gema, ou se é na clara, e se é na clara, se estás a trabalhar nas "boundaries".

F.B: Eu percebo o que estas a dizer e alias as cozinhas são um bom exemplo. São uma coisa completamente customizada. É um produto industrial completamente customizado e adaptado ao contexto, a qualquer sítio onde a queiras colocar, no entanto é modular e industrial.

B.S: Porque é que não há trabalhos nesse sentido de repensar a cozinha do século XXI? Quando estamos as fazer as cozinhas continuam a serem pensadas da mesma maneira que eram pensadas no modernismo. Só mudas os eletrodomésticos....

F.B. : Mas elas tem essa capacidade...nem precisas de fazer muita coisa. Mantendo aquele módulo e trabalhando tudo o resto, elas têm a capacidade de adaptar-se a várias circunstâncias.

B.S. Eu não vejo porque é que não seria possível conjugar a industrialização com a reabilitação. Vou dar-te outro exemplo que acho interessante na própria reabilitação, que é tu teres um pé-direito de 3 ou 3,20m. Há coisa melhor do que saberes que para além do pé direito normal ainda podes usar acima da cota? Imagina que queres desenvolver um apartamento T0. Colocas um módulo central e por cima desse módulo a tua cama, porque a altura permite fazeres isso, porque é que esse módulo não pode vir de fábrica? O Shigeru Ban tem um projeto incrível, não é reabilitação, é um mega open-space com a casa de banho fixa, mas os quartos são módulos com rodas. Aí também se consegue trazer a parte industrial. Depende muito do que estás a trabalhar, qual é a unidade e se funciona em relação direta com a pré-existência ou se funciona no interior da pré-existência.

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se continuam a utilizar componentes sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

B.S.: Tu disseste uma verdade absolutamente irrefutável, que hoje nós estamos a utilizar no que toca a sistemas ou processos, e seja reabilitação ou não, tu usas pladur na mesma, tu usas o mesmo soalho, tu usas o mesmo azulejo, seja reabilitação ou uma casa nova. Como é que eu posso reabilitar o azulejo, por exemplo? Tu sabes que tens aquelas estruturas divisórias que tiras o tabique [estuque] e a estrutura está lá, sobretudo no caso de Lisboa na baixa pombalina. E isso está muito na moda, muitos deles tiram o estuque e deixam a estrutura intacta e reabilitam a madeira.

F.B.: Aquele sistema tem essa capacidade, retirando o estuque podes usá-lo como base para outra coisa.

B.S.: Isso é inteligente, mas estamos a falar da baixa pombalina, isso não vai acontecer em...

F.B.: No tijolo aqui ao lado em São João da Madeira...

B.S.: Eu acho que tem a ver um pouco com a investigação que se faz. Há esse trabalho nas madeiras, já não há muito no que toca aos tijolos. Agora isso tem a ver um pouco com a sensibilidade de quem faz. O que é que é sustentabilidade? Se estás a usar um verniz ou um químico para tratar a madeira que não é natural, onde está a tua sustentabilidade? Da mesma maneira que tu estás em Lisboa e vais buscar uma pedra de Itália, qual é a tua pegada? Eu prefiro não carregar essa bandeira da sustentabilidade dessa forma fictícia, para não cometer erros destes...

...depois quanto tu dizes que estás a usar um sistema sustentável no interior, ou que desenvolves um módulo, ou que ele possa ser efetivamente sustentável, isso é muito interessante. Mas tens mais desvantagens que vantagens, a meu ver. Se for efetivamente sustentável, na ideia de material, na ideia de processo, na ideia da montagem, tudo isso for sustentável, permite-te construir e desconstruir, isso parece-me correto e coerente. Mas uma das críticas que eu faço é por experiência própria. Nós já vendemos cortiça para um evento que depois vai para outro e outro. Na terceira mudança o material já perdeu 50% da qualidade estética ou da qualidade técnica, porque já foi muito aparafusado e desaparafusado, ou durante a viagem lascou-se um pouco. Essa coisa de monta e desmonta, é algo que só resulta com os legos.

F.B.: Não é necessariamente assim, mas claro que há um limite da capacidade de desmontagem dos materiais naturais....

B.S.: É exatamente aí que eu queria chegar. É mais complicado, mas isso obriga-te a ir buscar estruturas metálicas que te dão total segurança. E então vem a pergunta qual é a sustentabilidade disso?

F.B.: Mas aí digo-te a mesma coisa, é sustentável na mesma. Se o objetivo for montar e desmontar 100 vezes, obviamente que não vais utilizar madeira. O facto de estares a usar o metal [aço], que também é reciclável...o aço não é necessariamente não sustentável, agora depende da forma como estás a utilizá-lo. Agora, relativamente à questão das divisórias de pladur. Se tu tens uma parede de pladur, a única alternativa para desmontar aquilo é deitar tudo fora, porque não consegues retirar os parafusos. O que isso significa é que aquele metal vai ser utilizado no tempo que estiver naquele espaço e depois vai para a sucata.

B.S.: Isso significa que a sustentabilidade muitas vezes obriga a trabalhar com um misto de materiais. Tem que ser sobretudo um processo inteligente e altamente tectónico, no processo de montagem e desmontagem. Imagina que tens uma divisória e queres abrir um espaço, as estruturas dos stands são muito nesta lógica. É uma estrutura metálica que se monta, desmonta e leva para outro sítio. Há n de marcas que trabalham esse tipo de lógicas, onde o revestimento ora é em mármore, ora é em madeira, ou cortiça. Isso é comum, não é inovador. A questão é a origem daquele metal? Mas tu dizes - "Eu posso ter um comportamento sustentável e saber a origem do metal e garantir que é reciclável" E eu pergunto – Quantas empresas existem em Portugal que estão a reciclar o metal e a usá-lo na indústria? Repara bem. Quando estive a trabalhar com o vidro eu perguntei-lhes – "Vocês estão a usar o vidro reciclado. Eu curtia usar o vidro reciclado.". Eles responderam – "Ih! Não se meta nisso! O que está para aí a dizer! Não lhe dá garantias." Era brutal nós conseguirmos dizer que estamos a conseguir acrescentar valor com vidro reciclado. Estrategicamente, enquanto diretor criativo, curtia dizer que nós estamos a usar processos digitais, mas também estamos a usar vidros que já foram um garrafão, e de repente tínhamos uma lógica circular. Vamos lá fazer disto [o produto em vidro] economia circular. Bem! Eles fizeram tudo para convencer-nos a não usar vidro reciclado. Porque o grau da investigação dentro do vidro reciclado não estava no patamar que permitisse dar propriedades do vidro, ao nível de rachas, falhas e consistência do vidro. Em vez da indústria estar preocupada em depurar o processo até chegar a um patamar próximo ao vidro corrente, ao ponto de as pessoas não se apercebam que é vidro reciclado. Eu perguntei – "O que é que vocês fazem com o vidro reciclado?" – "Vai para os garrafões." Fazem garrafões, aqueles que tem aquela coisa branca a cobrir e não vez o que é. Porque podem ir com todos os defeitos e falhas e não topas. É uma pena! Estamos aqui a perder uma área de negócio. Porque se alguém garantisse, se houvesse uma linha de investigação...E eu falo do vidro e o mesmo dos metais... [5:28]

[07:28] ...e é isso que eu acho interessante, a coisa existir, mas no cerne. Se me dizes que vais usar um metal, eu pergunto-te - conta-me a história do metal.

5) Consideras que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

B.S.: Sabes que a idade dá nos um pouco isso, essa maturidade. E não é só idade é tu perceberes que estás na terra, isto pode parecer um pouco uma seita religiosa, mas começas a perceber o que tu deixas para os teus filhos. Eu tenho sentido isso. E quando tu começas a fazer arquitetura ou design, começas a ficar cada vez mais interessado no ciclo de vida dos materiais.

E tu falaste de uma coisa muito importante, é que efetivamente os ciclos de vida são diferentes. E o que é curioso é tu perceberes não só a origem do material como a possibilidade de tu o reciclares ou mesmo reutilizar. Que é saber, não digo o cliché dos três Rs,...

Vou-te dar outro exemplo. Nós começamos a trabalhar com membranas, a ideia é nossa, mas não fomos nós que desenvolvemos o processo, foi uma amiga nossa. E então eu perguntei – "Mas então e a cortiça de onde é que vem?" Então eu sugeri que em vez de usarmos a cortiça que vem das árvores, começarmos a reciclar a rolha. Da rolha fazemos um fio e do fio fazemos o nosso produto. E ela – "Eh pá, não tinha pensado nisso, isso é interessante." Interessante porquê? A rolha teve aquela utilidade temporária, acabou, morreu, tu pegas, desfazes e utilizas num produto que se calhar vai durar mais 100 anos. Isso é incrível! Interessa-nos cada vez mais perceber isso. O material que eu vou usar, como é que o material vai envelhecer. Tu consegues chegar ao nível... E costumo perguntar. Quem é o louco que vai colocar na lixeira uma chaise-lounge do Corbusier ou uma cadeira de plástico do Eames? Livra-te! Alguém minimamente informado, o plástico pode estar a desfazer, pode ter acabado... Mas tu conseguiste criar uma design ou uma linguagem, que enriqueceu tanto, ganhou tanto valor que o material envelhece e ganha outro estatuto. E quando dizes o material, dizes o betão. Tu falas de uma cadeira e eu falo de um edifício.

F.B.: Tu aí estás a introduzir outra coisa, o facto de ter desenho por si só já aumenta o ciclo de vida.

B.S.: Mas isso também é importante, tu saberes que aquele betão que estás a utilizar, seja sustentável ou não, não o podes reutilizar, mas sabes que ele vai durar anos, e vai envelhecer, e ninguém o vai pintar, o vai cobrir, podem dar-lhe um tratamento. Se houver uma estratégia sustentável e ecológica a médio / longo prazo a coisa ganha uma força totalmente diferente. Então essa ideia de perceberes o ciclo ...mesmo que, por exemplo, utilizaste caixilhos de madeira sabes que daqui a cinco ou dez anos tens que os pintar, mas assumir isso como algo, em vez de sai um alumínio entra outro alumínio. Se tu começas a ter essa preocupação, todo o teu design é muito mais verdadeiro, genuíno e não entramos em demagogias. Que é a ideia que estás a fazer um projeto que é todo ele muito claro, muito sustentável, mas depois vais ver na cozinha que tu desenhas e não fazes a separação do lixo, deixas que o cliente se lembre que tem que fazer a separação do lixo. E eu digo, calma, se tu dizes que vais melhorar o espaço, a construção e os usos, tens que entrar nos hábitos do cliente. Tens que dizer que o próprio arquiteto pensou na maneira como ele vai usar os resíduos. Quando as pessoas abrem aquela porta e está um espaço, não para um, mas para três por alguma razão é. O arquiteto pensou de uma maneira mais abrangente. Da mesma maneira que os japoneses têm o hábito de queimar a madeira, que é para lhe dar aquela capa e mais anos de vida, e agora os nórdicos estão a utilizar, isso é interessante ao saber que ao queimar, dar aquela cor não vais ter que te preocupar com o acabamento porque ela vai envelhecer de uma forma espetacular. Repara que nós voltamos ao início, a maturidade dá-te a ideia de perceber porque é que aquele material é assim na Suíça, e como é que podes tirar real partido dele, e como é que tu projetas a pensar no material, tirando partido das suas propriedades, e como é que tu pensas no passado – que é a sua história, no presente – que é a tua utilização, e no futuro - que é a utilização dos outros ou do seu envelhecimento. Essa ideia de conseguirem implementar o conceito temporal no teu processo de trabalho é espetacular e faz muita diferença. Trabalhar com o tempo interessa-nos. Costumo dizer que somos do atelier que trabalha no tempo e no espaço, não nos interessa trabalhar só no espaço, interessa-nos trabalhar também no tempo. E tu estás também a trabalhar no tempo. Queres que isso seja reconfigurável, queres que isso dure, queres que vocês tirem daqui e coloquem ali. Então tu estás a trabalhar espaço e estás a trabalhar tempo. E quando nós começamos a trabalhar muito mais o espaço e o tempo, e muito mais o espaço para a foto...agora tiras uma foto, mas passado 3 anos já não posso tirar uma foto porque está completamente diferente e está miserável. Fixe é tirares uma foto depois...[14:45]

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concordas com essa afirmação?

B.S.: A parte do processo digital, da fabricação digital, não é?

F.B.: Na verdade, o processo todo de design-to-production...

B.S.: Sem dúvida! Nós costumamos dizer que a grande vantagem da fabricação digital é não termos que entrar em linhas de produção e quantidades industriais, numa lógica teórica é um facto. Se me perguntares se é útil. Costumo dizer que é tudo uma questão de escala. Nós no atelier trabalhamos entre o protótipo e o mockup. Se o protótipo é uma maquete da escala 1:5 ou 1:10 e o mockup à escala 1:1, nós temos que perceber que a fabricação digital é útil para ambos. Da mesma maneira que podes usar a impressão 3D para fazer um modelo, nada te impede de fazer a fachada do mesmo edifício na escala 1:1. [17:40]

[18:30] Eu sou um fã incondicional da fabricação digital. É uma coisa que me dá imenso gozo porque eu estou literalmente a trabalhar a todas as escalas. Eu não preciso de ler um livro ou um artigo para perceber o que é, as vantagens, porque posso simplesmente dizer a minha experiência. E digo-te, concordo plenamente contigo quando dizes que é possível. Com uma CNC de 2x2 ou 3x2m já consegues reabilitar, trabalhar ao nível do interior. Não vou deixar de fazer porque é preciso de quantidades, é uma grande vantagem. E repara que não é só a questão das quantidades, a democratização...eu costumo dizer, nós somos pobres, nós em Portugal somos pobres, os atelieres são pobres, com exceções. Não quer dizer que não possas ganhar dinheiro, mas tu não tens dinheiro para investir...

F.B.:... em investigação

B.S.: ...estás a perceber? Os outros ateliers têm. Vê o departamento de investigação do Herzog, os BIG tem BIG ideas, uma outra empresa só para fazer research. O Gramazio e Kohler tem a faculdade e tem 2 milhões anuais ou bolsas europeias absurdas. E repara que se calhar estamos a passar por uma geração espetacular de criativos. Nos se calhar estamos a passar por uma geração muito boa de arquitetos, designers, etc., mas nós não temos a possibilidade de ter uma CNC com boas dimensões. Nós não temos a possibilidade de ter impressoras de grandes dimensões. Porque não temos condições a nível de espaço e condições económicas para manter. Porque a ideia é que se tu compras uma CNC, tens que ter alguém para dar rotatividade, para dar rendimento à máquina. Não podes dizer que tens ali a tua CNC e que volta e meia queres fazer um ensaio de uma fachada. Não podes dizer a um cliente que nos próximos três dias vais estar no teu laboratório a fazer uns ensaios com moldes. E seria excecional. Porque se tu vais para uma empresa, não só te vão pedir números mínimos, como vão dizer – “O que? Eu vou parar a produção para fazer uma brincadeira que nem sei se vai para a frente!?” Eu não me importo nada de pegar num saco de betão e mexer no cimento, por a minha quantidade de areia, e ir monitorizando, e fazer ensaios. Nem que no final fique tudo estalado. Nós não temos em Portugal o hábito de comunicar o processo em arquitetura. Encontrar plantas num site já é uma sorte. Chama o Fernando Guerra, ou outro para tirar umas fotos bonitas e está feito. Nós perdemos muito, e quando te digo que trabalhamos no in-between... Nós vamos ver uma exposição de arquitetos modernistas e vês esquissos, desenhos, maquetes, estudos processos, ensaios, mockups, devaneios artísticos sobre plantas...perdeu-se tudo.

F.B.: Também por causa de uma questão de tempo...tempo e dinheiro

B.S.: Perfeitamente, o tempo e dinheiro. O que acontece atualmente é como não temos a possibilidade de ter essas facilidades, ou não temos a capacidade de contratar alguém a fazer este tipo de coisas - pegares numa ou duas pessoas e trabalhares só estas lógicas e apresentar o processo - faz com que estejamos a perder uma oportunidade incrível.

Uma oportunidade de momento, o momento perfeito em que isto podia acontecer. Tens o conhecimento...[23:00]

[24:53]...se estamos a perder uma oportunidade de ouro, estamos. Porque o grau de investigação, não só pelo tempo, mas também pelo dinheiro e pela abertura dos industriais para acrescentar valor e fazer coisas muito controladas. Não é só mass production...

F.B.:...mas essa é a lógica que eles conhecem...

B.S.: Se estás a falar de uma cozinha tens que ir para uma carpintaria, que te aceite, que tem uma CNC e te deixe trabalhar naquilo. Eu estava a fazer a critica da cozinha, mas não é fácil customizares uma cozinha porque a tentativa e erro é grande. [25:40]

[26:08] Estive em Milão há pouco...e o vencedor do pavilhão satélite, que é um evento paralelo à feira de Milão, foi um tipo que repensou a cozinha, feita toda numa CNC... e desenvolveu o sistema: mesa, cozinha, armários, tudo feito em CNC. Fui ver, professor universitário... É um investigador que está numa faculdade, se calhar teve acesso a uma CNC... e fez um protótipo. Que desilusão! [27:20]... [27:57] Mas ele conseguiu fazer porque teve as ferramentas. Imagina que estás num projeto e teres as ferramentas de testar e fazer uma cozinha, a sala com um móvel feito à medida, tens dois pilares de pedra e o móvel é feito em CNC...isto é muito rico. O móvel faz parte da estrutura e tu sabes que não vais ver um móvel igual. É uma oportunidade que se está a perder. [28:27]

[37:30]...Eu tenho a sorte de ter CNC disponível, mas nem todos os ateliers tem essa sorte. E essa coisa de tu conseguires ter um laboratório na cave onde podes produzir, maquinar, e testar, é excecional porque pode dar azo à possibilidade de tu criares uma ligação direta com a obra. [38:15]

[42:00] Nós estamos a fazer uma investigação que não vês, não dá para comunicar no Facebook. Mas esta coisa de conseguires ligar o teu workflow quase do script à construção, e tu saberes exatamente o que acontece em cada fase, e dominares cada uma das fases – generativo, performativo, BIM, produção, execução, mockup, obra – tu conseguires dizer que dominas todas ou pelo menos equacionas isso como uma cadeia de processos, é excecional! Que é o grande desafio que nos colocam... Portanto, eu acho que estás no caminho certo.

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

B.S.: No que toca à nossa experiência, todo o mobiliário que estamos a desenvolver nunca é tipo IKEA. No que toca à GenCork, isso também não é assim, tem que ser sempre montado por profissionais. Mas não quer dizer que não conseguisses montar. No nosso caso concreto, obriga a ter um conhecimento prévio. Acho que tem que ser um design muito honesto, no sentido de ser claro e não ter truques. Quando tu dizes que é um produto que tem que ser utilizado, e otimizado, e produzido e assemblado por qualquer pessoa, para além de colocares a fasquia muito alta, estás a que a reflexão da tua parte seja muito detalhada. Não basta desenhares a peça ou o produto, tens que antecipar o processo de montagem. O que é excecional como desafio, mas é muito mais complicado. Tu tens que ter o dobro do esforço, de desenvolver o processo para criação e para assemblagem. O que é que faz com que esta mesa do IKEA seja excecional? É a possibilidade de nós conseguirmos montá-la aqui, com um livro de instruções. Mas isto veio antes. Logo o designer antes de começar a produzir sabia que estas eram as condicionantes. Quando nós desenvolvemos a mesa de desenho para a Viarco, já sabíamos que as pernas tinham que ir fora. A pessoa tinha que montar a mesa em casa. O módulo principal podia ir todo assemblado, mas as pernas tinham que ir separadas. E porque é que isso era importante? A mesa era tão grande que sabíamos que se fosse necessário ir de elevador ou passar numa porta, se fosse inteiro não dava. Tinha que ser como os pianos, entrar por uma janela. Então sabíamos que no projeto todo o desenho tinha que ser pensado com esse conceito.

F.B.: Claro, que é uma coisa que normalmente no projeto de arquitetura não é feito...não se pensa no processo de montagem.

Eu sabia que tinha que usar este “packaging”, ou esta maneira de fazer o “packaging”. Nós tínhamos a dimensão de uma palete, que tínhamos que cumprir. Se estiveres a fazer uma mesa para ti, fazes o que quiseres, mas aqui tínhamos que cumprir a dimensão da palete senão ficava mais caro, as pernas tinham que ser montadas em situ, tinha que ser uma coisa que se mudava em 3 passos. ... O que é que nós usamos? Nós usamos o Grasshopper para fazer o mobiliário. Embora não haja nenhum algoritmo, nenhuma minimal surface, mas nós usamo-lo como uma ferramenta para ir respondendo a um conjunto de questões pertinentes. Criar uma peça e ele rebater-te todos os elementos em verdadeira grandeza para produção. E paralelamente, tu conseguires todos os desenhos técnicos prontos para maquinação, e ter uma ideia clara do sistema de funcionamento e assemblagem. Tu consegues testar a assemblagem no grasshopper usando parâmetros. O meu contributo é precisamente esse, tu começares neste processo, o que é que é fácil montar. Um exemplo é o desgaste do parafuso na madeira, é algo que estivemos uma semana e meia para resolver. Que parafuso é que eu vou usar para não desgastar a madeira. Nós fomos até ao esforço que um ser humano faz a apertar um parafuso. Pensar o design na lógica de "user experience", é como o utilizador usa, monta e desmonta...[1:08:22]

[1:11:10] O grande conselho que te dou é que tens de inverter o processo. Começar a pensar pela experiência do utilizador e só depois é que chegas ao design. Ou então, que é muito mais difícil, é durante o teu processo de criação já teres na mente todas as condicionantes. Ao fazer um risco, já sabes que aquele risco tem implicações. Mas se tens que fazer um script, não tens hipótese, tens que começar pelo limite da embalagem de transporte. E vais desconstruindo o processo até chegares à forma final. Tens que inverter no fundo ou então tens que ter o processo de construção e transporte implícito no teu design.

8) Os sistemas de divisórias desmontáveis são considerados à-priori mais flexíveis. No entanto, que critérios devem ser tidos em conta no desenvolvimento de um sistema construtivo de divisórias desmontáveis para que ele seja realmente flexível?

B.S.: Voltando à questão da gema e da clara, isso é incontornável, porque obriga-te a perceber a questão dos ângulos, sobretudo a parte tectónica, a parte estrutural. Se está a fazer algo que é "skin" ou se estás a fazer algo que é autoportante. E o problema do autoportante tem a ver com se a estrutura é um U, L ou Z, todos esses elementos que te vão condicionar a tua estrutura. E outra coisa muito importante que tens que ver de forma detalhada é o rácio altura / espessura. Quanto mais alta e fina for a estrutura mais insegura ela é. Quase que tu podes criar uma condição técnica. Se tu dizes que a estrutura tem 3m por 4 cm, tens que trabalhar em L, ou tens que trabalhar em U, ou tens que trabalhar em +. Tudo isso obriga-te a perceber muito bem a ideia de proporção entre espessura e altura... Tens mesmo que conhecer muito bem a parte tectónica de todo o processo, como é que a altura e a espessura vão condicionar as diferentes configurações. Tu podes dizer que gostavas de ter algo adelgaçado, muito fino, muito subtil, mas isso mata-te logo à priori a possibilidade de ter uma estrutura linear. Se tiveres uma estrutura linear o embasamento tem que ter um impacto completamente diferente...

F.B.: Sim, mas os exemplos que estás a dar estão relacionados com estruturas desmontáveis mas que não tem uma ligação com a base ou com as paredes.

B.S.: Se for autoportante no caso de não precisar de estar preso...

F.B: Aqui não é bem o caso, porque as divisórias entre compartimentos...uma coisa é ser amovível, outra coisa é ser desmontável. Há ali uma ligeira diferença, o caso que estás a falar é mais amovíveis...

Já falamos sobre ...como é que tu escondes um parafuso, ou como é que ele não existe. Que tipo de material é que estás a usar ao ponto de conseguir camuflar. Se tu dizes que escondes o parafuso, está intimamente ligado com a maneira como a estrutura entra, como material entra na estrutura. Não pode ser de fixação tem que ser de deslizar. A ideia de criares um diagrama a explicar todas as possibilidades rapidamente chegas à conclusão que é desta forma, é quase hierárquico. Se vais assemblando, depois a desconstrução ou desmontagem tem que ser no sentido oposto. Isso é interessante, sobretudo a ideia de encaixe. Estás quase a pensar numa lógica, não digo “bottom-up” mas quase. Porque o “up” é fácil de resolver, o “bottom” é que é tramado. A maneira como resolves o detalhe é que é muito complexa. Quase que tu começas pela tectónica porque resolvendo a tectónica...quantas vezes tu vês um tipo X desenvolve um sistema e depois n pessoas apropriam-se do sistema para ir trabalhando sobre aquele sistema, é igual. O grande desafio é muito mais o sistema do que o mobiliário. Dou-te um exemplo, se o IKEA diz que desenvolve um sistema de encaixe sem parafusos, eles podem fazer uma coleção de mil produtos com aquele encaixe. Difícil não foi desenvolver os produtos, difícil foi desenvolver o encaixe. É aí que tu tens que te focar, sobretudo numa logica muito mais “bottom-up” do que “top-down”. Top-down não vais lá porque o bottom condiciona-te o up. Resolvendo o detalhe tu vais rapidamente evoluir.

F.B.: Sim, é verdade. Eu já tenho essa experiência. Eu estou a desenvolver uma forma de encaixe que permite...porque não há. Porque eu estou a trabalhar com madeira cortiça. E não há nenhuma forma, quer dizer há os japoneses, mas aí tens que ter acesso a todas as direções, tu não consegues ter uma placa que fique completamente lisa que não tenha a visualização do encaixe.

...é um mega tema de doutoramento, porque obriga mesmo a fazer n “joints”, n sistemas de conexão. Tu podes demorar 3 anos a desenvolver um sistema e uma semana a desenvolver um mobiliário...

F.B.:...tu estás a dizer que é bottom-up e eu concordo plenamente. Há uma relação entre os tipos de encaixes e os sistemas construtivos que consegues fazer. Mudando o tipo de encaixe, o tipo de sistemas que consegues fazer são diferentes. E tem sido precisamente isso, eu exploro quais são as possibilidades deste tipo de encaixe gerar sistemas construtivos que atinjam um determinado objetivo.... [1:18:45]

9) Os requisitos regulamentares para uma parede divisória são relativamente baixos quando esta compartimenta espaços interiores. A ETAG03 define os requisitos de estabilidade, mas não estão definidas na regulamentação nacional exigências especificas para o comportamento acústico ou térmico. Tendo em conta o objetivo do presente trabalho que critérios de performance devem ser cumpridos pela divisória a desenvolver?

B.S.: [1:25:25) ... como é que ela se comporta ao nível do impacto? Se absorve, se reflete. Tu sabes que não podes ir a correr e dar um murro numa parede de pladur. Isto é muito comum na arquitetura contemporânea americana, é tudo feito em gesso cartonado e estrutura de madeira, a reabilitação é toda feita nesse sentido. E tu sabes que se deres um muro com muita força aquilo fragmenta-se... Ou seja, ela é estável, ela não vai cair porque está presa no chão e no teto. Mas tu sabes se apanhares um balanço e não houver um travamento na diagonal, quase que consegues rasgar de um lado a outro e levas o isolamento interior contigo. E perceber essa ideia de robustez, em que tu tocas na parede e é oco, é falso, é fake.

F.B.: Questões táteis, questões visuais...

B.S.: Acho que isso pode ser superinteressante, tu trabalhares a nível acústico.

F.B.: Realmente esse é um dos aspetos mais negativos do pladur. Muitas pessoas que não gostam do pladur comentam precisamente esse aspeto - que é oco ao toque. Depois ficam a pensar que tem bichos lá dentro.

B.S.: Que há vida lá dentro!

10) O custo de um sistema ou componente construtivo é fundamental para determinar a sua viabilidade, no entanto sendo este um sistema desmontável devem ser considerados outros custos? Que tipo de custos?

B.S.: Acho que os custos estão relacionados com o que é o propósito...

F.B.: Aqui a questão até nem está bem formulada porque aqui questão a considerar seria: o que é que é comparável? Porque eu já tive essa experiência, e tu tiveste lá e viste, o custo de uma solução em cortiça e que explore as potencialidades estéticas da cortiça, a modelação, a combinação com outros materiais, há-de ser necessariamente mais cara, porque o material é mais caro. Agora quando comparas com outras soluções existentes, há dificuldades de critérios no que estás a comparar, dai a questão do custo. O que é que é importante considerar nesta situação como um custo e o que é que seria um custo aceitável?

B.S.: Da minha experiência tu tens tantas condicionantes. Tu tens um custo de prototipagem, tens custos de produção, mas depois tens todos os custos de otimização. Agora estamos a trabalhar com uma empresa especialista em acústica, outra em tintas, outra em vernizes, tudo isso são custos de otimização que vão muito para além da produção. E depois nós temos custos de marketing e custos de comunicação. Ou seja, eu tinha que te perguntar qual é o fim. Se dizes que é só para fazer investigação não precisas de marketing e comunicação. Mas na verdade tu precisas de 10% para fazer a obra ou o produto e 90% para o comunicar. Atualmente o que gastamos em marketing e comunicação é mais do que gastamos em desenvolvimento. Se fizeres uma feira em Paris, estás a fazer um investimento de 50 mil euros, que é marketing e comunicação da marca, que é mais do dobro do que gastamos em desenvolvimento.

A GenCork ou qualquer outra marca que estamos a desenvolver é um produto de uma mega equipa. São quatro ou cinco empresas para conseguires ter uma marca operacional. A nível do GenCork, os testes de som é uma empresa que faz, os testes de estabilidade, para termos os certificados, é outra empresa que faz. Toda a parte de comunicação é feita por outra empresa. A única coisa que nós efetivamente fazemos lá, na Sofalca, é nos aqui desenvolvemos os padrões e eles fazem a maquinação e a prototipagem, tudo o resto...há outras empresas que são aglutinadas no processo.

ANNEX C – Interview with Joaquim Teixeira

Joaquim Teixeira is an architect and professor at FAUP (Faculty of Architecture of the University of Porto). PhD in architecture at FAUP with the title "Salvaguarda e Valorização do Edificado Habitacional da Cidade Histórica. Metodologia de Intervenção no Sistema Construtivo da Casa Burguesa do Porto (2014)", his research is focused on the subjects related with protection and renovation of built heritage. The interview was conducted on January 18th, 2018 at the Faculty of Architecture in Porto. The interview was interrupted at the end of the 7th question.

J.T.: Eu li as questões e estive a refletir sobre elas. E para refletir sobre elas, escrevi um bocado sobre elas. Todas estas questões que colocas fazem refletir, levantam temas muito interessantes. Não acho isto nada uma perda de tempo, porque isto faz que reflitamos sobre o que temos andado a fazer. Elas levantam alguns temas que eu já tinha pensado mas sem me dedicar muito a eles.

1) A reabilitação tem ganho uma relevância crescente no panorama nacional. Quais são as maiores dificuldades com que os (arquitetos / engenheiros / construtores / indústria) se deparam nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação?

J.T.: Uma parte da minha opinião vai ser ideológica. É inevitável que as dificuldades sejam muito diversas. Eu provavelmente vou falar pela parte dos arquitetos, eventualmente os construtores, não sei se posso dizer grande coisa pela indústria, a não ser relativamente aos malefícios que a indústria nos tem causado e aqui começo já pela parte ideológica. Isso não transparece muito na minha tese de doutoramento, mas foi a partir da investigação do doutoramento que eu comecei a desenvolver uma consciência critica relativamente ao mundo em que vivemos que me deixa com os dois pés atrás. Também foi a leitura dos teóricos que no fundo construíram uma espécie de percurso, de pensamento, à volta do património, designadamente um autor que eu desconhecia do meu curso, que se chama John Ruskin. Que para mim era um visionário, embora fosse um conservador em termos ideológicos. Ideológicos porque ele não era um revolucionário. É muito diferente de um seguidor dele que é o William Morris, que está abertamente associado à esquerda, por reação aos malefícios e às transformações da revolução industrial. Como reflito pouco sobre estes temas não tenho uma fundamentação filosófica. Eu sei que vivemos numa mudança de paradigma, da qual não se conhecem muito bem os contornos. E essa mudança de paradigma assenta necessariamente numa atenção muito maior relativamente ao meio ambiente em que vivemos. E eu quero acreditar que a única maneira de sobrevivermos em condições minimamente decentes é... não sei se há um processo em curso irreversível, mas, não sei se as próximas gerações serão muitas, mas viver como se tem vivido até hoje não sei se será possível. Mas eu quero acreditar que tem de haver uma mudança porque há algo latente a vários níveis, não só sociais, mas ao nível de modelos que herdamos da revolução industrial.

Todos sabemos que a indústria se transformou numa espécie de mecanismo predador. A indústria não está a saber gerir a sua atuação, eu diria que num extremo é quase autofágica. Cada vez mais uma camisola que eu compro tem de durar menos para eu voltar outra vez a comprar, porque não há outra forma de a indústria ser rentável sem ser produzir camisolas em massa. Há um artigo no Público, que li mais ou menos no início do meu doutoramento, que transformou a minha forma de olhar para as coisas, e esse artigo é sobre a lâmpada de Livermore. É uma lâmpada incandescente que está num quartel em Livermore nos Estados Unidos em funcionamento constante há 113 anos. Esse artigo era sobre a primeira...

F.B.: Uma reunião entre vários industriais da indústria das lâmpadas para concertarem a duração das lâmpadas.

J.T.: A obsolescência programada. A seguir foi o nylon. O nylon é um material que foi descoberto que é duma resistência absolutamente incrível. A obsolescência do nylon foi sendo reduzida, ou aumentada depende da perspetiva...

F.B.: E a nível da construção achas que isso existe?

J.T.: A nível informático isso existe, a obsolescência programada está em tudo. As lâmpadas incandescentes consomem imenso, as outras que não consomem custam o triplo, o quadruplo, o quíntuplo de uma lâmpada incandescente. Eu nunca fiz contas, mas...a lâmpada de led não me traz vantagens a mim, mas a uma corporação internacional que está a impor este produto. Eu estou de uma forma um bocado informal a expor o lado ideológico de que falei inicialmente. O que acontece relativamente à construção é que a descartabilidade da construção não é tão fácil como a descartabilidade de uma camisola. Há que ter algum cuidado, embora se continue a construir em massa. O censo de 2011 dá como existentes no nosso país 735000 alojamento vagos para o aluguer. O que é que se faz com isto? Não se conhece verdadeiramente o perfil destes alojamentos, na altura, creio eu, não era fácil determinar se era construção nova ou construção existente, se era existente quantos anos tinha. Sendo certo que, ao que tudo indica, irá haver uma regressão demográfica, a construção [em excesso] vai continuar a aumentar. [14:00]

J.T.: [21:40] Eu estou mais por dentro da construção pré-industrial, dos edifícios antigos da construção tradicional. Temos estado a desenvolver trabalhos sobre a construção do início do século XX que tem demonstrado, uma evidência que já se suspeitava, de uma transformação paulatina dos sistemas construtivos. E posso afirmar com alguma segurança, porque já vamos no segundo ano de amostragem, que essas obras mostram uma coexistência de sistemas e materiais tradicionais com materiais novos. O betão armado é o mais evidente, mas também há alguns metais, designadamente o alumínio, que não fazem parte da construção tradicional. Muito raramente surgem edifícios integralmente construídos com estrutura porticada de betão, mas a grande maioria é de parede de pedra e laje de betão armado. Lajes de betão armado, mas com estruturas primárias e secundárias que permitem espessuras de lajes muito reduzidas. Há uns cerâmicos novos e há a introdução das telas asfálticas. Mas tudo isto coexiste, e eu diria que a grande transformação é no desenho e por consequência na linguagem do edificado. Mas mesmo na organização, a matriz tradicional da casa ainda é possível ser encontrada no início do século XX...[24:30]

F.B. : Nós temos todo este período de industrialização. Esta construção desenfreada nova começa nos anos 30 /40 na europa e nos anos 60 em Portugal. Há uma expansão brutal de construção nova em Portugal nos anos 60, e passa a haver muito mais construção nova que construção tradicional. Uma mudança de lógica com expansão para as periferias...

J.T.: Isso também foi ideológico. Foi o estado e os bancos a financiar para as pessoas comprarem casas novas. Porque os centros históricos foram esvaziados.

F.B. : E agora tu tens uma coisa completamente diferente...

J.T.: Que é o fenómeno do turismo...

F.B. : Mas o turismo veio preencher, foi mais rápido do que o resto. E curiosamente maior parte do investimento é privado, não é público. O benefício é dado pelo público, mas é recolhido pelo privado. Ou seja, há um momento em que não é “possível” construir mais porque já há mais casas do que famílias.

J.T.: [27:05] Há um outro aspeto que é curioso. O nosso país dentro da União Europeia é o primeiro ou o segundo com maior nível de segunda habitação.

F.B.: Mas há uma mudança de paradigma. Uma redução do investimento em construção em geral, com uma redução da construção nova. Temos um decréscimo da construção nova.

2) Alguns autores sugerem que a tendência de crescimento da reabilitação em detrimento da construção nova se mantenha, levando a que Portugal se aproxime da média europeia. Partilha desta opinião?

J.T.: Sim, mas isso é dito há muitos anos. Eu falava há pouco da opção que os governos pós 25 de abril tomaram. Foi uma opção estratégica, ideológica, com os bancos, de financiar a construção, porque não quiseram saber para a intervenção no existente. Também falo na minha tese, desta consciencialização à escala mundial dos perigos desta sociedade moderna que surge na crise do petróleo dos anos 60. Falo do grupo de Roma que encomendou um estudo matemático e cujas previsões sobre o esgotamento dos recursos naturais que se tem vindo a confirmar, do impacto ambiental que a industrialização tem infligido ao planeta. E repara, que estamos ainda no âmbito dos países supostamente desenvolvidos. Quando os países emergentes começarem a crescer...repara isto é um problema que está em primeira linha.
Essa mudança era inevitável porque não era descartável. Não temos aterros sanitários para demolir e construir de novo, é inevitável que se tivesse que estancar toda a indústria que durante décadas serviu os valores do desenvolvimento económico. Era inevitável e por isso temos o assalto aos centros históricos, a partir do momento em que houve alguma margem de manobra dos bancos para financiar, que para o bem e para o mal estavam mais ou menos intactos. No caso do Porto, há uma questão que já extrapola a intervenção fachadista. Há um aumento da área de construção, o que significa que se está a aumentar a densidade.

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil standardização, necessitando além disso de mais mão-de-obra do que a construção nova. Tal parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

J.T.: Desde logo começo por dizer, que não concordo bem com a afirmação que “a reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil standardização”. Não concordo com o carater pontual. Porque a reabilitação é um termo que abrange várias ações, que podem ir do restauro até à reconstrução, com a introdução de novos elementos. Eu não sou um fundamentalista, não sei se isso se depreende na minha tese. Algumas pessoas não perceberam ...que um edifício antigo que não tem instalações sanitárias em condições, naturalmente deve ser dotado de instalações sanitárias, de acordo com as nossas exigências da atualidade. Ou se não tem acessos verticais mecânicos deve ser feito um esforço para que eles existam. Eu acho é que há outros aspetos que devem ser equacionados de uma forma mais racional, se não tem aquecimento isso deve ser tratado, já o mesmo não digo relativamente ao ar-condicionado. Porque estes edifícios têm desempenhos incríveis. Uma colega está a fazer um doutoramento sobre a térmica do edificado histórico do Porto e tem chegado a algumas conclusões sobre a térmica e as fachadas. Nomeadamente que há um elemento que tem sido menosprezado, pelo menos nos estudos que eu conheço, que são as portadas e que tem um papel muito importante no controlo térmico destas casas.

F.B.: Mas a nível da standardização? Quando falo em pontual é ao nível da arquitetura. Estamos a falar de diferenças de casa para casa, se situação para situação. Pontual é a esse nível. Há pouco falavas em casas de banho, existem casas de banho modulares e poderíamos por uma casas de banho modular, mas para isso tínhamos que esventrar o edifício todo para ela entrar, porque não entra pela janela. Teria que entrar pela cobertura possivelmente.

J.T.: Isso não é muito modular, é quase uma espécie de móvel que não te cabe na casa.

F.B.: É desse sentido que falo quando me refiro a pontual. As soluções que é possível introduzir, não digo que o elevador vá ser especialmente feito para aquilo,

J.T.: Tem que ser necessariamente...

F.B.: Não é isso, a estrutura do elevador é feita especialmente para aquilo, mas o elevador não. É um elevador standard adaptado, especialmente a caixa, o mecanismo é um mecanismo standard.

J.T.: Tudo o resto pode ser adaptado...

F.B.: Especificamente à condição do edifício. Ou seja, do ponto de vista da arquitetura, dos sistemas, há uma necessidade de adaptação. Por isso falo de cirúrgico e pontual. Se vou introduzir uma casa de banho tenho que ver como é o edifício, como é a sua mecânica, tenho que ver se faz sentido introduzir ar-condicionado ou não, porque os edifícios têm um determinado funcionamento. Tenho que o estudar como é que ele funciona antes de poder dizer que aquela é a solução ideal...
...porque uma coisa é estarmos a falar de uma casa do porto do século XIX, outra é falarmos de um edifício dos anos 80 na periferia. A intervenção é completamente diferente, tem que ser pensada especificamente para ali. E as dimensões, no caso específico das paredes divisórias, não tem nada a ver num caso e no outro.

J.T.: Sim, sem dúvida. Eu diria que são universos muito diferentes... [42:00]
J.T.: [49:00] ...Relativamente, à tua pergunta. A intervenção na construção tradicional, nos edifícios históricos, é uma intervenção que obedece a imperativos patrimoniais, mas também a ambientais. No meu doutoramento queria a questão ambiental antes da questão patrimonial, mas o meu orientador não concordou. Quando li a tua pergunta escrevi – "A reabilitação é um termo que abrange um largo espectro. Em função do estado do edifício ela pode ser moderadamente intrusiva a severamente intrusiva, abrangendo partes ou a globalidade da edificação" - Eu não tinha ainda percebido em que contexto estavas a colocar aquela questão do cirúrgico ou pontual. Depois ainda digo – "O restauro poderá constituir uma componente da reabilitação e assim será pontual e cirúrgico." A questão é que como não há concorrência, quem ficou foram os resquícios, os personagens que se lembraram de tirar um curso de restauro e que atualmente se designam de restauradores. Não existem pessoas que façam estuques, nem tabiques, nem argamassas, já quase que nem de marmorite, tudo isso se perdeu. Um dos autores portugueses que eu acho mais interessantes que fala de património e de todas estas questões e o José Aguiar. Ele fala de na construção passar a existir um processo ao contrário, do que terá sido ainda o processo dos arquitetos que foram nossos professores que aprendiam muito na obra. Porque nos anos 80 ainda existiam muito bons profissionais, mesmo depois daquelas levas dos anos 60/70. Mas uma boa parte dos bons profissionais que tínhamos, o Siza tem um texto a propósito da piscina das Marés em que fala desse fenómeno – os mestres carpinteiros, provavelmente os últimos herdeiros das corporações de ofícios que ainda foram formados nos manuais de construção do Segurado, esses todos desapareceram. O José Aguiar diz que é através da investigação que se deve recuperar muito do saber que ainda pode fazer sentido para a atualidade, por exemplo as argamassas. Nas argamassas está por exemplo a voltar-se à cal... Isto para dizer-se que se voltou a algum know-how pré-industrial. A revolução

industrial pôs em causa séculos de saber que correspondem ao pré-industrial, que a partir de um determinado momento, esse saber e esses sistemas vão sendo substituídos até que desaparecem. E o que digo aqui é – "para que serve e quem serve a pré-fabricação e a automação? A um modo de vida baseado no consumo desenfreado de produtos de fraca qualidade? Cuja obsolescência alimenta uma indústria anómala que vive do consumo de recursos naturais e da crescente poluição ambiental, com uma crescente produção de resíduos muitos dos quais tóxicos, com impactos ambientais e consequências nefastas para o nosso planeta. No que diz respeito à habitação e com os devidos ajustes a todas as nossas necessidades, sou da opinião que não precisamos de megaempresas, corporações internacionais que só servem interesses de uns quantos, precisamos sim de uma indústria à escala das cidades, das comunidades e das pessoas. Acredito que esta espécie de industria artesanal iria fomentar a mão-de-obra qualificada, uma economia local e consequentemente melhorar a auto estima social. Por outro lado, esta indústria estaria mais voltada para as especificidades arquitetónicas e construtivas locais e culturais das comunidades. Esta indústria faz todo o sentido numa sociedade futura em que a prática sustentável da arquitetura e da construção será fundamentalmente caracterizada pela intervenção no edificado existente e menos na construção de raiz."

F.B.: Os problemas da automação de que falas normalmente são mais graves quando a industrialização serve um consumidor final, porque se pensares numa indústria que serve um consumidor "não-final", que tem peso e conhecimento no que está a comprar, por exemplo os barcos ou os aviões, tu tens uma automação que serve realmente a qualidade e a durabilidade dos produtos... Há determinadas circunstâncias em que a indústria está realmente a servir um aumento de qualidade pela experiência da produção. Poderá não servir outros aspetos como a personalização, mas há circunstâncias em que a automação e a pré-fabricação foram de facto positivas para o aumento da qualidade. Isso não significa que a produção artesanal não possa ter mais qualidade, mas na produção industrial tu tens uma qualidade espectável, o que permite a substituição. Por exemplo, as cozinhas hoje em dia são um sistema industrializado, modular. Tu sabes que se fores ao IKEA comprar uma cozinha, se daqui a 3 anos precisares de substituir uma peça, ou um módulo, ou uma porta podes. Quando a industrialização é neste sentido, define um sistema que é modular e intermutável e que dá realmente a oportunidade aos utilizadores de interferir e o adaptar às suas necessidades, que é o que o Habrakan fala quando se refere a open building, estamos a falar de outro tipo de industrialização que está ao serviço das pessoas... Quando falo de automação, falo de máquinas CNC que abrem a possibilidade de produzir séries pequenas à escala local. Por exemplo, eu posso ter uma pequena máquina ali que te fabrica para ti coisas que tu queres especificamente para o teu contexto, com qualidade controlável e resultados que controlas ao nível do desenho e da produção.

J.T.: Sim, não entendo muito bem isso. Mas já agora gostava que me explicasses com um exemplo, porque isso não serve para todos os produtos. Não sei para que é que isso pode servir. A última coisa que eu desenhei foi um fecho em latão para uma porta de correr. Fui ao Carvalho Batista e ele produziu-me aquilo, levou-me 70 euros. Provavelmente a CNC resolvia aquilo, mas é uma coisa muito simples, confinada a um material. Porque ela não produz um computador, não produz uma camisola que eu gostava de ter.

F.B.: Não vejo porque não. A camisola especifica para ti seria possível...

J.T.: Quem diz uma camisola diz um sapato...

F.B.: Sim, isso existe. A Nike e a Adidas já fazem isso, mas são grandes corporações. Tem sistemas de impressão 3D para produzirem solas de sapatos adaptadas a cada pessoa. Um bocado como o alfaiate fazia, que ia medir as dimensões e depois fazia uma camisola à tua medida. A nível de roupa também há uma empresa americana que te permite, usando um telemóvel para digitalizar o teu torso, fazer camisas à medida. Tu escolhes o colarinho, tu escolhes os punhos, um pouco como faz um alfaiate. A nível de objetos existem vários sites, um deles é o Shapeways. Faz principalmente impressão 3D, tem lojas para os designers colocarem os seus produtos, mas também podes imprimir, numa série de materiais, um desenho qualquer que fizeste ou alguém te fez. Por exemplo quero substituir uma ferragem qualquer que tenho num movel antigo e que não consigo encontrar quem a faça, eles podem imprimir....

F.B.: Há pouco estava a falar das cozinhas e lembrei-me de um exemplo na minha casa. Comprei-a há 5 anos e no ano passado a dobradiça de uma das portas partiu. Eu pensei que era simples, bastava ir a uma loja qualquer e comprar uma nova. Mas, não consegui porque o fabricante tinha feito uma inovação na parte que fixa à porta, um fecho de abertura rápido, em vez de ter os dois parafusos tinha dois pinos que entram na furação da porta. Isso significava que não podia usar uma dobradiça normal porque os parafusos não tinham onde apertar. Se fosse buscar a outro fabricante também não ia funcionar. Porque as dobradiças deles, patenteadas, tem um sistema de fecho rápido, mas com encaixe diferente, propositadamente talvez, para evitar que não utilizes outra coisa que não o sistema deles. Portanto, há limitações. Um dos grandes malefícios da indústria é quando a inovação é usada para defender os interesses deles e limitar as possibilidades do consumidor de intervir na sua própria estrutura e renová-la por ele próprio, que seria uma das grandes vantagens de ter um sistema aberto.

J.T.: Por isso é eu estava a achar o exemplo do IKEA um bocado estranho. Os produtos são substituídos. Eu vou dar um outro exemplo nas janelas de alumínio. A janela de madeira vai perdendo as características, mas pintas ao fim de 5 anos e ela vai-se regenerando. A janela de alumínio, se for anodizado, não há podes renovar. Haveria, mas não acredito que alguém vai desmontar a janela, voltar a anodizar, montar e voltar a meter no sítio, não acredito. As lacadas acredito que vão durar mais tempo. Mas se a porta sofrer um estroncamento que partiu uma travessa ou uma couceira, e se tiver mais de vinte anos, dificilmente vais encontrá-la no mercado. Vais ter que substituir a porta por outra nova que vai ficar mais ou menos igual às outras. Se fosse madeira podias pintar os caixilhos todos, só para não teres as cores diferentes. Se for alumínio lacado não vais lacar os outros todos.
Mas voltando ao tema anterior, isso da dobradiça não se resolvia com uma CNC?

F.B.: Aquela dobradiça? Com a tecnologia atual de impressão 3D, ia ser muito caro para o valor da dobradiça. Isso poderá mudar, mas por enquanto o custo de impressão 3D em metal é muito alto. Há quem use a impressão 3D para motores de automóveis, mas o custo do motor não se compara.

J.T.: Nós produzimos imenso lixo. Inclusivamente o Pacheco Pereira diz que vivemos numa sociedade de lixo, penso que ele não se está a referir particularmente ao lixo material, mas eu acho que para além do lixo imaterial, vivemos numa sociedade de lixo material.

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se continuam a utilizar componentes e sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

J.T.: Parece-me que a intervenção no existente produz uma enorme quantidade de resíduos se for baseada na demolição sistemática.

F.B.: Que é o que hoje acontece. Se pensares em paredes divisórias, em pladur ou em tijolo, não há outra alternativa à demolição se quiseres retirar a parede daquele sítio.

J.T.: Estou-me a lembrar de um edifício do Corbusier que o Teles mostrava, que era o Pavilhão Suíço. As paredes interiores eram um sistema tabicado, mas feito em estrutura de madeira e platex. Nós só não fazemos assim porque ninguém se lembra de fazer assim.

F.B.: Os sistemas de madeira muitos deles são desmontáveis. Quando falo disto, refiro-me aos sistemas construtivos de paredes divisórias que temos: parede de tijolo, gesso cartonado, que são as mais utilizadas. Mas na reabilitação não porque tijolo é demasiado pesado. Mas se quiseres mudar uma parede de sítio, tu tens que deitar tudo abaixo, nem sequer a estrutura do pladur consegues aproveitar.

J.T.: Ainda assim, numa altura em que se devia estar a promover os valores ambientais, os resíduos de construção deviam ser taxados a valores elevados. Porque se o fosse, pensariam duas vezes antes de agir. Isso iria fazer pensar melhor as práticas de intervenção. Por outro lado, os resíduos de construção podem ser reutilizáveis ou recicláveis. Ou seja, se para urbanizar pagas uma taxa à câmara, se vais produzir resíduos e não há condições para os reutilizar, esses resíduos podem e deviam ser taxados...

F.B.: Então na tua opinião o problema é não existir taxação dos resíduos...

J.T.: Esse é um, não é todo. Aquilo que está em questão é o desconhecimento. Eu creio que por natureza o ser humano é bom e que quando atua em detrimento dos outros ou do planeta, o faz por ignorância e por sobrevivência. Eu creio que no campo da arquitetura e da engenharia, a ação dos técnicos é sempre direcionada de acordo com a formação e o universo do conhecimento. Um engenheiro que foi formado para calcular estruturas de betão, quando vê uma estrutura de madeira deformada diz que tem que ser substituída. Um empreiteiro que durante as últimas duas décadas andou a fazer pontes e autoestradas, ou então edifícios na periferia que deram cabo da paisagem... À partida estas ações são por desconhecimento. Por outro lado, no percurso da construção não há agentes reguladores...
Os obstáculos são os mesmos de sempre. A suposta reutilização nunca chega a concretizar-se. Dou o exemplo do caixilho de alumínio. Este sistema afinal também se degrada com o uso e o tempo de vida, tendo permitido constatar-se a sua difícil reabilitação. A anodização ou a

lacagem implicam a desmontagem total dos caixilhos, o que inviabiliza a sua remontagem. Os acessórios e as ferragens desaparecem com o tempo no mercado, tornando penosa a sua substituição. Mesmo no caso de mudar algumas peças, a sua substituição pode revelar-se impossível pois as séries podem ser substituídas ao fim de algum tempo. A utilização de sistemas construtivos desmontáveis e reutilizáveis...eu parei nesta pergunta porque ocorreu-me uma lembrança curiosa. A reconstrução da baixa pombalina, e por consequência todo o fenómeno de expansão urbana que constituiu a nossa "baixa almadina", está assente numa standardização enorme. Não obstante essa standardização há uma cidade com uma diversidade incrível. Tens uma cidade regrada e disciplinada. Para os pensadores iluministas esta era a cidade ideal. E detive-me nesta questão. Que particularidades tinha esta standardização, do século XVIII, que permitiu esta cidade e que é diferente da standardização de hoje? Porque por exemplo, eu não suporto o mobiliário do IKEA. Eu acho a ideia do IKEA incrível, mas não há paciência para aqueles candeeiros do IKEA que vês em todos os sítios, porque normaliza, nivela. E isto encerra um lado negro, aquilo é barato, as pessoas compram e daqui a dois anos fartam-se e substituem por outra novidade do IKEA e aquele vai para o lixo. E o lixo é o aterro, é o oceano. Varres o lixo para debaixo do tapete.

F.B.: Mas não será um problema social também? Esse desperdício, também é porque é barato, ou porque tem pouco valor monetário, material e histórico. Mas isto é conjuntural não se limita exclusivamente ao IKEA, ou achas que sim?

J.T.: Há outros, mas a Vitra não faz.

F.B.: Então achas que o problema é o não ser suficientemente caro.

J.T.: Não, não há mínima dúvida que uma cadeira da Vitra é muito melhor do que uma cadeira do IKEA, em termos construtivos. É bem construída, os materiais são melhores. Não usa plásticos. A madeira não tem nós, é escolhida por isso é que é caro. E é pele, o tecido é bom. Um sofá da Vitra, custa cinco vezes mais do que o sofá do IKEA....Se eu comprar um sofá da Vitra que custa cinco mil euros, achas que eu vou pensar em substituir aquilo daqui a dez anos? Só se me sair a lotaria, ou outra coisa qualquer.

F.B.: Se vais gastar tanto dinheiro tens que escolher mesmo o sofá que gostas.

J.T.: Mas não achas que isto é uma postura ambiental?

F.B.: Sim

J.T.: Eu estou agora a lembrar que há uma marca que fabrica muitos produtos que o Dieter Rams criou. É uma marca inglesa que se chama Vitsoe. Eles fazem uma publicidade na altura dos saldos que diz, “nos não fazemos saldos porque os nossos produtos são para a vida.” Mas dura gerações. Os primeiros produtos que se designa de design, tem um mercado semelhante ao da arte, mas isso já é negócio. Mas o que eu quero dizer com isto é que custa muito, mas...era isso que acontecia antigamente. Relativamente a tudo. Eu usei um relógio que o meu pai ofereceu ao meu avo. O meu pai ofereceu ao meu avô por gratidão, e custou um salário. Aquele relógio ainda funciona, é de corda, não se atrasa e tem mais de cinquenta anos. Este Swatch atrasa-se e nunca vai durar, mesmo que o aparelho funcione tudo o resto se vai deteriorar. Esse relógio não é um relógio suíço, não é nada de especial. Eu acho que devíamos, em função da nossa vida, comprar produtos que são sustentáveis neste sentido, que são duráveis, que são bons, que têm valor. E eu acho que isto é transponível para a arquitetura, a solução não é continuar a construir e substituir.

F.B.: No caso da habitação ou nos escritórios, as necessidades no momento em que compras uma casa não são as mesmas ao fim de alguns anos. As necessidades vão mudando, e essa mudança implica alterações na organização do espaço, às vezes por alterações tecnológicas. Nada dura para sempre e isso implica alteração. Não podemos construir as paredes divisórias com o mesmo objetivo de longevidade com que construímos a estrutura do edifício. Há níveis diferentes de durabilidade, porque as necessidades vão mudando. Pode não fazer sentido mudar de casa só porque mudaram as necessidades, porque nasceu um filho, e não quero demolir.

J.T.: Sim essa casa pode até ter um valor afetivo...

F.B.: Nessa medida há níveis de diferentes dessa durabilidade de que falas na arquitetura. O relógio Patek Philip que tem um valor sentimental não é o mesmo que a parede entre a sala e a cozinha que afinal preciso de deitar abaixo porque agora as minhas necessidades são diferentes.

J.T.: Sem dúvida, as casas para serem úteis tem que ser utilizáveis, praticáveis e isso tem que se adaptar às necessidades das pessoas. Desde logo, relativamente à casa dita burguesa, há uma questão à priori: como transformar uma tipologia que estava vocacionada para uma família grande quando atualmente o modelo de família e a sua dimensão não têm a ver com o era originário. Portanto, a casa para sobreviver tem que ser versátil, flexível. Eu penso que essa flexibilidade deve aproveitar o máximo das pré-existências. ...O senso comum gosta de open-spaces, portanto há que deitar tudo abaixo para ter open-spaces. Pessoalmente não sou adepto, mas tudo bem. Portanto é inevitável que se perca, principalmente este património doméstico. Eu acho que o edificado deveria ser constituído por layers que tu sobrepões e que podem coexistir partes existentes...

F.B.: Isso é o que fala o Stewart Brand, num livro de 96 que se chama “How Buildings Learn”, ele não é único, como os edifícios tem seis camadas...

5) Considera que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

J.T.: Eu digo que sim mas não é determinante. É importante avaliar caso a caso. A tua questão tem particularidade. O existente, relativamente à casa do Porto, e constituído por um sistema construtivo que tem componentes com desempenhos diversos, principalmente a alvenaria e a madeira. Se nós introduzirmos um novo componente com outro ciclo de vida, o que é que vai acontecer? Eu acho que à partida os ciclos de vida não criam conflitos necessariamente.

F.B.: Quando falo de ciclos de vida não é ciclos de vida dos produtos mas ciclos de vida do uso, como estávamos a falar à bocado das camadas do Stewart Brand...é desses ciclos de vida.

J.T.:...é que eu estava a associar à construção.

F.B.: Isso é uma coisa que alguns autores falam. Existe uma discrepância entre os ciclos de vida do material, ou seja, uma parede de tijolo pode durar tanto como uma parede de pedra e muitas vezes nas intervenções nas casas do Porto do século XIX deitam-se abaixo paredes, não porque as paredes estão em mau estado, mas porque se quer mudar o espaço por outra razão. É nesse ciclo de vida do espaço e não dos materiais...

J.T.:...porque se confunde. Como falas em componente ou sistemas construtivos com ciclos de vida diferentes... geralmente na linguagem técnica dos engenheiros usam muito o ciclo de vida. Eu não consigo compreender muito bem a pergunta. A independência entre componentes, em concreto aonde queres chegar?

F.B.: São os critérios que eu estou a tentar desenvolver. Como estava a dizer no início fui buscar critérios a vários sítios. À reabilitação, especificamente o que é que da experiência da reabilitação de edifícios tradicionais se pode tirar, porque é um dos âmbitos a que me estou a limitar. Eu não me estou a limitar aos edifícios do Porto do século XIX mas à reabilitação em geral. No caso dos edifícios do Porto do século XIX existem exemplos de critérios para a intervenção. Estou também a pegar em critérios especificamente desenvolvidos para o open building, e um dos critérios que os autores referem é a independência entre os componentes. A independência é considerada um dos critérios fundamentais para a possibilidade de desmontar e reutilizar os materiais ou os componentes com a mesma função, mas noutro local. Há casos em que não é possível separar os componentes porque eles estão colados.... é nesse sentido que falo da independência.

J.T.: Eu acho que esta questão não se aplicará só à reabilitação, mas à construção em geral. Numa perspetiva ambientalista, sustentável, de ação da construção sustentável é obvio que para que melhor seja gerida a regeneração, reutilização e reciclagem dos materiais faz todo sentido que eles sejam separados e independentes. Aqueles critérios que eu avanço na minha tese são os das cartas, não inventei nada. Aquilo está nas cartas, nos documentos internacionais de património. As cartas são consensos, um património incrível porque não se substituem, são acrescentadas. Emanam dos congressos internacionais e traduzem consensos de pessoas que se interessam por estas temáticas. Que pretendem, não trazer soluções para resolver problemas concretos, mas conceitos que ajudem a refletir para soluções mais adequadas e mais amigas da proteção do património e da conservação.

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concorda com essa a afirmação?

J.T.: Eu digo que sim, desde que compreenda e se integre no existente. No caso da reabilitação, desde que ela compreenda o existente e se integre de uma forma harmoniosa nele, não me parece que seja um problema.

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

J.T.: Se essa atividade não ultrapassar o âmbito do mobiliário desmontável, parece-me absolutamente inofensivo, caso contrário se ela conflituar com a construção existente parece-me perigoso, no sentido que pode ser danoso para os utentes e para a própria edificação. Não sei se percebi bem a tua questão. Pareceu-me que me estavas a colocar a questão no sentido em que se trataria de um sistema que é manuseável pelos utentes. Se eu tiver jeitinho para isso, posso fazer bricolage, era isso?

F.B.: Sim. Posso desmontar a minha parede como se fosse uma mobília e levo-a comigo para uma casa nova que quero dividir de outra maneira e monto a parede que já tinha no outro lado. Isso, como dizes e bem, e diferente se tiver interferência em sistemas infraestruturais...

J.T.: Eu não sei bem o que dizer. Mesmo relativamente ao carro esqueço-me de ver se aquilo tem água. Não tenho jeito nenhum para montar um candeeiro. Eu acho que a construção é demasiado complexa para envolver os utentes...

F.B.: ...mas temos imensos exemplos de autoconstrução. Não só em Portugal, como no Brasil. Quando há bocado falavas da construção tradicional, de como os saberes eram transmitidos, o saber não só era transmitido dentro das corporações como era uma coisa relativamente dispersa. Não é por acaso que temos imensos trolhas, porque uma parte do conhecimento construtivo era relativamente vernacular, havia os mestres que sabiam mais, mas coisas simples as pessoas sabiam fazer.

J.T.: Sabes que no gótico, havia o segredo, só dessa forma é que conseguiam garantir o contrato. Vai ser construída a catedral de Reims, por exemplo, então entregavam a um determinado mestre de obras, construtor, arquiteto, que era conhecido porque já tinha feito uma catedral que era majestosa. É obvio que nas nossas corporações de ofícios a arte não era tão preciosa como as estruturas do gótico, a arte das argamassas, da realização de escaiola, de produtos para conservar a madeira. A ideia que eu tenho é que isto não era assim tão difundido, porque as pessoas tinham de garantir a sua subsistência... Para começares a prestar um serviço de estucador tinhas que estar inscrito na tua corporação.... Tenho feito investigação em documentos da Câmara do século XVIII e verifico que havia mais regras do que se julga. Havia regras, havia multas.

ANNEX D – Interview with José Amorim Faria

José Amorim Faria is a civil engineer and Assistant Professor of the Faculty of Engineering of the University of Porto. He has a degree in Civil Engineering by FEUP (1982); Masters in Building Construction (FEUP) (1986) and PhD in Civil Engineering by the University of Porto (1996). His research is focused on building construction technologies, particularly on those based on wood and derivates. In his PhD dissertation he developed a prefabricated demountable partition system in wood. The interview was conducted on January 19th, 2018 at the Faculty of Engineering in Porto.

1) A reabilitação tem ganho uma relevância crescente no panorama nacional. Quais são as maiores dificuldades com que os (arquitetos / engenheiros / construtores / indústria) se deparam nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação?

J.A.F: As gerações mais novas de Arquitetos e Engenheiros estão a adaptar-se muito bem ao novo paradigma e aos novos desafios. As Universidades estão há cerca de 10/15 anos a dar mais formação especifica e essa circunstância tem ajudado. O problema está no tecido empresarial de construtores muito centrado em tarefeiros e subempreiteiros muito mal preparados. O negócio assenta sobretudo na questão financeira. Não há conhecimento suficiente para perceber por exemplo que em reabilitação a mão-de-obra representa 60 a 65% do custo e que, nesse contexto, a produtividade, o saber fazer bem a primeira, a capacidade para aproveitar o máximo da pré-existência, a capacidade para distinguir o valor no edificado existente constituem questões fundamentais. Muitos construtores fazem reabilitação usando as metodologias que conhecem muitas delas completamente focadas na construção com estrutura de betão armado e alvenarias de bloco cerâmico. Conheço, no entanto, algumas empresas com grande know-how de reabilitação e restauro que estão a fazer um excelente trabalho, a ganhar dinheiro e a crescer (os promotores terão um papel fundamental distinguindo e premiando os que sabem fazer em detrimento de todos os outros!

2) Alguns autores sugerem que a tendência de crescimento da reabilitação em detrimento da construção nova se mantenha, levando a que Portugal se aproxime da média europeia. Partilha desta opinião?

J.A.F: Sim. Concordo totalmente com essa opinião, embora entenda que isso ocorrera num período de 1 geração (20 a 30 anos). Os motivos: envelhecimento da população; existe edificado suficiente para as necessidades populacionais; haverá decisões políticas no sentido da descentralização; Portugal e um país "estreito" e será cada vez mais fácil chegar ao interior de carro (de imediato) e de comboio (no futuro próximo). A população nas cidades de pequena e media dimensão ira aumentar bastante no seculo XXI, seguindo um fenómeno semelhante ao que ocorrer por exemplo na Alemanha (aproveitar escolas, Politécnicos, Universidades, Teatros e Hospitais do interior montanhoso do país e fundamental (sobretudo no Norte e Centro mas também em Évora, Beja e outras vilas mais pequenas do Alentejo.

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil "standardização", necessitando além disso de mais mão-de-obra do que a construção nova. Tal parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

J.A.F: Concordo totalmente com o que refere. A resposta passa pela individualização dos espaços e funções e pela individualização/complementaridade dos sistemas construtivos (exemplos: criar um ático todo novo num edifício antigo modernizando totalmente a solução de cobertura e de aguas pluviais; individualizar programas na reabilitação de um Museu, de um Hospital, de Solares, Palácios ou casas antigas com qualidade; resolver fundações, paredes estruturais e estrutura com grande respeito pela pré-existência, aproveitar o mais interessante do antigo existente e adotar soluções novas muito inovadoras e prefabricadas no "miolo" interior (restantes paredes, revestimentos, acabamentos, infraestruturas em geral - "redes")

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se continuam a utilizar componentes sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

J.A.F: Aqui já não concordo totalmente. A sociedade ainda não esta preparada para reciclar quando essa solução não e a mais económica!!

A dicotomia publico/privado enfatiza ainda este problema o que neste momento, pelo menos em Portugal, ainda e mais agravado pela falta de dinheiro do setor publico para investir o que leva o Estado em geral a optar sempre pelo mais barato. Mais uma vez refiro que o que refere e mais um problema político e filosófico do que uma questão importante na economia real.

5) Considera que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

J.A.F: Esse e um critério fundamental!! Nos EUA por exemplo as construções menos perenes são em geral projetadas para 20 anos de vida!! Existe uma necessidade permanente de adaptar o edificado de modo a torná-lo mais compatível com os usos mais modernos, a evolução tecnológica, as tendências ao nível do crescimento ou redução da dimensão das famílias, as modas, etc. E fundamental projetar de modo que o "miolo" possa ser reformado regularmente com o mínimo impacto possível. Considero por isso este trabalho como muito importante para começar a desbravar caminho para que os sistemas "desmontáveis" possam aumentar em número. De qualquer forma entendo que tal e importante para reduzir o tempo de demolição previa e o "lixo" e incomodidades causadas e não para permitir reaproveitamentos. Em geral, as soluções desmontadas dificilmente podem ser usadas em outros usos dado que a standardização do edificado não existe e esses materiais e componentes dificilmente encontrariam "obra" onde ser colocados sem gastar muito dinheiro na adaptação!

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concorda com essa a afirmação?

J.A.F: Concordo 100%. Terá de começar nas Universidades, continuar nos Arquitetos e Engenheiros, chegar aos construtores para depois chegar aos subempreiteiros e Operários. O BIM e o CAD/CAM são os melhores exemplos que ilustram o que refere.

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

J.A.F: Aprender com outras indústrias!! Seguir os procedimentos de gestão da indústria automóvel na perspetiva da conceção, fabrico e montagem em fábrica e na obra. Para criar soluções desmontáveis, pensar no processo de desmontagem como algo reversível do processo de montagem (fazer-desfazer relativamente semelhantes). Nesse contexto, as soluções deverão usar ligadores/sistemas de ligação reversíveis; soluções coladas são inaceitáveis, soluções por encaixe podem causar muitos problemas na reversibilidade!!

8) Os sistemas de divisórias desmontáveis são considerados à-priori mais flexíveis. No entanto, que critérios devem ser tidos em conta para o desenvolvimento de um sistema construtivo de divisórias desmontáveis para que ele seja realmente flexível?

J.A.F: Tem de ser pensado como um Kit de componentes. Tem de ter componentes para todas as situações particulares. Tem de ser pensadas todas as ligações e situações especificas (canto, angulo aberto, angulo fechado, padieira, ombreira, ...). Devera ser limitado o âmbito para soluções retilíneas já que as soluções curvas são muito menos fáceis de padronizar. Terá de se pensar na padronização de revestimentos e acabamentos para tornar a solução mais económica. As recentes tendências da indústria automóvel são também um bom exemplo a seguir (combinação de soluções/acabamentos para satisfazer soluções "costumer oriented").

9) Os requisitos regulamentares para uma parede divisória são relativamente baixos quando esta compartimenta espaços interiores. A ETAG03 define os requisitos de estabilidade, mas não estão definidas na regulamentação nacional exigências especificas para o comportamento acústico ou térmico. Tendo em conta o objetivo do presente trabalho que critérios de performance devem ser cumpridos pela divisória a desenvolver?

J.A.F: Os requisitos a satisfazer são os 7 definidos no RPC em que o contributo para a estabilidade global não e o assunto mais importante, devendo a divisória garantir a sua própria estabilidade para as ações correntes (choque de corpo mole, choque de corpo duro, ação de batimento de porta, pressão/depressão causada pelo vento).

A questão de durabilidade e muito importante. Facilidade de limpeza e manutenção do aspeto são também importantes. Analises de custo global considerando os custos com limpeza e desmontagem/demolição são também importantes pois "potenciam" a importância das soluções prefabricadas/desmontáveis/reversíveis. No caso presente deste trabalho o critério desmontabilidade e também um parâmetro fundamental.

10) O custo de um sistema ou componente construtivo é fundamental para determinar a sua viabilidade, no entanto sendo este um sistema desmontável devem ser considerados outros custos? Que tipo de custos?

J.A.F: Resposta parcialmente dada na questão anterior. Fazer analise na perspetiva do LCA (Life Cycle Assessment) para a vida útil de projeto (10 anos? 20anos? Nunca mais do que isso!). Considerar custo inicial + custo limpeza + custo desmontagem/demolição. Poderá considerar um valor "não numérico" para a facilidade de reaproveitamento que se traduziria numa "redução do custo global baseado numa percentagem.

Sugiro comparar os custos de uma solução tradicional de blocos cerâmicos, de gesso cartonado e de divisórias modernas desmontáveis - alumínio?? com a SUA solução. Os desempenhos térmico, acústico e de Segurança contra incêndios deverão ser semelhantes!! Seguir uma via de comparação tipo "analise multicritério" não me parece uma via razoável para um doutoramento de base tecnológica.

Questões (Online)

1) Além destes artigos / tese, e tendo em conta o âmbito da minha investigação, que outros sugere consultar?

J.A.F: Sugiro ir ao site www.eota.pt no separador "publicações EOTA" encontrar as ETAGs 003, 016 e 023 e porventura a 007 que lhe poderão interessar e que servirão de guião ao seu processo de conceção.

Um sistema de divisórias inovador na Europa deve ser concebido respeitando a ETAG003. Se for menos ambicioso respeitara apenas a ETAG016 e porventura a 023 para componentes, unidades para a construção.

Sugiro que pesquise sistemas inovadores no que lhe interessa por marcas/patentes/nomes que conheça e encontre o número de ETA respetivo que poderá fazer download no site referido se conhecer o código ou a marca ou a referencia... Encontrar soluções com ETA é fundamental!!

Não tenho feito pesquisa nos últimos anos neste domínio específico pelo que não conheço nomes de investigadores/universidades que se dediquem ao tema. Eu procuraria sempre só livros e artigos mais recentes (também teses ou similares) sobre o tema. Quando eu fiz a pesquisa para o meu doutoramento na altura não encontrei nada.... Apenas livros genéricos de Arquitetura ou Construção sem grande valor para servir de referência num trabalho académico, mas bons para aprender sobre o tema!

2) Relativamente ao sistema construtivo que desenvolveu na sua tese, o MADLEVE, tenho as seguintes questões:

1.1. Como correu a adoção do sistema na prática?

J.A.F: Na altura a empresa Mesquita Madeiras apoiou a minha investigação e financiou a construção do protótipo. Destinava-se a ser usado (eventualmente...) no sistema de prefabricação total de casas de madeira que tinham (e que tinha DH do LNEC...). Decidiram não adotar a solução e melhorar o desempenho acústico usando placas de gesso cartonado. O sistema base não cumpria a legislação acústica e tinha várias deficiências em termos de aspeto arquitetónico por as juntas terem cobre-juntas a vista muito inestéticos. Entretanto a empresa mãe (construtor AMMesquita fechou...). Assunto a debater na nossa conversa. Tema 1

1.2. Que critérios / exigências acrescentaria se no momento atual revisse o sistema construtivo que desenvolveu?

J.A.F: Em termos de exigências não houve grande evolução. Fundamental seguir o definido no Regulamento dos Produtos de Construção, seguir a metodologia para marcação CE. As 6 exigências essenciais agora são 7 (foi acrescentada a sustentabilidade...). As restantes exigências mantem-se mais ou menos similares (ver capítulos 2, 3 e 5 da minha tese de doutoramento. Hoje a durabilidade e a sustentabilidade em geral são a questão fundamental.

3) Na data em que desenvolveu a sua tese, os sistemas industrializados de construção eram muito incipientes em Portugal, sendo os sistemas tradicionais em alvenaria à data quase hegemónicos. Passados 22 anos como define o panorama da adoção deste tipo de sistemas?

J.A.F: Não concordo com o que refere. Apos o 25 de Abril ocorreu um boom brutal de sistemas prefabricados em Portugal que durou até cerca de 1983. Nessa altura, a crise económica fortíssima que Portugal sofreu na altura e depois a entrada na UE em 1 de janeiro de 1986 mudaram tudo com a entrada do dinheiro fácil europeu (10 anos do Cavaco Silva...). Considero que a construção na altura do dinheiro fácil regrediu em vez de progredir. Agora, a falta de dinheiro esta outra vez a aguçar o engenho e a pôr os agentes da construção (não só as Universidades...) a tentar fazer mais com menos dinheiro e nesse campo a prefabricação joga um papel fundamental.

No que me diz respeito, ocorreram ainda dois "booms" recentes associados à Minha casa Minha vida no Brasil e ao plano do José Eduardo dos Santos em Angola para seguir um programa paralelo e construir casas para os angolanos... Os construtores andaram a procura de sistemas prefabricados e soluções completas feitas em Portugal ou localmente para satisfazer essa procura e tentar ganhar (mais, muito mais...) dinheiro.

Em Portugal, a adoção dos sistemas é muito baixa já que o investimento em Construção nova desceu para mínimos históricos!!

No Mundo continua a ser um tema fundamental, em geral associado as diversas famílias de materiais. Naquela que conheço melhor (a madeira...) a investigação em novas soluções prefabricadas é brutal recorrendo a CLT, sistemas com contraplacados de última geração, etc. Há também uma procura de construir mais alto em Madeira o que para mim constitui um erro estratégico grosseiro!!

4) Os sistemas e subsistemas construtivos de madeira tem uma adoção muito limitada em Portugal. Quais são os entraves à sua adoção mais generalizada? Os clientes? Os projetistas? Ou os empreiteiros?

J.A.F: Difícil responder. Julgo que o principal entrave é o preço. As soluções são caras em termos relativos quando comparadas com outros países. A abordagem do Mercado e também errada (e sobretudo comercial com pouco Know-how nacional) e o cliente potencial desconfia...

Há vários problemas... Assunto também que podemos debater na nossa conversa - Tema 2

5) Assistiu-se a um grande progresso na racionalização e industrialização da produção e dos métodos de processamento de produtos derivados da madeira nas últimas décadas. Nomeadamente, com a introdução ou generalização de novos derivados, máquinas CNC, conectores metálicos otimizados, melhores adesivos, etc. Isto veio tornar a construção em madeira mais competitiva. Por outro lado, a madeira foi redescoberta como um dos mais importantes materiais renováveis para a construção sustentável. Qual é o seu ponto de vista acerca do impacto destes desenvolvimentos na construção?

J.A.F: A madeira maciça (nomeadamente a madeira de folhosas mais nobres) será sempre um bem relativamente escasso e que será cada vez mais caro. Irá progressivamente tornando-se num material "de luxo" e será usado preferencialmente para acabamento na Construção Civil e outros usos: revestimentos/obra de marcenaria/marroquinaria.

Para estruturas, continuará a haver sempre madeira proveniente das zonas frias (Rússia, Canada, Escandinávia, Países do Báltico, Polonia, florestas da Alemanha, Áustria, Norte de Itália, Escócia, zonas montanhosas dos USA, ...) a ser usada em estruturas de madeira. Os restantes países têm tendência apenas para exportar a madeira com maior valor económico em geral de folhosas mais densas. África continuará a ser um dos principais fornecedores de madeira de folhosas de grande qualidade, mas esta será cada vez mais usada apenas em revestimentos / acabamentos e outros usos.

Nesse contexto, julgo que a sua afirmação acima "... tornar a construção em madeira mais competitiva" é verdadeira, mas aplica-se sobretudo aos derivados de madeira e destes claramente aos mais modernos e recentes como o CLT e o UHPP. Os desenvolvimentos tecnológicos que refere acima estão a ser usados sobretudo no desenvolvimento de soluções e sistemas que usam derivados de madeira.

Os desenvolvimentos tecnológicos mais recentes nos equipamentos de fabrico, BIM, CAD/CAM e sobretudo nos sistemas de ligação estão a ter um papel fundamental na mais recente procura da inovação na construção por parte de empresas, investigadores e universidades em geral. A questão da "construção sustentável" está também a ser importante no processo de "retoma" da fileira mas aí julgo que é uma questão mais política e sociológica e que não tem um real impacto no desenvolvimento dos negócios da fileira fora do núcleo dos países mais desenvolvidos do Mundo (não me parece por exemplo que essa seja uma questão relevante na China, India, Ásia em geral...).

A questão da madeira ser um material facilmente renovável também constitui a minha opinião mas envolve bastantes questões: Os derivados tem resinas na constituição e são dificilmente recicláveis; a madeira continua a ser muito usada como combustível - destino mais corrente dos resíduos; em reabilitação de estruturas a madeira "antiga" tem um valor muito elevado e é integralmente reciclável com pouco trabalho de valorização mas subsiste a questão da mão-de-obra necessária para a reutilização (desmontagem cuidada, retirada de pregos e parafusos, novas operações de corte/maquinação, melhoria do aspeto exterior - por exemplo por lixagem - para poder ser usada à vista, armazenamento/stockagem por comprimentos/secções/espécies - como se de pecas de automóvel se tratasse... -, etc). O uso fundamental é para derivados (fabrico de estilha), tipo aglomerados ou contraplacados, e para usos futuros em reabilitação. Este constitui o uso mais "nobre" e fundamental e que é essencial conseguir implementar de forma corrente por comerciantes de materiais da fileira, com a ajuda de proteção política e a sensibilização das populações e de arquitetos, engenheiros e construtores.

Atualmente, a madeira é considerada um material fundamental na questão da "sustentabilidade da Terra em geral", não por ser um material facilmente reciclável, mas sobretudo por provir das florestas e estas constituírem o principal armazenador de carbono no planeta, o que implica que estas sejam geridas de forma integrada e em ciclo (semelhante ao ciclo da água), considerando todos os domínios e fatores envolvidos (propriedade das zonas florestais, incêndios, modelos de gestão das florestas com plantio, abates programados, silvicultura cuidada com limpeza das matas, podas de formação, modelo de comercialização, transformações diversas em madeira serrada, derivados de primeira, segunda, terceira e quarta geração, classificação e certificação dos materiais "novos", classificação e certificação dos materiais usados - ainda inexistente... -, reciclagem muito parcial. O ciclo da água é um ciclo relativamente fechado em que as quantidades no início e fim dos ciclos são relativamente semelhantes. No que se refere ao ciclo da madeira, no fim de cada ciclo haverá muitas perdas sobretudo causadas pelos incêndios e lenha para aquecimento o que implica que será necessário replantar e usar as cinzas como adubo natural - Plantar arvores permanentemente de forma inteligente e ordenada e saber gerir a floresta (crescimento, abate, replantação) constituirá sempre a atividade fundamental para que a "construção em madeira" e todos os outros potenciais usos da madeira se mantenham como uma das atividades fundamentais do Homem.

6) Na sequência da questão anterior, focando em particular nas máquinas CNC e os desenvolvimentos que estas tiveram, alguns autores falam do ressurgimento dos encaixes em madeira motivado pelo aparecimento de máquinas CNC capazes de os realizar em fábrica, mas também pela generalização do uso de braços robóticos. É uma linha que tem muita força nos centros de investigação de arquitetura europeus (IBOIS Lausanne, ICD Stuttgard, ETH Zurich, etc). Qual é a sua opinião acerca relevância deste tipo de técnicas tradicionais de ligação da madeira na contemporaneidade?

J.A.F: Concordo totalmente com tudo o que refere. Continuo a pensar que a "robotização" constitui a base fundamental da inovação em sistemas construtivos que usam madeira e derivados.

Julgo que os usos em sistemas não estruturais usarão sempre madeira maciça (caixilharia, soalhos, lambrins) mas também derivados para baixar os custos.

Os sistemas estruturais usarão sobretudo derivados.

As soluções à base de sistemas de prefabricação total e também os sistemas de prefabricação parcial fechados terão tendência a aumentar (essa constitui uma tendência geral da construção moderna mais desenvolvida - não apenas da construção que usa madeira e derivados).

Os centros de investigação que refere representam núcleos de investigação dos países mais fortes do Mundo em investigação em madeira na atualidade. O CLT foi inventado em Graz na Áustria. A investigação de topo é toda germânica e um pouco menos do Norte de Itália (sobretudo no Trentino/Alto Adige) e Escandinávia (Dinamarca, Suécia e Finlândia). Os anglo-saxónicos (USA, Canada, UK, Austrália, Nova Zelândia) vão neste momento a reboque da Europa...

Dai ser importante encontrar ETAs para perceber se essa investigação está ou não a chegar ao mercado...

Tenho muitas dúvidas. Penso que há poucas ETAs...

Julgo que a maior parte (quase todas...) das soluções criadas e estudadas no sistema de investigação não chegarão nunca a ser produzidas por industriais do setor em regime massivo!!

Temas 1.

Eu perguntei o que aconteceu com o sistema construtivo que desenvolveu e disse-me que houve problemas com a empresa-mãe...

J.A.F: Na altura saiu um novo regulamento de acústica, e as exigências especificas para o local onde eram para ser usadas aquelas divisórias do sistema que existia eram 34 decibel. Quando os abordei para patrocinarem a construção do protótipo, fui desafiado a desenvolver um sistema o mais desmontável que fosse capaz de fazer 40 decibel. Isso foi feito e os valores oscilaram entre 39 e 41 decibel, mas havia o problema das transmissões marginais.

Penso que essa questão do cumprimento regulamentar não seria um problema, mas seria tendencialmente mais caro do que as soluções standard de gesso cartonado e por isso eles começaram a migrar de um sistema totalmente em madeira para sistemas mistos. Outro aspeto importante eram os problemas de acabamento dos sistemas desmontáveis por causa da quantidade de juntas.

Posso esclarecer também que nos pós 25 de Abril havia grande necessidade de habitações, com muita gente a viver em condições precárias com duplo e triplo subaluguer. Por isso houve um boom grande de construção de habitação e sobretudo ao nível das escolas, porque houve um grande aumento do acesso ao ensino por parte das classes mais desfavorecidas. Isso levou a um grande incentivo do Estado à criação de sistemas pré-fabricados. Surgiram vários tipos, mas a maioria era à base de betão e madeira.

Entretanto, uma parte significativa das escolas e mesmo de edifícios precários de escritórios que foram feitos em madeira já foram demolidos.

F.B.: Depois de me falar disso recordei-me que estudei na minha adolescência em escolas préfabricadas...

J.A.F: Dependendo de onde é poderá ter estudado em escolas secundárias pré-fabricadas...

F.B.: De facto, estudei na escola André Soares que era completamente pré-fabricada em fibrocimento...

J.A.F: Sim, ainda havia o fibrocimento com amianto que era produzido por uma fábrica que fica aqui em frente à EFACEC...

ANNEX E – Interview with José Moreira

José Moreira is an engineer and director of LAMINAR, a plywood manufacturer of in Gaia, Portugal, with a long experience in wood derivates and prefabricated construction with wood in Portugal. The interview was conducted on January 15th, 2018 in Laminar offices in Gaia. A entrevista foi resumida para facilitar a leitura.

1) Assistiu-se a um grande progresso na racionalização e industrialização da produção e dos métodos de processamento de produtos derivados da madeira nas duas últimas décadas. Nomeadamente, com a introdução ou generalização de novos derivados, máquinas CNC, conectores metálicos otimizados, melhores adesivos, etc. Isto veio tornar a construção em madeira mais competitiva. Por outro lado, a madeira foi re-descoberta como um dos mais importantes materiais renováveis para a construção sustentável. Qual é o seu ponto de vista acerca do impacto destes desenvolvimentos?

J.M.: De há duas décadas para cá não surgiu nenhum produto novo nem de madeira, nem de derivado de madeira, pode ser que agora se utilize mais a madeira, por várias razões, nomeadamente por haver mais reabilitação que construção e as casas antigas utilizavam muito mais madeira. Portanto, a madeira realmente é um produto sustentável e reutilizável, mas a construção em Portugal sofre um problema que é a falta de normalização que é nomeadamente nas casas antigas e na reabilitação. Uma casa na Alemanha por exemplo, há três medidas de janelas, é claro que pode haver cinquenta, mas três são pré-definidas, aqui em Portugal, não há uma norma que diga que a largura ou as dimensões das janelas são standardizadas em três dimensões, cada projetista, cada construtor faz o que entende. Eu há uns anos trabalhei numa carpintaria, em que havia quatro prédios pertencentes à mesma construtora, portanto, a construtora era a mesma, o dono da obra era o mesmo, e cada prédio tinha as suas dimensões, tendo a carpintaria acabado por falir porque não dava vazão áquilo, tinha prejuízos enormes, e às vezes, mesmo dentro do mesmo prédio, de um andar para o outro já não serviam as carpintarias, veja só o custo que isto tem para quem faz a obra, para o dono da obra, que lhes é imputado pelo construtor e depois pelos fabricantes. Ou seja, a falta de normalização é um dos problemas. Voltando à madeira, há materiais mais baratos, mas a madeira tem algumas vantagens nomeadamente, o isolamento térmico, que agora é obrigatório nas casas, até nas reabilitações, tudo o que é para alugar ou vender tem de ter um certificado. O acústico em Portugal e Espanha não são, só no resto da Europa. Relativamente, às CNC sempre houve e sempre se usaram, agora estão mais aperfeiçoadas. Os materiais que saem dos derivados de madeira, que é o que mais se usam, são normalizados têm uma medida, ou duas, ou três, não têm todas as medidas, e depois têm que ser trabalhados de acordo com as dimensões da obra. Alguns arquitetos, se calhar não sabem quais são as nossas medidas standard, embora já tenhamos feito conferências e tenhamos um site que explica, e se formos à Europa as medidas são idênticas, mas terá de haver sempre adaptações porque os pés-direitos não são todos iguais, principalmente nas casas antigas que têm pés-direitos enormes e normalizar isso é difícil...

2) A reabilitação tem ganho uma relevância crescente no panorama nacional. Quais são as maiores dificuldades com que a indústria se depara nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação?

J.M.: Cada casa tem a sua medida, o pé-direito das paredes, até de um andar para o outro difere, há falta de normalização, sem dúvida, e tem de se adaptar, é por isso que a reabilitação em princípio por metro quadrado fica mais cara, porque tem os resíduos, tem os cuidados obrigatórios para ter que manter a fachada, etc..

(...)

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil standardização, necessitando além disso de mais mão-de-obra do que a construção nova. Tal parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

J.M.: Uma reabilitação fica mais cara que uma construção nova. Numa construção nova o Estado pode intervir através de regras, se há normalização é na construção nova, de raiz.

Em princípio, a carpintaria e o construtor seguem as instruções dos projetistas, dos arquitetos, devido à sua experiência, havendo mais dificuldades numa reabilitação do que numa construção de raiz, daí se gera uma enorme dificuldade de conciliação entre as duas tendências.

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade

de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se continuam a utilizar componentes sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

J.M.: Existem em escritórios sistemas construtivos de divisórios desmontáveis, mas não na habitação, porque julgo um escritório ser mais volátil que uma habitação, quer em termos de mudança de localização espacial, quer em termos de necessidade de uso por mais pessoas. Numa habitação, poderemos estar a entrar nesse âmbito da necessidade de alteração/adaptação da tipologia devido também aos alugueres, à necessidade de alojamento de curta duração, e sim, acredito que no futuro isso será uma criação válida. E hoje há a perspetiva pela maior parte das pessoas, que já não veem que a casa será para a vida toda, esse processo de sistemas construtivos de divisórios desmontáveis será um instrumento para a mobilidade que se precisa e para acentuar essa mudança de mentalidades.

5) Considera que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

J.M.: Nalgumas partes da casa, acho que tem bastante interesse poder ser algo amovível, portanto, existir uma divisória que serve de parede, que seja opaca e que possa se mover, para diminuir e arranjar mais espaço noutro compartimento, ou mesmo para unir dois compartimentos, mas isso terá de ser projetado desde o início porque as partes estruturais têm de estar separadas. Na casa onde vivo, teria condições para mudar o que tenho, mas as paredes são todas em tijolo, portanto seria uma bagunça tremenda deitar abaixo as paredes para fazer seja o que for. Ter paredes amovíveis teria vantagens, seria algo inovador e revolucionário.

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concorda com essa a afirmação?

J.M.: Nós somos fabricantes de placas mas para uma carpintaria isso faz sentido porque permite uma oferta muito mais diversificada do que as placas lisas.

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

J.M.: Tem que ser mais simples do que montar um móvel. A experiência que tenho em montar moveis do IKEA é que sobram sempre peças, ou faltam. Em Portugal, não sei se ainda há a mentalidade que existe no exterior porque o custo da mão-de-obra ainda é baixo. Por exemplo, é muito normal lá fora serem os próprios proprietários a montar os móveis de cozinha. É necessário que haja uma alteração de mentalidades dos portugueses, mas é uma possibilidade porque há 50 anos não havia Do-It-Yourself e hoje é completamente diferente. Vendemos muito para grandes superfícies como o Maxmat ou o Leroy Merlin, mas sempre em dimensões cortadas....62x62 ou 62x125. E painéis relativamente finos, nunca mais do que 8mm, 9mm. Portanto o que eles vendem são painéis finos e pequenos.

8) Os sistemas de divisórias desmontáveis são considerados à-priori mais flexíveis. No entanto, que critérios devem ser tidos em conta para o desenvolvimento de um sistema construtivo de divisórias desmontáveis para que ele seja realmente flexível?

J.M.: Adaptação de perfis – a questão dos perfis é um factor importante, pela sua estética: por exemplo um perfil de alumínio combina com um escritório, com uma feira, mas não combina numa habitação um perfil de alumínio a suportar as divisórias. Portanto, o estudo do encaixe é importante e até a ligação dos próprios painéis uns aos outros, porque eles não vão ser simplesmente encostados, os painéis têm larguras fixas: 1 m, 1,25 m, 1,50 m, os nossos painéis para as feiras têm 60cm de largura porque assim aproveitamos dois, e um dos factores importantes é o aproveitamento dos painéis porque eles têm como já referi dimensões fixas, porque fazer uma largura especifica de um painel só se faz se for em muita quantidade, é preciso otimizar a produção.

Portanto, dimensões e encaixe para ficar sólido e estético.

9) Os requisitos regulamentares para uma parede divisória são relativamente baixos quando esta compartimenta espaços interiores. A ETAG03 define os requisitos de estabilidade,

mas não estão definidas na regulamentação nacional exigências especificas para o comportamento acústico ou térmico. Tendo em conta o objetivo do presente trabalho que critérios de performance devem ser cumpridos pela divisória a desenvolver?

(...)

J.M.: Do ponto de vista da resistência ao fogo em edifícios públicos, e, o comportamento acústico em habitações.

10) O custo de um sistema ou componente construtivo é fundamental para determinar a sua viabilidade, no entanto, sendo este um sistema desmontável devem ser considerados outros custos? Que tipo de custos?

J.M.: Há custos do material, industriais, e custos de distribuição, logística e comerciais, e o que cada vez pesa mais é a mão-de-obra. O ideal era já ir tudo pronto para montar e evitar os custos de mão-de-obra que são custos altos.

Resumidamente, são os custos de mão-de-obra e os custos de logística, distribuição que devem ser otimizados.

ANNEX F – Interview with Paulo Mendonça

Paulo Mendonça is an architect and Associate Professor at the Architecture School of the University of Minho. He graduated in Architecture by the University of Porto, he has a Masters in Design and Marketing and a PhD in Civil Engineering by the University of Minho. His research interests include Sustainable construction, new materials and processes, lightweight construction, architectural membranes and building rehabilitation. He developed several demountable partition systems, including AdjustMembrane. The interview was conducted on January 16th, 2018 in Guimarães Shopping.

1) A reabilitação tem ganho uma relevância crescente no panorama nacional. Quais são as maiores dificuldades com que os (arquitetos / engenheiros / construtores / indústria) se deparam nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação?

P.M.: A questão da reabilitação envolve sempre mais mão-de-obra. O paradigma será menos industrialização, ainda que se possa industrializar alguma coisa, mas será sempre mais complicado por um carpinteiro a industrializar uma reabilitação de um casa antigo do que uma casa de raiz. Na construção nova tem havido uma tendência para a industrialização, nomeadamente pré-fabricação, construções modulares. Embora eu não tenha dados estatísticos, mas seguramente que assisto a um crescimento de empresas que trabalham na construção modular, ou seja, construção nova com base em soluções pré-fabricadas modulares. Mesmo a própria indústria já produz soluções mais vocacionadas para a construção modular.

Na reabilitação, apesar de não ser impossível criarmos soluções modulares, e se calhar o objetivo do AdjustMembrane vai também no sentido da reabilitação. Aliás, não é só da reabilitação, um dos aspetos que eu considerei foi a possibilidade de ser usado em edifícios que estavam em construção e que foram abandonados por causa da crise. Havia muitas estruturas que estavam devolutas por falta de viabilidade económica e que se calhar poderiam ser terminadas se... aliás, é um paradigma que passa por envolver um bocado da autoconstrução no processo, que tem surgido em algumas soluções que tem sido divulgadas recentemente, como os Lacaton Vassal ou o Aravena. Digamos que é construção pensada para autoconstrução com uma série de componentes para as fachadas. Esse é o paradigma que preocupa não só os países que têm mais necessidade de reabilitação, como também os países que têm necessidade de construção nova. Pensar essas soluções faz sentido, especificamente no caso dos países mais industrializados, como a Alemanha ou a Suíça, onde a mão-de-obra é muito cara e o custo da construção está muito condicionado por esse fator. Nós aqui nem tanto, nós podemos apostar em soluções com mão-de-obra mais intensiva que podem ser mais sustentáveis, nomeadamente na reabilitação, que é à partida mais sustentável do que a construção nova, porque se aproveita material existente, mas obriga a mão-de-obra mais intensiva.

Participei recentemente numa mesa-redonda em Aveiro promovida pela secção regional dos arquitetos, e alguém da audiência, que não era arquiteto, perguntava o que achávamos da autoconstrução. Discutimos que a autoconstrução quando é construção nova tem muitos entraves, regulamentares, câmara, licenciamento, questões burocráticas que vai onerar o custo e aumentar o tempo. Aquilo que eu sugeri que é mais fácil, face à realidade da legislação, foi a autoreconstrução. Nada me impede de reconstruir a minha casa, porque não há necessidade de licenciamento, desde que saiba o que estou a fazer...

2) Alguns autores sugerem que a tendência de crescimento da reabilitação em detrimento da construção nova se mantenha, levando a que Portugal se aproxime da média europeia. Partilha desta opinião?

P.M.: Atualmente a construção tem descido, o volume de obra de construção e o volume de negócios tem baixado, mas a percentagem de reabilitação tem subido.

F.B.: É verdade. Há outro fator importante, se olharmos só para habitações, a adição de novos fogos por ano relativamente aos existentes tem decrescido desde 2000 e está neste momento perto de 1%.

P.M.: Não há necessidade de alojar, a não ser a procura que tem crescido nos centros das cidades. Mas continuam a sobrar muitos edifícios devolutos na periferia das cidades e no interior ainda mais....

P.M.: Acho que há esse crescimento, mas não há necessidade, a não ser nos centros, de termos mais fogos, portanto é inevitável... Daí fazer sentido a questão da auto-construção, porque se adapta melhor à deslocalização das necessidades de procura.

P.M.: Tenho um colega de doutoramento que está a trabalhar numa iniciativa que se chama “La Casa por el Tejado”. Ou seja, o que eles fazem é basicamente construções modulares em cima dos edifícios existentes. Procuram edifícios que tenham capacidade de ampliação, que não tenham preenchido a cércea do ensanche de Barcelona, mas também já tem feito coisas em

Madrid e noutras cidades, mas sempre em cidades que têm mais procura no centro. Constroem em estaleiro a construção modular, os módulos, as peças, e depois com grua vão colocá-la no sítio....

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil standardização, necessitando além disso de mais mão-de-obra do que a construção nova. Tal parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

P.M.: Se nós queremos manter a solução tradicional, nas conferências da construção em adobe acabam sempre por aparecer os ortodoxos ou puristas que dizem que temos que fazer o adobe tradicional, que não podemos colocar isolamento, que temos que ter a parede estrutural, etc. Eu não tenho uma perspetiva assim radical, acho que todas as soluções podem ter potencialidades, mas também podem evoluir para soluções contemporâneas que funcionem mais de acordo com aquilo que é expetável atualmente. Nós podemos ter uma solução mais industrializada, mas deslocalizada para a obra, por exemplo ter uma máquina a fazer blocos de terra compactada in situ no Alentejo. Naturalmente que cada caso é diferente. Se for no centro da cidade para fazer uma ampliação de uma construção existente não será viável. Acho que devemos analisar o caso e procurar soluções mais sustentáveis, também sobre o ponto de vista económico. Se conseguimos ter uma solução mais sustentável do ponto de vista ambiental, mas ela custe muito mais do ponto de vista da mão-de-obra, pode ser que tenhamos que procurar compromissos. Se a industrialização nos permitir baixar o custo e ao mesmo tempo ser uma solução sustentável, ótimo! Normalmente as soluções mais sustentáveis na construção tradicional são soluções com mão-de-obra intensiva. Mas se conseguirmos converter isto numa questão de justiça social, é um bocado como acontece na India, ninguém vai fazer uma obra com máquinas ou comprar material industrializado, a não ser que sejam coisas que não se conseguem produzir manualmente. O sítio onde essa questão da mão-de-obra ao máximo é em África...

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se continuam a utilizar componentes sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais

preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

P.M.: É logo a primeira das estratégias de construção sustentável, que é o Reduzir, Reutilizar e Reciclar. Se calhar por ordem hierárquica o primeiro é reutilizar, eu tenho que ver se existe alguma estrutura lá e tentar aproveitar o que existe. Depois reciclar eventualmente. Se houver algum material, estruturas, sobras ou resíduos que não possa utilizar como estão, mas que possa voltar a assemblá-los de outras formas ou em última linha reciclar. E por fim reduzir que é a estratégia que eu explorei na minha tese de doutoramento...

F.B.: Exatamente, uma das coisas sobre a qual também fala é que os processos e sistemas usados hoje ainda dia produzem ainda muito lixo quando se verificar ser necessário desmontar ou demolir para alterar a construção. Não fará mais sentido pensarmos e usarmos já na reabilitação sistemas construtivos desmontáveis?

P.M.: Sim, e isso é o mesmo na construção nova. Infelizmente a nossa construção nova tem uma percentagem muito baixa de reutilização, mesmo de reciclagem. Praticamente todos os resíduos da construção tradicional vão para aterro sanitário. Apesar de haver diretivas europeias no sentido de se incorporar...do ponto de vista da nossa construção tradicional fica mais caro fazer essa incorporação e até ambientalmente, se feito um estudo caso-a-caso se calhar não é assim tão favorável como seria expectável. Já o mesmo não acontece com os resíduos pétreos da exploração de pedra, que se unem a outro tipo de resíduos para produção de betão e tem um impacto significativo na redução do uso de materiais nas obras foram feitas no final do século XX. Enquanto as construções tradicionais eram feitas com soluções desmontáveis, eu posso ir lá e buscar a madeira nem que seja na última linha para queima, mas seguramente muita dela pode-se aproveitar para outros usos. A construção antiga tem isso, mesmo as pedras podem ser montadas noutra circunstância, mesmo os vidros podem ser reutilizados ou reciclados. O mesmo já não se pode dizer dos vidros duplos que utilizamos atualmente, com filtros de baixa emissividade, já não se podem reciclar.

F.B.: Mas então se os sistemas desmontáveis fazem tanto sentido, quais são os obstáculos que impedem que sejam adotados de uma forma mais generalizada?

P.M.: Acho que é mesmo a tradição de construção que nós temos do século XX. Porque dificilmente encontrámos um empreiteiro que se disponha a fazer um tipo de construção diferente do convencional. Por isso acaba por ser a solução mais económica. Se olharmos para a habitação social ou de custo controlado, vamos sempre encontrar o betão e o tijolo, porque é a solução mais económica para a resposta ser funcional e em termos de exigência regulamentar... Depois também há muitos obstáculos à questão da auto-construção. Uma habitação social, seguramente as pessoas teriam todo o interesse em se envolver na sua construção. Um bocado como os exemplos do Aravena. Não estamos assim tão longe da realidade dele. Se calhar também há outros interesses que ultrapassam a questão ambiental. Se calhar o que se tem que onerar é a questão ambiental. É conseguirmos impor soluções que, podem não ser ao mesmo custo, aliás foi isso que tentei provar na minha tese, tenham o mesmo desempenho ou melhor, com muito menos impacto ambiental. Fiz um protótipo que demonstrava que eu podia construir um edifício agora com muito menor impacto ambiental, com soluções que podem ser feitas pelos mesmos funcionários, no caso eram funcionários mais habituados a trabalhar em reabilitação, mas podiam ser até os próprios locais ou podiam ser arquitetos. Eventualmente uma pessoa desempregada poderia sentir-se mais útil se fizesse a sua própria casa. Não vejo porque é que uma habitação de baixo custo não pudesse incorporar auto-construção e ao mesmo tempo que se optasse por usar soluções de mão-de-obra intensiva e mais sustentáveis, nomeadamente as construções tradicionais. Nós não precisamos de inventar a roda. A construção tradicional, do centro histórico do Porto, Guimarães ou Braga, Aveiro, Lisboa, essa construção sob ponto de vista ambiental funciona muito melhor do que a construção atual ou convencional contemporânea.

F.B.: Usava materiais locais...

P.M.: Usava desconstrução.

F.B.: E tinha alguma standardização na dimensão dos vãos...

P.M.: Sim, e na dimensão dos lotes e tudo. Eles quase que até no projeto poupavam porque as casas eram quase todas iguais…na dimensão das janelas, na dimensão das vigas. O facto de terem aquela largura era porque era a dimensão máxima ou ótima para uma estrutura de madeira.

F.B.: É preciso arranjar uma arvore com aquele comprimento e transportá-la. Depois há quem argumente que reabilitar edifícios como estes e melhorar o seu comportamento térmico, é ambientalmente mais eficaz do que fazer construções atuais que cumpram NZEB. O que demonstram é que uma habitação deste tipo construída agora, por muito eficaz que seja [energeticamente] demora pelo menos 100 anos a apanhar a outra...

P.M.: Depois ainda há o custo de fim de ciclo de vida, o custo da demolição. Nós vemos que agora é mais valorizada uma construção do século XIX do que uma construção dos anos 70. Mesmo em termos arquitetónicos, e é menos flexível, menos sustentável, sobre todos os pontos de vista, eventualmente com algumas exceções.

5) Considera que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

P.M.: Não sei se conhece o livro do Brand, How Buildings Learn, em que ele fala dos seis layers. Na questão da sustentabilidade temos que olhar para o que está na primeira linha e pode ser desmontável e facilmente substituído e atualizado, que de fato é a compartimentação. Primeiro é o mobiliário, mas esse por definição já é móvel. Agora a questão que eu tinha no desenvolvimento do AdjustMembrane era fazer que ele fosse mais como um móvel, que fizesse parte do meu mobiliário. E daí ter uma solução que era facilmente desmontável e remontável.

O nosso nunca teve uma estrutura com maior durabilidade, ainda que os móveis até possam, os móveis podem durar a vida toda e ainda ficar para os netos....

F.B.:...falando da construção que se faz cá agora. Para a maior parte das pessoas, até há bem pouco tempo, uma casa era para a vida inteira. Conceber que as paredes divisórias não fossem aquelas definidas no momento do projeto, era uma coisa que nem lhes passava pela cabeça. Mas a verdade é que ao fim de alguns anos, se voltarmos a falar com essas pessoas até dirão que fariam de outra forma... será que no contexto atual fará mais sentido, haverá da parte das pessoas uma consciência mais forte acerca da impermanência do espaço interior e de como ele é dividido?

P.M.: Num seminário na Suíça...há dois anos em que eu fui mostrar precisamente esse trabalho da flexibilidade. Foi uma tese de doutoramento de um aluno que trabalhou mais a questão da flexibilidade. Um dos exemplos que ele estudou foi um edifício, penso que na Holanda ou na Alemanha, onde praticamente todas as paredes eram móveis. E ela conhecia esse exemplo e contestou que na prática as pessoas acabavam por não mudar nada. Aquilo permite rebater as paredes e ficar tudo openspace. A cozinha é um balcão e a casa de banho ...são os únicos espaços que estão condicionados aquela utilização. Ela dizia “Ah mas depois na pratica as pessoas acabam por não mexer nas paredes, fica sempre com a mesma organização, vão é trocando os usos.” Na prática ...é sempre melhor poder mudar. Ainda que haja pessoas que não queiram mudar, e queiram ficar com as divisórias permanentemente no mesmo sítio, ou até queiram manter a memória do quarto e, portanto, não pensam em alterar. .. A flexibilidade permite-me explorar todos os cenários, portanto não força que as pessoas fiquem restrita aquilo que foi definido.

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concorda com essa a afirmação?

P.M.: Sim, claro. Faz porque em obra tenho variações. Estávamos a falar há pouco de haver algumas medidas mais comuns, mas também nunca era exatamente igual. Por exemplo, na minha casa um andar tem 3,12m outro tem 3.25m... Se bem que eles também tinham essa flexibilidade, o tabuado do tabique pode ter a mesma dimensão e depois o rodapé tapa a diferença…as placas de gesso cartonado também têm uma dimensão standard

F.B.: Sim, tem uma dimensão standard que é cortada e adaptada em obra. A adaptação de todas as soluções tradicionais é feita na obra. Mas estamos a falar de sistemas construtivos modulares em que para ser económico tem que estar restrito a um conjunto de medidas.

P.M.: O que eu tinha previsto nessa solução era uma subdivisão, tinha um módulo mais pequeno que tinha 75 mm, e esse era o módulo a partir do qual posso cortar. Poderia fazer menor que isso, mas depois perdia as ligações. E depois para o máximo não havia limite, se quisesse podia fazer uma solução com painéis quadrados 60x60. Houve uma altura que até tínhamos a possibilidade de implementar uma solução num escritório...com 3 m. E a ideia aí seria era fazer um painel para aquela dimensão. Um painel único com largura de 1,20m...mas podia ser 60 por 1,23m. E nesse caso pensámos que seria mais fácil fazer painel único. E implementar logo a altura toda...depois se quisesse organizar o espaço era sempre com aquela altura.

F.B.: Em escritórios é uma coisa que faz sentido e é utilizada há muito tempo. Divisórias de escritório que são moveis, modulares, desmontáveis e até há muitas empresas que mudam de escritório e levam-nas com eles porque podem reutilizá-las e reorganizar espaços noutros locais. Em habitação é que é mais raro...

P.M.: Em habitação é que é uma solução que não é muito...Mas em habitação faz mais sentido que seja auto-construção. Num escritório também não se está à espera que os empregados montem as divisórias, talvez dependa do tipo de empresa...

F.B.: Se bem que há uma marca americana de divisórias chamada DIRTT de divisórias para escritórios, que se gaba de as divisórias serem fáceis de montar, e que dá como exemplo uma empresa de sapatilhas cujos empregados de dois em dois anos reconfiguram os seus escritórios, sem intervenção de técnicos externos. Mas é um caso específico.

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

P.M.: É a questão da fácil montagem e desmontagem, ser quase por encaixe como as soluções tradicionais, ou dos jogos japoneses. Há de certa forma sempre um quebra-cabeças naquilo...

F.B.: Pois, mas isso é que não convinha. O IKEA é um bom exemplo de uma coisa assim e ainda ontem entrevistei uma pessoa que me disse isso, com o IKEA há sempre peças que sobram ou que faltam e a minha experiência é exatamente a contrária, está sempre tudo certinho, nunca me faltou nada e nunca me sobrou nada.

P.M.: Com os moveis da Moviflor já tive alguns percalços de me faltarem coisas ou o parafuso não dar muito bem, ou a furação não estar exatamente no sítio. Mas no caso do IKEA aquilo é tão testado, a quantidade de peças que fazem, e a quantidade de lojas que têm é tão grande. A Moviflor é uma coisa mais à escala local, e se calhar tem coisas produzidas na China, e são produzidas numa escala em que não permite ser testado. No IKEA devem montar 5 ou 6 moveis antes, desconheço, mas deve haver um gabinete onde devem estar uns indivíduos a montar cinco ou seis...

F.B.: Mas também o próprio folheto, não sei como é na Moviflor, mas no IKEA o folheto vem com descrições...

P.M.: Sim, no caso da Moviflor era um bocado esquisito por causa das coisas que vêm da China com aquelas traduções.

F.B.: Já por isso o IKEA não tem texto nenhum é só desenhos.

P.M.: Aí está, porque se calhar já tem uma equipa de pessoas que desenham, de designers para pensar na questão da comunicação da montagem.

F.B.: No caso de uma divisória como esta, a minha opinião é que a comunicação seria uma coisa fundamental. Um dos problemas da solução que desenvolvi em 2015 era como é que eu, porque aquilo era feito com muitas peças montadas no local, cortadas por máquinas CNC, mas a montagem era toda feita à mão, como é que se comunica a uma pessoa. Primeiro as divisórias variam sempre, as peças sempre diferentes, mesmo que estejam numeradas, como é que se comunica a alguém que não conhece o sistema e não tem experiência de construção, a ordem e a lógica de montagem? Um bocado como os puzzles japoneses, a dificuldade é saber...

P.M.: O desafio é vir sem manual.

F.B.: Certo, mas numa construção deste tipo se calhar tinha que vir.

P.M.: Mas aquilo [os puzzles] tem situações realmente engenhosas, só com encaixe eu conseguir uma montagem. Se calhar pode ser explorado o contrário, ter uma solução que não preciso de nenhum desenho, que seja muito intuitiva a montagem. Esse seria o grande desafio. Outra hipótese é que aquilo seja auto-montável, como com as membranas.

F.B.: Também há uma investigação sobre self-assembly structures...

P.M.:...ou com CNCs e braços robóticos. Ou coisas como aquelas tendas que se abrem e elas se montam.

8) Os sistemas de divisórias desmontáveis são considerados à-priori mais flexíveis. No entanto, que critérios devem ser tidos em conta para o desenvolvimento de um sistema construtivo de divisórias desmontáveis para que ele seja realmente flexível?

P.M.: Sim isso por acaso foi o tema da ...havia uma serie de parâmetros de flexibilidade que passava pela questão de como se juntavam, ...o facto de ser transparente ou não, o facto de ser translucido, havia diferentes níveis de flexibilidade que se poderia introduzir. Ou seja, eu posso chegar a uma divisória de fole e abrir ou fechar totalmente, ou posso ter uma de pivots que fique parcialmente no meio, portanto já temos aí um nível diferente. Posso ter um painel que rode ou um painel tipo portão que seja de enrolar para cima. O portão pode ser mais pesado, já posso precisar de um mecanismo, e aí a flexibilidade pode ser mais condicionada porque preciso de ter um motor, por exemplo, e ter um espaço onde ele se recolhe, aquela caixa na parte superior que me reduz a altura. Se tiver uma cortina, eu posso abrir e só fica ali uma calha fininha.

F.B.: Portanto, aí estamos a falar de outro tipo de considerações como seja, se ela é desmontável, eu tenho que ter um sítio onde a possa guardar.

P.M.: Sim, se ela ocupa espaço quando está montada e desmontada. Depois também temos a resposta que ela vai ter em termos funcionais. Se ela for já for muito flexível já não pode ser um bom isolante acústico e aí já me pode condicionar se eu quiser usar aquilo entre uma sala e um quarto. Isso é uma coisa a considerar, embora não haja exigências regulamentares de isolamento acústico dentro de um fogo, mas na prática é preciso alguma privacidade entre o quarto e a sala.

F.B.: Pode estar uma pessoa a dormir e outro na sala a ver televisão...

P.M.: E não há nenhuma exigência regulamentar nesse sentido, mas as pessoas também vão procurar alguma qualidade de vida. No entanto, se for uma pessoa só não tem esse quesito. Eu posso ter uma gama de produtos, que por exemplo para um solteiro tem uma solução que não tem isolamento e que seja o mais flexível possível....

Portanto, esses requisitos têm mais a ver com a exigência própria daquele agregado do que propriamente com a exigência regulamentar.

F.B.: Portanto, na tua visão essa questão acústica é importante? Quando falava acerca dessa divisória um dos critérios que introduzia era a questão acústica, mas também a questão térmica.

P.M.: Sim, também exploramos a questão térmica, apesar de também não ser uma exigência regulamentar. O nosso regulamento olha para o fogo como uma unidade, é quase indiferente, a não ser pela questão da massa térmica, mas se eu tiver uma divisória que não tenha massa térmica é indiferente se ela é ou não estanque, ou se ela tem ou não isolamento. Claro que ela pode também ter massa térmica e ser permeável. Pode ser tijolo de vidro por exemplo, que tem massa térmica e eu vejo mais ou menos. Isso também vai de certa forma condicionar um bocado a flexibilidade. Posso ter uma divisória translucida, que até seja um ótimo isolante acústico e térmico, mas que, no entanto, não me satisfaz em termos de privacidade.

9) Os requisitos regulamentares para uma parede divisória são relativamente baixos quando esta compartimenta espaços interiores. A ETAG03 define os requisitos de estabilidade, mas não estão definidas na regulamentação nacional exigências especificas para o comportamento acústico ou térmico. Tendo em conta o objetivo do presente trabalho que critérios de performance devem ser cumpridos pela divisória a desenvolver?

P.M.: Mas isso é a questão mecânica, nós escrevemos um artigo sobre isso. E aí fez-se os testes de impacto.

F.B.: Mas na verdade, quando estamos a falar de requisitos, e todos os que falamos anteriormente são requisitos arquitetónicos. É transparente, não é transparente ou tenho privacidade ou não, são coisas mais difíceis de aferir do que as regras que nos aparecem nessa norma.

P.M.: Tem flexibilidade também pode ser é transparente ou não e aí já será outro nível de flexibilidade.

F.B.: E depois há ainda outras questões como seja a infraestrutura. Eu posso ou não ter infraestrutura lá dentro. Tenho acesso ou não a essa infraestrutura depois de a montar. À partida se é possível haver infraestrutura tem que haver uma forma de a montar, mas muitas vezes não há forma de reverter o processo sem demolir o conjunto todo. E isso também seria um critério então?

P.M.: Sim, sim. Na desconstrução e na montagem.

10) O custo de um sistema ou componente construtivo é fundamental para determinar a sua viabilidade, no entanto sendo este um sistema desmontável devem ser considerados outros custos? Que tipo de custos?

F.B.: A única coisa que ainda não falamos foi do custo. O custo inicial do sistema é uma coisa importante, mas para além desse custo existem uma série de outros custos que advêm de ser uma divisória desmontável. Depois também sendo uma divisória para um utilizador final há outro conjunto de custos, como por exemplo o transporte, que um empreiteiro consegue diluir...

P.M.: Há uma economia de escala...aqui pode pôr-se todos esses custos no utilizador, como num movel. Quando um cliente vai ao IKEA não está a fazer contas ao tempo de montagem nem ao transporte. Por acaso é uma informação que eles deveriam dar, o tempo de montagem. Eu posso ter dois produtos em que um demora 10 minutos a montar e outro 10 horas, e se a diferença entre eles for 10% não compensa. Aí nesse caso das divisórias poderá ser uma coisa relevante a informar, se bem que isso é um bocado subjetivo. Se houvesse muitas soluções no mercado poderia haver uma espécie de normalização, como nos automóveis, e aí o tempo de montagem poderia ser um critério.

F.B.: Mas em termos de critérios, uma coisa é a prática comercial, outra é uma avaliação científica. Porque na prática comercial até posso querer vender sem dizer qual é o custo.

P.M.: Depois estaria o desempenho, a questão ambiental ...aspeto, como nos pneus se têm a certificação de eficiência energética, certificação ambiental do produto, podia também ser o desempenho acústico, qual o nível de isolamento que consigo, mas de uma forma que as pessoas percebam.

P.M.: Do mesmo modo a questão ambiental....seria importante haver uma normalização da comparação do comportamento da solução relativamente a determinados parâmetros. Por exemplo, em relação à solução de referência, isto é igual...

F.B.: Foi o que vocês fizeram, compararam com o pladur, e o tijolo e depois tinham oito soluções de materiais que poderiam integrar uma solução e fizeram uma avaliação.

P.M.: Isso se calhar para as pessoas é a melhor forma, tentar face à solução convencional comparar os parâmetros para as pessoas terem uma ideia.

11) Desenvolveu um sistema construtivo desmontável de divisórias, o AdjustMEMBRANE. Este sistema não foi comercializado? Não era o objetivo?

P.M.: Não era objetivo, aliás nós tentamos através da interface do mestrado, fomos apresentar isto a Lisboa a uma feira de renovação. Fui apresentar a algumas empresas também.

F.B.: Mas patentearam a última solução que desenvolveram?

P.M.: Sim, patenteamos, só que, entretanto, já não continuamos a pagar a patente. O registo está lá, mas não está ativo. Se eu quiser agora vender a patente já não sei se posso, deixei de pagar as prestações de renovação. De qualquer maneira, se alguém tentar submeter uma patente com as mesmas especificações, pelo menos nas instâncias europeias não vai conseguir. Mas quem quiser fazer isso na China...

F.B.: Falta o custo de manutenção...

P.M.: Acho que assim, à primeira vista...sugiro-lhe que veja o nosso artigo. Tem algumas coisas que pusemos como parâmetros para verificar se há alguma coisa que falta.

F.B.: Da comparação disto com o vosso artigo, a primeira coisa que ressalta é que o vosso artigo está estruturado numa lógica de avaliação da sustentabilidade. Então tem o triângulo da sustentabilidade, com os três fatores: económico, social e ecológico. Depois distribui as coisas de acordo com esses parâmetros...

P.M.: Depois tem os pesos que faz parte dessa metodologia. Ou seja, estar a hierarquizar ou dar uma distribuição diferente, só se for por inquérito, mas no fim de contas é uma metodologia que é desenvolvida através de inquéritos, através de benchmarking a soluções existentes ou de referência. Acabo por fazer sempre isso quando faço artigos ou apresento a tal solução, procuro sempre comparar com a referência, pelo menos uma....

F.B.: Até porque estes tipos de critérios servem para desenvolver uma solução. E quando estou a desenvolver uma solução há uma parte que também tem a ver com as opções do projetista, que não podem ser consideradas científicas. Porque uma determinada solução pode ser muito boa para uma determinada aplicação, mas para isso não o pode ser em várias outras. Aqui há uma opção de target, eu quero que isto seja para um determinado fim e dou os pesos de acordo com esse objetivo. Há ainda o nível da comparação com as outras soluções que se usam nessa aplicação. Nesse sentido, a segunda coisa que pedia era destes critérios quais seriam os mais relevantes tendo em vista que é dentro da arquitetura, para utilizadores finais e para reabilitação.

P.M.: Dentro de hierarquia poria primeiro as exigências ETAG, as exigências obrigatórias. Logo à partida, se eu não cumpro com a norma de segurança de funcionamento de uma solução não a posso comercializar. Depois eventualmente a questão da desmontabilidade ...depois a questão acústica e de segurança contra incêndio. Isso são situações com as quais as pessoas se vão preocupar primeiro. Depois a questão do custo porque para ser rentável tem que ter um custo competitivo. Depois há aqui questões que acabam por se repetir, como o sistema construtivo desmontável e reutilizável, como a questão da durabilidade dos encaixes, a questão da modularidade, ou questão da flexibilidade geométrica, ou da intermutabilidade. Acabam por ser parâmetros que estão relacionados. Podem repetir nalgumas situações. Como é que eu vou avaliar se o sistema construtivo é desmontável e reutilizável sem ao mesmo tempo estar a ver a questão da modularidade, ou a questão da intermutabilidade ou a questão da durabilidade dos encaixes. Isso tem que estar ao mesmo tempo, tem que pensar na solução do encaixe e ao mesmo tempo a pensar na durabilidade dessa solução.

Também será diferente se é para mudar todos os dias... os ciclos. Uma gaveta tem que testá-la para vários mil ciclos,...

F.B.: Aqui será cinco ou seis...

P.M.: ...aqui se calhar não vais ser mais do que isso. Portanto pode não ser tão importante por esse aspeto. Depois também há a questão das garantias, tenho que dar uma garantia que isto funciona durante X tempo. Não sei se isso será um entrave à comercialização. Mas posso ter que dizer como num carro, ou são X anos ou X mil quilómetros. Aqui será X montagens, 50 montagens ou 20 montagens. Mas não sei se será difícil controlar isso... nos moveis do IKEA pode acontecer isso, aquilo moer se eu desmontar e montar muitas vezes.

F.B.: Acontece. Alguns deles só consegue 3 ou 4 vezes. Aqueles armários de quarto. Tive um amigo que mudou de casa várias vezes e na última vez já não funcionava. E não é um parâmetro que as pessoas pensem no momento da compra, mas no meu caso deveria ser explicita...

P.M.: Isto tem uma limitação de montagens e desmontagens, porque no caso do IKEA se em vez de um aglomerado naquele sítio reforçarem para uma peça já lhe poderá dar outra robustez. Mas também vai aumentar o preço.

F.B.: Neste caso não havendo nada de comparável também não se pode ficar mal. Dizias-me há bocado "se tiver 10 desmontagens as pessoas não vão querer", se calhar não porque não vão avaliar com base nisso. Haver uma desmontagem já duplica o valor daquilo que tem, em teoria pelo menos, porque não quer dizer que não sejam precisas outras peças para resolver a diferença entre o espaço onde vou aplicar a solução e o espaço onde a tinha.

Depois ainda há um conjunto de outros critérios, por exemplo: eu desmonto a minha divisória, coloco-a no sítio novo, que garantias tenho que vou conseguir arranjar peças que me faltam, ou que se danificaram, e o que é que faço às que já não servem? Portanto, há um conjunto de dúvidas que não são muito simples de resolver, seria garantido por uma empresa que já estaria no mercado...

P.M.: Pois, isso foi um bocado o nosso caso. Por exemplo, quando chegamos à questão da produção para termos a solução a um preço competitivo precisávamos de fazer moldes, e esses moldes custam 10 mil euros. Para um IKEA se calhar isso não é nada, ou para a Lego, eles têm milhares de moldes, mas vão vender milhões de peças daquele molde. O nosso mercado como é muito pequeno, se calhar nos EUA isto era mais fácil. Faltava-nos uma empresa parceira que fosse ao mesmo tempo uma empresa que produzia, que soubesse da produção e que resolvesse as questões que surgem numa linha de produção. Um IKEA conseguiria à partida saber os custos de produção de uma coisa destas. Porque uma coisa é produzir e montar protótipos, fazer uma peça ...e aliás os ensaios que fizemos foi com protótipos, porque se fizéssemos os ensaios com peças finais elas seriam muito mais robustas e iam ter uma resposta muito melhor seguramente. A questão é que não tínhamos verba para produzir de uma forma industrializada.

ANNEX G – Interview with NCREP

NCREP is engineering consultancy that provides services in structural rehabilitation of common building stock and built heritage. The interview was conducted with João Miranda Guedes and Tiago Ilharco, two of NCREP partners, at NCREP office in Porto, on January 22nd, 2018.

João Miranda Guedes holds a bachelor's degree, a master's degree and a PhD in Civil Engineering from the Faculty of Engineering of the University of Porto in the area of seismic behaviour of concrete structures. Tiago Ilharco holds a degree in Civil Engineering and a master in Built Heritage Rehabilitation from the Faculty of Engineering of the University of Porto.

A problem with the recorder prevented the answers to the questions 6 to 9 from being recorded. Immediately after the interview, the interviewer summarized the replies to those questions. Yet, these cannot be considered a faithful transcription of the authors words and are marked as such.

1) A reabilitação tem ganho uma relevância crescente no panorama nacional. Quais são as maiores dificuldades com que os (arquitetos / engenheiros / construtores / indústria) se deparam nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação?

T.I.: ...precisamente, a indústria estava virada para a construção nova e de repente saltou tudo para a reabilitação. Os intervenientes saltaram também, mas sem saber "nadar" e por isso vês muitas empresas que antes não faziam reabilitação mas agora fazem mas com muitas dificuldades técnicas. Percebes que as empresas que normalmente faziam reabilitação têm muitas dificuldades em arranjar técnicos, porque há muito mais solicitações. Técnicos ou mão de obra de qualquer tipo, carpintaria, estuques, serralharia, pichelaria, tudo. O que é que isso provocou? Há muito volume de trabalho, as empresas de construção estão com muita dificuldade em responder bem porque não tem mãos a medir e não tem técnicos para acompanhar as solicitações todas. Isso faz com que os preços aumentem imenso.

F.B.: ...não é só cá no Porto?

T.I.: Acho que é generalizado. É claro que em Lisboa e no Porto as coisas têm mais...mas não é porque as empresas de Braga estão em Lisboa a fazer obras. Eu acho que isso acontece em todo lado, se alguém tiver uma solicitação a Norte vai pedir preço e os preços já estão mais altos também. Para além dos preços, os prazos também se têm dilatado. E há muitos empreiteiros que nem apresentam preço. Houve um salto de uma indústria enorme de obras públicas para uma indústria muito mais pequena, que não foi devidamente acautelado porque este boom da reabilitação é recente.

F.B.: E do vosso ponto de vista? Vocês são uma empresa especializada em reabilitação e propõe soluções que não são muito comuns para o resto dos engenheiros que não têm a vossa experiência. Sentem dificuldade a esse nível?

J.M.G.: O que o Tiago estava a dizer, resulta também de outro problema. Porque de facto a nossa indústria de construção civil estava dirigida para o novo, a própria formação nas escolas é dirigida para o novo. Portanto, não é só o facto de as empresas e os gabinetes se terem redirecionado para a reabilitação. É um salto sem saberem nadar porque também não tinham essa formação de base nas escolas. E algumas continuam a não formar para isso. Este défice de conhecimento é que resulta depois em muitas das más interpretações da reabilitação, e das más intervenções que depois vemos no terreno. Por isso este diálogo com outros pares nossos que não têm este background da reabilitação torna-se difícil, precisamente por causa do défice de formação de base. A mudança foi muito rápida e não permitiu que as pessoas acompanhassem, as escolas também não se anteciparam a esta mudança de paradigma da construção. Grande parte dos problemas que discutimos, resultam da falta de conhecimento. Eu acredito que as pessoas fazem o que sabem com as melhores das intenções, o problema é que esse know-how está desfasado da reabilitação, em particular da reabilitação das estruturas de alvenaria de pedra, terra ou tijolo, ou estruturas de madeira.

Agora também se nota que isto se está a atenuar, nomeadamente na arquitetura, onde os novos arquitetos estão muito mais sensibilizados para uma reabilitação da manutenção e não da reconstrução. Já trabalhamos com muitos arquitetos que tem essa visão. Percebem, quando nos pedem um diagnóstico, que isso é fundamental para perceber o edifício, que isso vai condicionar a sua própria arquitetura. Portanto, isso está-se a alterar, mas é um processo lento. Aqui a formação de base está em falta, e não estas pós-graduações que existem que não são suficientes para colmatar o défice de conhecimento. Porque grande parte das pessoas não tem tempo, dinheiro ou disponibilidade para fazer estas pós-graduações, e por isso ficam-se pela licenciatura, que deve dar uma boa formação de base. Completar este défice apenas com pós-graduações é pouco.

2) Alguns autores sugerem que a tendência de crescimento da reabilitação em detrimento da construção nova se mantenha, levando a que Portugal se aproxime da média europeia. Partilha desta opinião?

T.I.: Nunca pensei muito nisso, mas acho que faz algum sentido que seja essa a tendência.

J.M.G.: Continua a não haver grande investimento em obra pública. Que é o grande motor da construção nova. As empresas que não tem essas encomendas vão virar-se mais para a obra do privado. E neste momento o privado está a fazer uma aposta em imobiliário existente e não uma aposta em novos edifícios. E uma das coisas que acho que se nota, é que toda esta crise interna e com repercussões externas, levou a que as pessoas, por exemplo deixassem de acreditar na banca, de uma forma muito simplista. E por isso já não queriam ter o dinheiro investido da mesma forma que nos anos anteriores. Então viram uma boa forma, ligado a este ambiente positivo, à reabilitação, à renovação das cidades, ao turismo, de investir o dinheiro e as suas economias. Isso é algo que fazem na reabilitação, por causa deste contexto positivo, eles preferem investir em algo que existe e vai ter uma repercussão no turismo, e nas próprias mais valias que pode tirar desse investimento. Acho que isso acaba por ser um dos motores do desenvolvimento da própria reabilitação. É um desvio de fundos daquilo que eram os investimentos tradicionais para os novos investimentos, e um deles é o investimento no imobiliário. Isso é um sinal de que há um desvio da economia para outros setores, relativamente ao que estava a acontecer anteriormente. Eu acredito que isto ainda vai ter uns anos para crescer.

T.I.: Depois há um dado novo que tem a ver com a vinda de estrangeiros nos últimos anos. Isso tem a ver com o facto de Portugal ser um dos países mais seguros do mundo. Acho que tem a ver com...

J.M.G.:...as benesses fiscais.

T.I.: ...exatamente, os reformados de uma série de países que não pagam impostos cá. O facto de cá o imobiliário ser baratíssimo até há dois anos atrás, em relação às outras cidades europeias. Apesar de haver exceções, conseguias comprar coisas no centro de Lisboa a 2000€/m2, agora já vai em 12000€/m2 em alguns sítios. E se calhar nunca vai voltar para os valores anteriores...

F.B.: ...Pois, isso é uma dúvida que eu tenho. Achas que se vão manter os valores atuais?

T.I.: Sim, depois da bolha que houve em 2008 os valores voltaram a descer. Mas se calhar este fenómeno é um bocado diferente, não sei...

J.M.G.: Assisti a uma palestra de um entendido, que dizia que vão se criar, num futuro distante, menos valias relativamente ao património que se está a comprar agora. Ou seja, é um património que está sobrevalorizado relativamente aquilo que é o próprio mercado, por isso é inevitável que mais tarde dê direito a menos valias. Mas o que ele dizia relativamente à bolha é que neste momento não está em cima da mesa a criação de uma nova bolha porque grande parte desses investimentos estão a ser feitos com fundos próprios. Mas isto são previsões de futuro, valem o que valem...

T.I.: A verdade é que os valores estão a crescer a um ritmo alucinante. Mas a verdade é que há ainda muita matéria-prima para trabalhar na reabilitação.

F.B.: Sim, é um facto. Nós temos muito mais habitação do que famílias em Portugal. Portanto, a tendência é que não se construa mais a não ser que haja uma razão especifica para isso. Mas é uma situação que já existe desde 2000, no entanto nunca tinha acontecido esta reversão, provavelmente por haver uma distorção do mercado causada por outras questões, possivelmente os bancos porque lhes interessava grandes investimentos e não pequenos investimentos difíceis de gerir.

T.I.: Eu acho que o drama vai ser mais no património edificado dos anos 60 a 90 do que neste património no centro histórico, em zonas mais interessantes. Agora falar naquelas zonas à volta de Lisboa ou à volta do Porto, Loures... 60 a 90, foi uma fase em que se construiu imenso com má qualidade, são sítios menos atrativos e por isso vão ser zonas que vão ficar mais degradadas facilmente e vão ser menos procuradas.

F.B.: E que tem um problema acrescido que é a propriedade horizontal. Porque enquanto maior parte dos edifícios históricos são propriedade vertical, o que torna muito fácil o investimento numa escala significativa...

T.I.: E esses edifícios tem muitos problemas também que são muito difíceis de resolver precisamente por isso, porque há uma série de proprietários que não chegam a acordo.

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil standardização, necessitando além disso de mais mão-de-obra do que a construção nova. Tal parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

J.M.G.: Não pensei muito sobre o assunto, mas já existem sistemas de pré-fabricação no mercado, como as famosas paredes de pladur, que se adaptam perfeitamente à reabilitação. Eu não posso é lançar uma medida standard no mercado, tem que ser um sistema de pré-fabricação, mas que seja flexível ou adaptável às circunstâncias. Agora uma parede não deixa de ser uma parede, não deixa de ter a espessura que tem, não tem que ser obrigatoriamente, mas não deixa de ser um elemento plano que faz divisória entre dois espaços. Essas caraterísticas mantêm-se numa construção nova ou numa construção existente que vai ter uma intervenção que obriga à criação de novas paredes. Por isso eu acho que não será uma prefabricação tão standard como na construção nova, mas que também permite tirar partido dessas potencialidades.

T.I.: Eu acho que estas intervenções de reabilitação são sempre caso-a-caso. Por isso também é difícil arranjar técnicos e carpinteiros que trabalhe bem. Mas acho que há estes exemplos em que as coisas são um bocadinho mais standardizadas do que o normal.

F.B.: ...Ao nível das paredes já há de facto alguma standardização.

T.I.: Sim. Paredes, se calhar nas estruturas. O carpinteiro já não faz entalhes na estrutura, utiliza uns parafusos ou ligadores metálicos. E isso pode ser utilizado tanto para construção nova como para construção existente. Mas nunca vais ser como construir uma casa modular em que já vem tudo feito.

F.B.: Aqui também existe a questão da demolição que tem que ser sempre uma coisa seletiva e obriga sempre a mão-de-obra...

T.I.: Sim, pois há as preexistências que não existem numa construção nova...

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se

continuam a utilizar componentes sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

...Reutilizável já é. As vigas de madeira são reutilizáveis, mesmo as antigas, é possível desmontar e levar para outro sítio, caso não seja útil naquele local. O mesmo já não se pode dizer acerca das paredes de tabique. Não é possível desmontar a parede de tabique e montá-la noutro sítio. A mesma coisa não é possível com uma parede de pladur. As paredes de tijolo não são possíveis de desmontar, mas o mesmo não se pode dizer de uma parede de pedra.

T.I.: Nas paredes de tabique se quiseres desmontar podes, mas ninguém faz porque ficaria caríssimo. A de pedra já se faz porque é um material mais nobre. Mas as vigas de madeira ninguém desmonta, só em casos muito pontuais. Mas de facto podia-se fazer porque em termos de desperdício se ganhava bastante, só que os empreiteiros preferem colocar vigas novas porque dá menos trabalho.

F.B.: ...não tem que tirar pregos, não tem que as nivelar... Na questão da desmontagem das vigas há outro problema, é que normalmente elas estão encastradas nas paredes e desencastrá-las não é muito fácil sem desmontar ou partir a parede.

J.M.G.: Mas acho que não respondemos à tua pergunta...

F.B.: A minha afirmação é que sistemas desmontáveis seriam uma vantagem, não numa fase de construção evidentemente, mas numa fase do ciclo de vida do edifício de reorganização. Isto porque, havendo um sistema desmontável, em teoria, poderia reutilizá-lo em futuras reorganizações e reabilitações do edifício ou de outros edifícios. Que obstáculos é que anteveem? Porque não estou a inventar nada de novo. Há um professor da FEUP que fez uma tese de doutoramento sobre paredes em madeira desmontáveis, e há outros exemplos, mas nunca se adotou nada do género.

J.M.G.: A impressão que eu tenho relativamente às estruturas desmontáveis e remontáveis, que são muito interessantes, mas que depois na prática acaba-se por não desmontar e remontar. Tenho essa perceção se calhar errada. Por exemplo, eu tenho uma parede em casa que montei e que sei que é desmontável. Eu pensar que vou para outra casa e que vou desmontar aquela para montar...não sei acho que a nossa mentalidade ainda não está direcionada para aí. Porque muitas vezes em coisas mais simples, montámos e até é possível substituir, mas depois na realidade quando avaria deita-se tudo fora e compra-se outra coisa nova. A nossa sociedade está a mudar, mas ainda é muito do usa e deita fora. Esta mentalidade do reaproveitar, de levar o sapato ao sapateiro, é uma coisa que se começa a ver novamente, mas que quase deixou de existir.

T.I.: Acho que a tendência é isso começar a mudar. As pessoas começarem a ter mais preocupação com isso.

J.M.G.: Agora, o facto de poder ser uma coisa que se monta e desmonta, claro que tem vantagens. Que vai ter vantagens no futuro, terá com certeza se as pessoas estiverem sensibilizadas para isso e se tirarem partido disso. A minha dúvida é se vão de facto tirar partido disso. É um bocado como o que o Tiago estava a dizer. Eles preferem tirar as vigas e meter vigas novas, será que não é isso que depois se vai ver na prática? Eu acho que primeiro temos que mudar as mentalidades das pessoas e ver isso como algo positivo e algo que pode permitir que o próprio edifício se adapte a outras tipologias internas. As pessoas primeiro têm que incorporar esta mentalidade de aproveitar, de desmontar e remontar. Depois, talvez esses sistemas possam ter um impacto maior. É uma visão um bocado pragmática...

F.B.: É verdade. É uma coisa que já existe um pouco ao nível das cozinhas. Já tive vários clientes que desmontam cozinhas e as voltam a montar. Em dois projetos recentes isso aconteceu. Num dos projetos, a cozinha tinha 8 anos, desmontou-se a cozinha, fez-se outra organização e aproveitaram-se os módulos todos que tinha lá, portas e tudo o que foi possível aproveitar. O que não havia fomos buscar de novo. Aquilo é standard, são módulos, por isso não há nenhuma dificuldade em fazer isto. E agora noutra obra que estamos a fazer também aconteceu a mesma coisa. A cozinha já era mais velha e de carpinteiro, uma cozinha à medida, mas a senhora quer reutilizar a cozinha. Porque gosta, porque de facto não há nenhuma razão para não o fazer, porque aquilo é desmontável. Os módulos também são standard, a única coisa que é à medida é o exterior. E a cozinha também vai ser diferente, não vai ter a mesma geometria, vai ser mais pequena. Portanto, sim é uma questão de mentalidade, nunca pensamos nisso acerca das paredes. Mas se calhar muitas vezes também pensamos “ah isto não dá jeito...se fosse um bocadinho maior”, mas depois não fazemos nada porque só o trabalho que dá deitar abaixo e fazer de novo, mais vale não fazer nada. Essa é de facto uma das motivações para o uso das paredes de pladur, porque é muito mais fácil deitar abaixo se for necessário.

J.M.G.: É o usa, deita fora, não é?

T.I.: Eu acho que em relação à utilização de paredes, o segredo está, para além da mentalização que é fundamental, a facilidade com que se vai fazer isso. Se for um processo muito complexo, não se vai fazer.

J.M.G.: E o custo, também.

T.I.: Se é uma coisa simples e que as pessoas percebam que é simples. Se calhar fazem como fizeram com as cozinhas. Como as pessoas fazem cada vez mais com os móveis. Já os reutilizam muito mais.

F.B.: Sim, hoje em dia é que se deixou de reutilizar porque os móveis duravam gerações....

T.I.: Mas agora se calhar as pessoas dão mais valor a isso e preferem arranjar um móvel antigo porque é simples. Se nas paredes se conseguir um sistema que para as pessoas seja simples é capaz de cativar mais.

F.B.: São bastantes obstáculos...

J.M.G.: E acima de tudo eu acho que passa por uma mudança de mentalidade que eu acho que já está a ocorrer. Mas ainda estamos muito longe daquilo que acontece noutros países... Passando pela própria utilização dos materiais que já existem no edifício. Quando vemos alguns casos em que as pessoas deitam paredes de tabique fora só porque preferem pladur ou porque não acreditam na madeira. Para colocar no mesmo sítio. Isso não entendo, mas se isso é possível, se as pessoas preferem, porque associam o tabique a algo que não tem qualidade, um material pobre, ter uma parede de pladur no mesmo sítio. Se isso é assim, imagina o que é passares para outro tipo de soluções. É a mentalidade das pessoas que tem que mudar, que tem que perceber aquilo que têm, se pode ser mantido, se pode ser preservado. A minha opinião é se calhar errada, mas porque é que as pessoas acham que a parede de tabique não tem qualidade? Porque as argamassas desfazem-se mais e depois acham que aquilo não tem capacidade.

F.B.: Se calhar é uma coisa relacionada com a idade. Por exemplo, o meu pai até há pouco tempo dizia que relacionava estas técnicas construtivas com coisas velhas que tinham ficado. A casa dos avós era feita assim, os tetos eram saia e camisa, e eles sabiam fazer aquilo, mas não lhe davam muito valor. Depois apareceu o betão, e eles dizem “o betão é que é bom porque nunca mais acaba”. Também passa por uma questão de prioridades. Quanto é que deveria durar uma parede divisória. Se calhar não é assim tanto, porque ao fim de 20 anos vou mudá-la, para que é que eu preciso de uma parede divisória que dure 200.

T.I.: Claro que no tabique já se coloca outra questão, porque para além de parede divisória também é uma parede resistente. Não é diretamente comparável com uma parede divisória simples.

5) Considera que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

T.I.: Isto tem a ver com aquela questão da ligação ser o mais simples possível para que este sistema seja utilizado de forma mais aberta. Se desenvolver um sistema que permita isso conseguem matar dois coelhos de uma vez. Por um lado, tornam o sistema mais simples de utilizar, e por outro não estão a criar muito barulho e tornar as intervenções muito intrusivas.

J.M.G.: Mas à partida não estou a ver porque é que uma parede divisória não vai ser reversível, mesmo as paredes de tabique em muitos casos são reversíveis. O Tiago tem um exemplo curioso que é da sala dele. Ele quis de dois compartimentos criar uma sala única, tinha uma parede de tabique no meio. Havia dúvidas se a parede estava a suportar o piso de cima, mas tirando esses problemas todos, quando ele tira a parede de tabique o soalho era corrido.

T.I.: E tinha dois prumos e dois pregos, só. Ou seja, os pregos saíram e tu não fazes ideia onde estava a parede de tabique no soalho.

F.B.: Mas ficou a mancha?

T.I.: Nem sequer mancha ficou, porque o soalho foi raspado. Mas há muitos casos em que isso não acontece, em que a parede está ligada às vigas.

J.M.G.: Mas até são muito poucos os casos em que isso acontece. Às vezes o tabuado não vem até ao soalho e tem um pequeno pórtico de madeira para não ficar com o contacto direto, depois o rodapé tapa aquilo tudo. Por isso já nas paredes de tabique elas eram muitas vezes reversíveis. Reversíveis nesse aspeto, não estamos a falar se ela estava a descarregar alguma carga ali e ao tirar a parede pode formar-se um .... Mas tirando esses aspetos que são importantes e tem que ser contemplados quando se remove uma parede de tabique. Mas na maior parte dos casos, se o chão tiver bom, e tirando alterações nos tetos e aspetos decorativos, é uma parede reversível. Portanto, não deverá ser difícil, antes pelo contrário, acho que o difícil é ter uma parede divisória que não seja reversível. Porque se tem que criar uma coisa híper complexa.

F.B.: A única coisa poderá ser a questão dos sistemas integrados nas paredes. No caso das paredes de tabique isso não existe. Mas no caso das paredes de pladur é comum passar infraestruturas lá pelo meio. Quando falo de independência é também a esse nível, ou seja, eu poder intervir em cada um dos sistemas independentemente. Uma coisa que não é possível no pladur, ou noutra qualquer parede tradicional de alvenaria, é intervir nos sistemas que lá estão dentro sem partir a parede toda...

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concorda com essa a afirmação?

* Sim, concordo que é adequado...

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

* Simplicidade.

8) Os sistemas de divisórias desmontáveis são considerados à-priori mais flexíveis. No entanto, que critérios devem ser tidos em conta para o desenvolvimento de um sistema construtivo de divisórias desmontáveis para que ele seja realmente flexível?

* Montagem fácil. Flexibilidade geométrica. Adaptação ao contexto. Possibilidade de ser cortado se o espaço onde se vai colocar o sistema é mais pequeno, ou aumentar se ele for maior.

9) Os requisitos regulamentares para uma parede divisória são relativamente baixos quando esta compartimenta espaços interiores. A ETAG03 define os requisitos de estabilidade, mas não estão definidas na regulamentação nacional exigências especificas para o comportamento acústico ou térmico. Tendo em conta o objetivo do presente trabalho que critérios de performance devem ser cumpridos pela divisória a desenvolver?

* O comportamento acústico pode ser um fator diferenciador relativamente às soluções existentes. Em particular, é importante o comportamento aos sons aéreos. O comportamento térmico e a reação ao fogo não devem ser superiores ao necessário. Os materiais escolhidos indicam que a solução vai ter um bom comportamento térmico.

10) O custo de um sistema ou componente construtivo é fundamental para determinar a sua viabilidade, no entanto sendo este um sistema desmontável devem ser considerados outros custos? Que tipo de custos?

J.M.G.: Esse é um custo que vai estar colado a tudo o que nós comprarmos. Isso vai começar a distinguir as várias soluções, porque há aquelas soluções que vão demasiado caras por causa do impacto que tem, até podem ser muito interessantes, mas depois o custo para o utilizador vai ser muito elevado. Quem começar a desenvolver produtos agora tem que pensar nisso, porque mais tarde ou mais cedo vai ser questionado sobre isso e vai ter um custo acrescido que o utilizador vai ter que pagar. Por isso é que eu acho que a analise do ciclo de vida, o LCA, não há como fugir a isso, porque toda a sociedade e toda a económica vai nesse sentido. Fala-se nas energias renováveis, fala-se nisso tudo porque de facto todos os nossos bens passam a ter um custo para além do que era o custo base, efetivo, que pagamos até hoje. Eu acho que se desenvolvermos um produto, isso tem que entrar na equação. Primeiro para que possamos agitar a bandeira, que vende, e depois porque isso vai ter repercussões daqui a alguns anos no custo efetivo.

A questão do LCA também é um campo de batalha, porque todos os fabricantes que já estão no mercado querem defender os seus produtos que já lá estão...

J.M.G.: Mas eu acho que se esses aspetos não forem introduzidos na equação, acabam por mais tarde ou mais cedo ser uma falha. Aliás, a própria reabilitação só tem a ganhar com isso.

Porque a partir do momento em que o resíduo tem um custo muito grande, as pessoas já pensam duas vezes em substituir aquilo por outra coisa. Podemos fazer os discursos todos bonitinhos que quisermos, dizermos que somos todos muito mais sensíveis ao ambiente e mais sensíveis ao impacto que tudo aquilo que nós produzimos e fazemos tem no próprio ambiente e na nossa vida, mas se isso não tiver um custo efetivo, monetário, uma taxa que pagues, haverá dois ou três que de facto vivem de acordo com esses preceitos, mas o comum dos mortais só quando lhe aplicas uma taxa e um custo acrescido é que ele pensa nessas coisas, mas pensa porque lhe sai do bolso. E por isso é inevitável que aconteça, começou com os sacos plásticos, e ira acontecer com outras coisas, quer achemos ou não que é a forma correta. Vai acontecer em cada vez mais produtos, e cada vez mais o utilizador vai ter que pagar o custo efetivo. Por isso acho que é um custo que tem que ser já ponderado, mesmo que o utilizador não o pague ainda.

Agora ia vos pedir, sem tirar muito do vosso tempo. Estes são os critérios que tenho estado a considerar. Essencialmente tenho cinco critérios gerais: sustentabilidade, montabilidade, flexibilidade, performance e custo. Estes critérios têm alguns subcritérios que me ajudam a clarificar o que isto significa. Deste lado tenho coisas relacionadas com energia incorporada, materiais renováveis, independentes e aquilo que tinha falado há bocado. Na montabilidade, questões relacionadas com a comunicação com a pessoa que vai montar, com a simplicidade de montagem, e com a praticabilidade da montagem em sítios mais difíceis. Na flexibilidade tem a ver com as questões de flexibilidade geométrica, como o sistema se consegue adaptar às situações que é esperado que uma parede tenha que resolver, integração de infraestruturas e modularidade. Intermutabilidade tem a ver com a capacidade de trocar painéis ou partes do sistema, tem a ver com os encaixes. Personalização tem a ver com a capacidade que o painel tem de adaptar-se aos requisitos do utilizador. Performance, são os critérios de performance, estabilidade, acústica e questões térmicas. E no final são as questões de custo.

J.M.G.: O custo de reutilização é que tenho alguma dificuldade em compreender e como tu imputas isso algures.

O custo de reutilização poderia estar relacionado com determinadas coisas que não sejam reutilizáveis. Por exemplo, eu poderia ter um rodapé que não fosse reutilizável, fosse adaptado aquela circunstância e caso eu quisesse usar o sistema noutro sítio teria que deitar peças fora.

J.M.G.: Mas como é que tu ponderas uma coisa dessas? Isto é um custo que tu querias imputar aonde? Ao utilizador?

Não, não, é um custo que o sistema tem para que seja reutilizável.

T.I.: Para o utilizador que vai comprar saber quanto é que vai gastar se um dia o reutilizar?

Sim, eu poderia não divulgar essa informação, mas para ser rigoroso na análise teria que perceber que existe esse custo inerente ao...imagina que tens uma peça que é personalizada, estamos a falar da questão da personalização, se eu tenho peças que são modulares elas podem ser usadas em sistemas diferentes, se elas forem tão especificas que só dizem respeito aquele caso...por exemplo, imagina que eu estou a desenhar uma solução em que eu posso ajustar o rodapé para que ele seja igual aos existentes. Isso significa que aquela peça é daquele sistema, se eu a quiser utilizar noutra circunstância aquilo poderá não servir. É um custo um bocado esotérico, não é no momento de compra que se verifica dez anos mais à frente...

J.M.G.: Se eu pensar que a parede em si é uma parede despojada de revestimentos, rodapés, sancas, o que é que seja, estou eu aqui a hipotisar, constróis ali depois isto seriam tudo o quê? elementos secundários ou acessórios? Um rodapé é um acessório? Agora posso aplicar revestimentos ou não posso. Que tipo de revestimentos é que posso aplicar? São amovíveis ou não são amovíveis? Se eu tentar mudar para ali, vou mudar o quê? Vou mudar este módulo que comprei e vou ter que aplicar outros revestimentos. Vou ter que tirar os revestimentos que lá estão, se eu não quiser aqueles revestimentos, é uma parede de uma cozinha que passa a ser uma parede de uma sala. Teria que poder tirar os cerâmicos. Não sei como, há ou não possibilidade de aplicar novos materiais, mas isso é algo que a pessoa já sabe. Mas se isso forem tudo acessórios à própria parede e não fizerem parte da própria parede, porque para mim uma parede é fechar aquele vão. Tudo o resto são acessórios, são elementos arquitetónicos ou decorativos que permitem ter uma fachada que tem outro tipo cor ou textura.

Se eles não forem acessórios, ou seja, se estiverem integrados na própria parede já deixam de ser acessórios...

J.M.G.: Então aí passa a ser uma parede personalizada.

Exatamente, e aí já um custo real.

J.M.G.: É um custo real final para aquela parede, mas também pode criar obstáculos à reutilização.

Exatamente

J.M.G.: Por isso eu prefiro pensar num módulo cru, que até consegues vende esse modulo cru. E agora a pessoa já sabe que tem que ter ali um rodapé, e vai ter que aplicar um rodapé que é igual ao que está ao lado. Porque eu posso ter um rodapé baixinho, alto, trabalhado ou não, tu vais criar essas hipóteses todas nessa parede?

Eu desenvolvi uma solução em 2014/2015. E uma das opções que o sistema tinha era gerar um rodapé, basicamente uma placa de madeira, que ficava junto ao chão, mas com a altura do rodapé que lá estava. Depois tinha um sistema de painéis de madeira e cortiça, o contraplacado estava embutido na cortiça, e o contraplacado estava ali para dar resistência à estrutura, funciona um bocado como o pladur.

...para ser transportada e etc...

...para a cortiça ser transportada não se desfazer tão facilmente e para dar resistência à parede. Porque tinhas os montantes, e estes por si só não tinham muita resistência porque são muito fininhos, porque são muito altos e etc. É como no pladur, o painel de gesso cartonado é que dá resistência à parede no plano. E então eles estavam ali com a mesma função, o que significava que eu tinha um padrão que o utilizador poderia querer ou não e querendo poderia determinar que começasse a uma altura do chão e no teto. Então existia a possibilidade de gerar um rodapé que também tinha a vantagem de poder ser compatibilizado com rodapés existentes. Só que isso tem essa consequência, a partir do momento em que eu gero uma coisa que está compatibilizada com o existente eu tenho uma coisa que é personalizada e já não se adapta noutras circunstâncias. Já não é reutilizável.

J.M.G.: E por exemplo a impressão?

A impressão?

J.M.G.: É uma coisa personalizada, mas é um rodapé que é impresso, é um desenho que é impresso sob a parede.

Ah sim!

J.M.G.: É uma coisa personalizada impressa na própria parede.

J.M.G.: Tem uma vantagem que se eu quiser ir embora posso pintar por cima.

J.M.G.: Agora começam-se a falar de impressões em grande escala. Há aquelas pessoas que já fazem impressões em papel de parede impresso na altura, fazes o desenho e ele imprime-te o papel para tu meteres na tua parede, ou seja, impressão em grande escala. Mas são coisas doutras áreas, por isso estou a mandar bocas...mas o que continuo a imaginar a tua parede é uma coisa de base, sem revestimentos, sem rodapés adapta-se e fecha o buraco, com porta ou sem porta. Tudo o resto deveriam ser elementos que aí sim são personalizados que o próprio fabricante poderia personalizar, mas já não é a própria parede. Agora o que é que quer? Um rodapé assim, personalizado? Ou ele tem ou tem alguém que faz o rodapé e que vai lá e coloca. É um remate. Agora, pensares numa parede que se vai adaptar a todas as circunstâncias, parece-me uma coisa um bocadinho difícil, vais ter um custo acrescido que se calhar para o utilizador passa a ser pesado. Vais ter que caso-a-caso, ele vai ter que saber o que é que quer, fazer o formato do rodapé, o desenho, o corte. Vais ter que moldar aquele rodapé com aquele comprimento. Se pensares apenas numa parede como um elemento que fecha e depois tudo o resto são acessórios... Agora tens que permitir que a parede receba todos os acessórios, permitir rodapés, todo o tipo de revestimentos, enfim porque se não conseguires permitir todo o tipo de revestimentos passa a ter uma utilização mais restrita. Só dá para compartimentos onde não queiras aplicar cerâmicos na parede. Ok, pode ser uma hipótese, mas estás a limitar a própria utilização. Depois tens que puder remover esses cerâmicos, o caso do cerâmico ou uma pedra é a coisa mais impactante. Vais ter que permitir que ele remova, porque agora vai ter um revestimento diferente porque vai ter outra posição. Por isso se tiveres uma coisa de base que por colagem ou adição outros elementos amovíveis, eu acho que aí sim passas a ter uma parede que podes transportar para onde quiseres, com todas as limitações que já vimos das infraestruturas e etc. Se começas a ter uma coisa muito personalizada, a flexibilidade acaba por se perder um bocadinho.

Claro que sim

J.M.G.: Agora eu acho que tens que pensar num modulo, que tenha a possibilidade de adicionar essas coisas todas, mas ele próprio funcione em qualquer circunstância. Ele fecha isto em qualquer circunstância. Tá fechado, ok.

Pensar essencialmente o sistema e não os casos particulares.

J.M.G.: Exatamente, eu acho que os casos particulares deves deixar à margem e dizer que ele permite adicionar elementos que personalize a minha parede, mas a minha parede é isto. Não são os elementos decorativos. É como o tabique não é o rodapé, apesar de que muitas vezes o rodapé funciona como ...mas tirando isso à parte, não é o rodapé nem depois o trabalho de teto. A parede é aquela e agora adiciono-lhe coisas... Acho que devias pensar numa coisa mais tout-cour e o resto como adições que ele tem que permitir. Se não, não poderá ser flexível para usar neste ambiente e noutro tipo de ambiente que tem placagens

ANNEX H – Interview with Vasco Freitas

Vasco Peixoto Freitas is an engineer and full professor at Faculty of Engineering of the University of Porto. His research is focused on the hygrothermal behaviour of buildings. The interview was conducted at the Faculty of Engineering in Porto, on November 20th, 2018.

1) A reabilitação tem ganho uma relevância crescente no panorama nacional. Quais são as maiores dificuldades com que os engenheiros e os arquitetos se deparam nesta transição - de uma indústria orientada para construção nova, versus uma indústria para a reabilitação?

V. F. - Em primeiro lugar, as maiores dificuldades prendem-se com uma mudança tecnológica, as empresas não estavam preparadas para certas tecnologias, e essa transição tem sido feita com alguma dificuldade. Em segundo lugar, por outro lado, está-se a exigir uma velocidade ao processo de reabilitação que é incompatível com estudos, diagnósticos aprofundados e com projetos suficientemente pormenorizados que vai constituir um problema. Terceiro, embora haja uma flexibilização a regulamentação continua a ser uma perturbação e é fundamental uma regulamentação específica para esta área da reabilitação.

2) Alguns autores sugerem que a tendência de crescimento da reabilitação em detrimento da construção nova se mantenha, levando a que Portugal se aproxime da média europeia. Partilham desta opinião?

V. F. - Eu não tenho dúvida existindo em Portugal 4 milhões de famílias e 6 milhões de frações habitacionais, é expectável que a reabilitação tenha um peso crescente. Quanto maior é o PIB, mostram as estatísticas, maior é a percentagem de reabilitação face à construção, à construção nova em geral a nível mundial. No entanto, em Portugal nós temos a noção de que as estatísticas ainda não mostram isso, mostram ainda um maior investimento na área da construção nova, mas reconheço que as estatísticas associadas à reabilitação podem ser deficientes, podem estar por defeito, porque não há um registo completo. Em síntese, acredito que a médio prazo o peso da reabilitação em Portugal terá que ser muito elevado, equivalente ao da construção nova.

3) A reabilitação de edifícios, pelo seu carácter cirúrgico e pontual, é por natureza de difícil standardização, necessitando além disso de mais mão-de-obra do que a construção nova. Tal

parece ser contrário à tendência para a adoção de um maior grau de pré-fabricação e automação na construção. Como se podem conciliar as duas tendências?

V. F. - A reabilitação exige mão-de-obra especializada que não temos, e que perceba qual é a pré-existência em termos construtivos para poder atuar de uma forma correta, e reconheço que a pré-fabricação tem que ser adaptada, ou seja, tem que produzir uma espécie de elementos num kit, mas num kit que só parcialmente vai ser construído. Não estou muito seguro de que haja uma grande percentagem de pré-fabricação na reabilitação quando ela é não intrusiva, o problema é que muita da reabilitação que nós estamos habituados a fazer entre nós é uma reabilitação muito intrusiva, até posso utilizar quase esta palavra de "preservar a fachada" para manter o aspeto estético exterior, mas isso é da construção, não tem a ver com a reabilitação, no sentido clássico da reabilitação tal qual eu entendo, pouco intrusiva, eu acho que a pré-fabricação pode fazer sentido mas tem que ser pensada não como um todo mas como parte que possam ser integradas.

F.B.: A pré-fabricação parcial, nesse caso?

V. F. - Parcial.

4) Numa perspetiva ambiental, reabilitar é melhor do que demolir e reconstruir, a manutenção das estruturas existentes aumenta o seu tempo de vida reduzindo a necessidade de novos materiais e reduzindo consequentemente os gastos energéticos e as emissões. No entanto, o processo de reabilitação produz um volume significativo de resíduos, e porque se continuam a utilizar componentes e sistemas construtivos não reutilizáveis no processo de reabilitação, a importância destes resíduos no ciclo de vida do edifício ganha cada vez mais preponderância. A alternativa parece ser a utilização de sistemas construtivos desmontáveis e reutilizáveis. Que obstáculos antevê na adoção deste tipo de sistemas?

V. F. - Eu penso que a reabilitação é por natureza sustentável, porque aproveita imenso dos elementos existentes e obriga a aplicar menor volume de materiais, menor quantidade de novos materiais. Os resíduos são uma inevitabilidade, e portanto, eu acho que há que encontrar na lógica da recuperação, da reutilização de resíduos uma forma de os reutilizar tal qual como noutros sectores da construção. Eu acho que a possibilidade de se utilizar sistemas construtivos desmontáveis e reutilizáveis temos de perceber onde está a utopia e o realismo, de acordo com a minha experiência, sobretudo em construções antigas, aquelas em que a pedra, a madeira, a cal são os elementos essenciais, se há elementos estruturais que ainda eventualmente, possam ser reaproveitados ao nível de materiais de acabamento, etc., essa reutilização eu não vejo que seja algo de muito preponderante a médio prazo.

5) Considera que a independência entre componentes ou sistemas construtivos com ciclos de vida diferentes, no caso específico entre as divisórias e a restante construção, um critério importante a ter em conta na reabilitação?

V. F. - A análise do ciclo de vida é extremamente importante, mas temos que ser realistas e perceber até onde é que a podemos levar. No caso da reabilitação e no caso das divisórias, nós temos dois problemas importantes a ter em consideração. O primeiro, é que muitas das divisórias não são propriamente elementos secundários, são elementos principais no comportamento estrutural do edifício, não podem ser retiradas, demolidas de uma forma simples.

No caso concreto da pergunta que me está a colocar....

F.B.: Eu refiro-me especificamente às divisórias não estruturais...

V. F.: - As divisórias antigas são quase sempre estruturais, porque controlam a deformabilidade. E, portanto, eu diria assim: Nós temos necessidade de espaços diferentes e de dimensões diferentes dos compartimentos, mas essas velhas divisórias são elementos que são absolutamente imprescindíveis ao funcionamento deste tipo de edifícios. E, portanto, não sei se as podemos retirar e como é que aquilo que lá vamos por de novo se pode compatibilizar. É uma pergunta muito vaga por isso não sei se fui capaz de lhe responder completamente.

F.B.: O que eu estou a referir-me é aos componente e sistemas construtivos, ao facto de serem independentes. Alguns autores têm falado desta necessidade de haver uma capacidade das estruturas serem desmontáveis, e concretamente na reabilitação alguns autores têm referido que quando as intervenções são novas, que essas novas intervenções sejam separáveis da estrutura original permitindo a reversibilidade da intervenção ao original a qualquer momento. E é nesse sentido que esta questão vem.

V. F.: Eu percebi, agora colocando a questão da reversibilidade a resposta é diferente. Quando estamos a falar de património que faz parte de uma herança cultural que é preciso preservar, eu percebo o conceito de reversibilidade e dessa possibilidade de colocar soluções que imediatamente possam voltar atrás, mas cuidado que muita da reabilitação que nós temos que fazer é sobre o património corrente, e sobre o património corrente a reversibilidade pode ter algum significado, mas não tem o mesmo significado no património monumental, no património classificado, daquilo que é relevante. Por outras palavras, eu acho que as divisórias existentes fundamentalmente devem ser preservadas porque fazem parte do todo e da lógica construtiva, as novas divisórias que fará todo o sentido que possam ser flexíveis e que possam estar facilmente dissociáveis do todo.

6) Vários autores têm falado sobre as potencialidades que se abrem para a construção com a integração do desenho e da fabricação digital. Esta ligação instantânea e flexível entre o desenho e a produção parece ser particularmente adequada aos desafios da reabilitação. Concorda com essa afirmação?

V. F.: O futuro passa pela digitalização, e portanto, não tenho a menor dúvida, a conceção, o projeto, a reabilitação vão ter que utilizar essas ferramentas inegavelmente. É evidente que quando trabalhamos num objeto em termos conceptuais, que é uma construção nova, essa digitalização ou essas novas ferramentas são de muito fácil integração sem qualquer dificuldade e de uma enorme utilidade. Na reabilitação também tem essa mesma utilidade, só que o exercício é mais complexo porque temos um objeto com determinadas caraterísticas e quando se trabalha em BIM ou algo equivalente nós temos sempre um bocadinho mais de dificuldade na reabilitação do que na construção nova, mas não tenho dúvida de que para intervenções de grande importância económica o futuro passa claramente por dar maior ênfase e maior importância a essas ferramentas.

F.B.: Além dessa questão que referiu do BIM, mas eu quando faço esta questão levo-a um bocadinho mais além e penso especificamente na fabricação digital. Ou seja, na fabricação em que o desenho produzido no computador é útil para a produção dos componentes construtivos que permitem adequar o que é realizado ao contexto específico do que é a obra, ou no caso do que é a reabilitação. Como disse é muito mais complexo, porque obriga a fazer levantamento ou a ter uma imagem do real, tal qual ela existe e que de facto isso é muito mais complexo.

V. F.: Fabricação digital é sempre importante quando estamos a fazer algo que é industrializável. Quando estamos a trabalhar em verdadeiros protótipos, em que são protótipos que estão condicionados pela pré-existência é mais difícil, mas não estou a dizer que não seja possível e que não seja esse o futuro.

7) Tendo em conta que o objetivo da solução construtiva a desenvolver é que esta seja passível de ser configurada e montada ou desmontada por utilizadores sem experiência prévia em construção, que critérios devem ser considerados para atingir esse fim?

V. F.: Já nos anos 60 havia a visão em França pelo Professor Blacher que a construção era um kit, era uma construção por componentes, e portanto, só tínhamos que pegar nas peças do Kit, montá-las, e se as quiséssemos desmontar também as podíamos desmontar, e seguindo esse puzzle qualquer utilizador mesmo sem experiência o poderia fazer. Eu acho que esta lógica é uma lógica que é possível, é uma lógica que passado tantos anos eu diria que a construção continua a ser construção de protótipo, em tudo, seja nova ou de reabilitação, por isso é que há patologias, há problemas na construção, há sempre a diferença, cada edifício é um edifício... Eu diria que é preciso ter alguma prudência face à experiência do passado, em permitir que o utilizador tenha essa capacidade de poder montar e desmontar, portanto, não é um caminho que eu veja muito promissor num horizonte médio.

8) Os sistemas de divisórias desmontáveis são considerados à-priori mais flexíveis. No entanto, que critérios devem ser tidos em conta para o desenvolvimento de um sistema construtivo de divisórias desmontáveis para que ele seja realmente flexível?

V. F.: Existe um conjunto das exigências da física das construções que têm de ser tidos em consideração. Se não houver um método exigêncial para poder selecionar essas divisórias não terá sucesso, ou seja, terá de haver um conjunto de exigências feitas do ponto de vista térmico, acústico, de segurança, durabilidade, fogo, humidade, etc., e essas exigências depois terão de ser traduzidas por parte dos fabricantes num conjunto de valores que é o desempenho e que caracterizem verdadeiramente como é que o seu componente funciona. Eu por aí vejo um grande caminho, um grande potencial, mas se não for seguida uma lógica e um método exigêncial na seleção dessas divisórias nós cairemos numa abordagem qualitativa, somente qualitativa que não será a resposta aos problemas concretos.

9) Os requisitos regulamentares para uma parede divisória são relativamente baixos quando esta compartimenta espaços interiores. A ETAG03 define os requisitos de estabilidade, mas não estão definidas na regulamentação nacional exigências especificas para o comportamento acústico ou térmico. Tendo em conta o objetivo do presente trabalho que critérios de performance devem ser cumpridos pela divisória a desenvolver?

V. F.: Claro que as ETAG são documentos de enorme relevância. Claro que as primeiras exigências são sempre exigências de segurança. Exigências de segurança em divisórias prende-se claramente com exigências de estabilidade, com impacto, e com segurança contra-incêndios. Essas três exigências são...

Mas mesmo em divisórias interiores de compartimentação de espaços.

V. F.: Pode ter divisórias interiores que possam estar a separar um interior de uma zona comum dentro do edifício, portanto a questão do fogo pode colocar-se. Mas depois há outro tipo de exigências que têm que ser tidas em consideração. Exigências de carácter térmico, exigências de carácter acústico, higrotérmico relacionado com a humidade, exigências com o próprio processo de ventilação, toda essa integração, todas essas exigências impostas pela física das construções devem ser definidas e quantificadas. E mesmo que não exista um critério objetivo poderia haver uma recomendação. São coisas distintas. Uma recomendação é uma perspetiva técnica dizendo em que sentido é que se deve avaliar, não é uma obrigação, enquanto um requisito é uma obrigação, enquanto um regulamento é uma obrigação, uma recomendação dá uma indicação precisa do caminho que se deve seguir.

F.B.: Quando refere uma seleção exigêncial, entendemos que a solução não está definida totalmente, mas tem a capacidade de se adaptar a um conjunto de contextos onde existe exigências de comportamentos para essa parede, é isso?

V.F.: Não há uma solução, há-de haver um leque de soluções e essas soluções têm um certo desempenho, isso é o que o mercado vai definir, mas do ponto de vista conceptual para se poder escolher A B C ou D, cada uma destas soluções, é necessário ter uma matriz de exigências, e essa matriz de exigências depois tem de ser comparada com aquilo que é o desempenho. E no ponto de vista do projeto, não há um caminho único, há várias propostas alternativas, e essas propostas alternativas umas são adequadas e outras não são, depende dos contextos da aplicação.

10) O custo de um sistema ou componente construtivo é fundamental para determinar a sua viabilidade, no entanto sendo este um sistema desmontável devem ser considerados outros custos? Que tipo de custos?

V.F.: Numa linguagem muito geral, o custo tem a ver com o custo inicial, tem a ver com o custo de manutenção que pode ser preciso para estes sistemas, e depois tem de ser perceber qual é a durabilidade para perceber o fim de vida, e com isso estamos em condições de ter a ideia qual é o custo para um determinado período de vida. É evidente que se o sistema é desmontável e vai ser reutilizado, é preciso depois saber qual é o custo de reutilizar, de transformar e de adaptar, que já não é o custo inicial. Há sempre uma percentagem de materiais que não são recicláveis a 100%, portanto há sempre uma perda. E essas perdas são por degradação, a remontagem obriga a perdas. Eu lembro-me de estudar um edifício que estava num sítio e foi remontado noutro. A quantidade de novos materiais que foi necessário, porque os primitivos ao serem desmontados já não puderam ser utilizados, foi enorme. Essa parcela tem que ser tida em consideração. Agora para se ter números exatos é preciso repetir-se muitas vezes as operações para se ter uma base de dados suficiente para poder estimar custos médios do ponto de vista da reutilização do material. Evidentemente que do ponto de vista da sustentabilidade o transporte será importante, mas também o que é que possível reaproveitar e o que não se aproveita quais são os respetivos custos.

[20:00]
F.B.: Tem mais algum comentário que gostaria de fazer sobre o tema?

V.F: Não eu respondi-lhe um bocadinho a quente, no sentido de satisfazer o seu desejo. Eu percebo que o que está aqui é jogo é a cortiça, reciclada?

F.B.: Não, o aglomerado negro de cortiça e madeira. São os materiais base, não quer dizer que não possa ter outros, como falou do comportamento exigêncial.

V.F: Eu conheço bastante bem o aglomerado negro, estive na fábrica e conheço bem a pessoa que em Portugal mais a promove. Só para dizer que me parece um material em que os desperdícios podem ser sempre reaproveitados. Tem essa vantagem. A madeira que também vai utilizar do ponto de vista estrutural, é um material ...desde que as condições de humidade, imagine que é uma casa de banho, vai ter problemas complicados. Mas acho que a ideia é interessante. É um tema complexo na primeira leitura, mas estou a imaginar que tenha uma capacidade industrial de fazer um compósito em que está a madeira e está a cortiça, ou outro material de revestimento, e funcione como um kit flexível, com várias soluções alternativas. Explique-me só estes métodos computacionais de geração automática, o que é que pretende?

F.B.: Eu faço programação com ferramentas especificas para arquitetos e a ideia é desenvolver uma gramática de componentes construtivos que podem ser programados no computador e ele desenha o sistema construtivo propriamente dito. A ideia é que exista uma interface que o utilizador possa usar para captar o espaço, onde pretende fazer a intervenção. E depois ele próprio desenhar a sua intenção. Desejo construir aqui uma parede ou duas paredes, ou quero por aqui uma porta. Depois o que o sistema faz é automatizar o processo de geração da solução construtiva, obtém logo uma informação acerca do custo e pode fabricar a solução com CNC. Essencialmente é isto, e que o kit possa ser entregue, um bocado como o IKEA o faz, componentes planos, que são entregues no local e que depois o utilizador possa montá-los. O papel do sistema computacional, além de gerar a solução é também gerar as instruções de montagem. É uma parte muito complexa do problema, que é como é que um utilizador...primeiro temos sistemas que vão variar na forma, e na ordem de montagem, e temos que transmitir..

V.F: Há bocado abordei o problema da montagem, mas nessa lógica que agora me explicou, dizendo assim. Eu tenho algo que é plano, que é simples, que é facilmente transportável, algo que pode ser reciclado, mas realmente eu preciso de um auxiliar na perspetiva de conceção, escolha e montagem do sistema. Isso faz todo o sentido. Há bocado falou das interfaces e também faz todo o sentido. Quando está a aplicar sobre um pavimento rígido deformável, quando tem contornos em pedra, mas isso é pormenorização. A palavra pormenorização não esteve aqui, mas eu acho que a montagem tem que passar por um conjunto de pormenores tipo, que representem quase tudo e depois quando está a fazer a conceção para o caso concreto tem um componente mais simples e depois são remates que obriga a ter umas peças ou acessórios ou componentes ou dispositivos que permita montar tudo. Isso é um grande desafio.

F.B.: Especialmente no caso da reabilitação quando estamos a falar de edifícios antigos em que a parede terá um rodapé, ou então um lambrim, o teto pode ter uma sanca, eventualmente o chão pode estar deformado. São situações muito complexas. Muito obrigado, se quiser...

V.F: Engraçado que eu nunca fiz nenhum trabalho de investigação com cortiça a não ser nos anos 80, que era o regranulado de cortiça na térmica, mas eu acho que a cortiça é um produto português muito interessante. Que faz sentido ser avaliado economicamente e tecnologicamente e essa ideia do kit e das interfaces, portanto eu acho que tem aqui um tema interessante que eu só agora, depois das perguntas que fez, é que estou a perceber de uma forma um bocado mais global. Dizendo assim, eu quero montar uma cozinha e tenho um sistema que me ajuda a dizer todas as peças disponíveis, todos os parafusos, eu podia ter a cozinha toda e chego ali a uma empresa qualquer, compro tudo numas caixinhas e monto. Depois se quiser desmontar quase que deito tudo fora, porque depois é mais difícil desmontar....

F.B.: Mas é possível, nas cozinhas.

V.F: Sim eu posso remontá-la num sítio qualquer. Portanto numa divisória não importa o que tenho, se é um pavimento de betão, se é uma parede disto ou daquilo, eu tenho uns componentes mais ou menos pensados de madeira e cortiça, e com isso eu estou em condições de arranjar uma espécie de um kit que eu próprio monto e tem que satisfazer um certo desempenho. Eu não estava a pensar nessa flexibilidade toda do armário de cozinha.

F.B.: Foi buscar o armário de cozinha e é precisamente um dos exemplos que eu estou a utilizar. Alias, uma das grandes dúvidas acerca disso é como é que apareceu o armário de cozinha? Porque o armário de cozinha é um kit, e tem todas as vantagens...eu posso a qualquer momento alterar uma porta, ou alterar as portas todas se quiser mudar o aspeto do armário. Eu posso tirar um componente e comprar no mercado outro igual e colocá-lo no mesmo local. À partida ou na maior parte das vezes, embora às vezes haja problemas, as ferragens são substituíveis. Portanto, tem um conjunto de aspetos úteis para este tipo de circunstância. Não sei como surgiu, acho que não houve ninguém que tivesse inventado isto. Foi uma coisa que foi ao longo do tempo aparecendo...

V.F: Passou a ser tudo modular, enquanto não era modular era mais difícil. Depois quando os eletrodomésticos passaram a ter todos as mesmas dimensões...

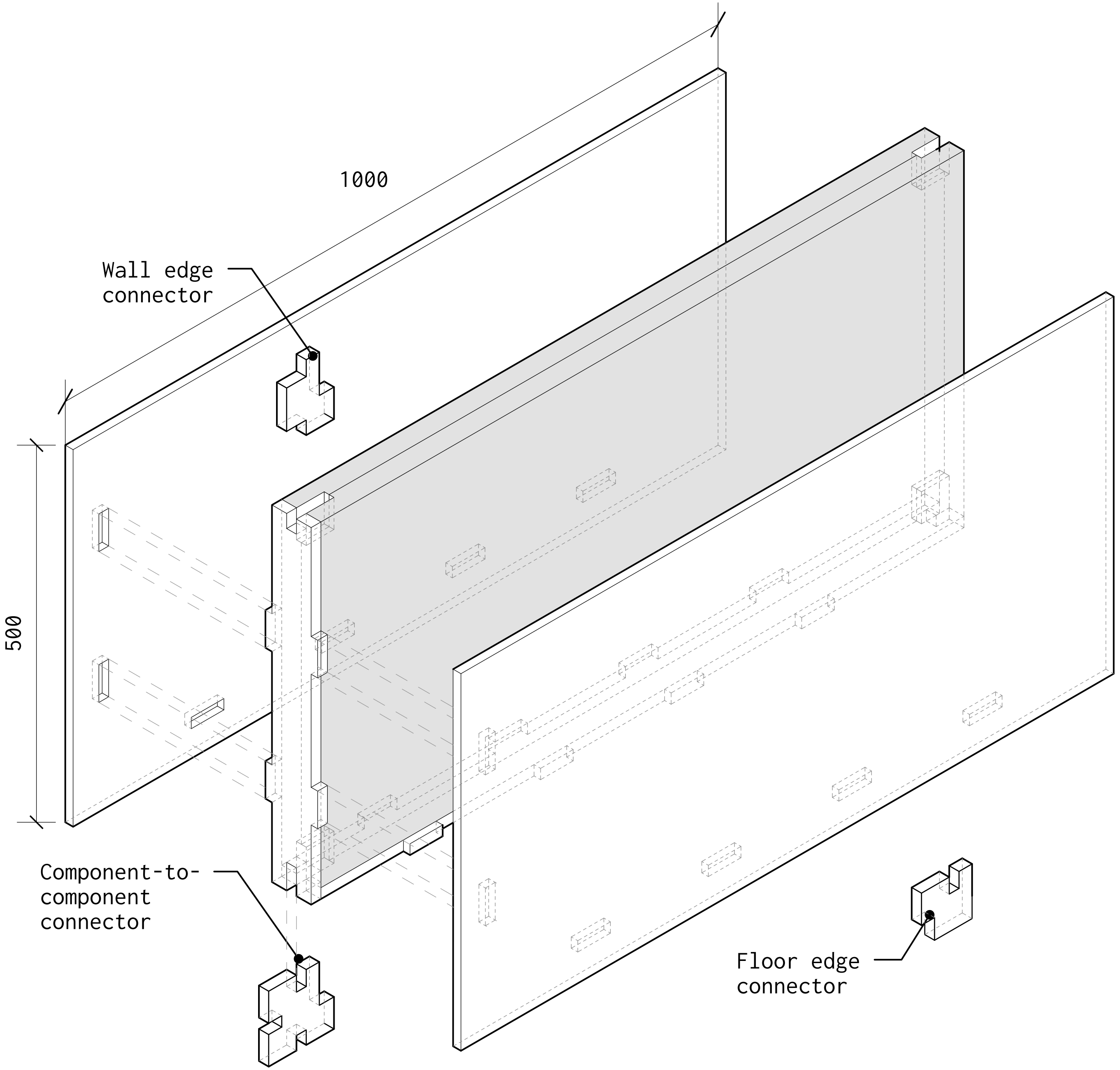
F.B.: Pois, mas eles passaram a ter essas medidas porque se adaptaram ao sistema, e quem é que propôs o sistema?

V.F: Alguém pensou se calhar.

F.B.: O pouco que sei acerca dessa questão é que foram os fabricantes de máquinas para carpintaria que foram promovendo as máquinas o que levou de certa forma os fabricantes de cozinhas e eletrodomésticos se começarem a adaptar aquela solução. O que levanta questões sobre o que eu estou a fazer, se deve ser pensado desta forma. Se tem que ser uma coisa aberta, modular. Porque a reabilitação põe esta questão que é idealmente um sistema pré-fabricado para ser reutilizável e para ser sustentável, deveria ser o mais modular possível. Portanto os componentes deveriam ser o mais iguais possível, mas por outro lado a reabilitação impede que isso seja assim. Porque são tudo casos específicos em que eu vou ter que me adaptar ao que existe e por isso vai haver muitas peças que não vão poder ser reutilizadas. Qual é o equilíbrio que eu estabeleço entre o que é modular e o que não é modular. Isso é uma das questões mais difíceis de abordar.

V.F: Aqui nas divisórias há o problema exigêncial. A cozinha tem poucas exigências, tem algumas exigências de forma e geometria, etc, mas cuidado que a física das construções dos edifícios nas divisórias tem algum significado: térmica, acústica e o fogo. E isso é mais complicado porque tem que funcionar aí a pormenorização, a ligação aquilo que são os pontos críticos dessa solução, sabendo quais eles serão é fundamental.

ANNEX I – Open reWall v2



Author
Filipe Brandão, Arq

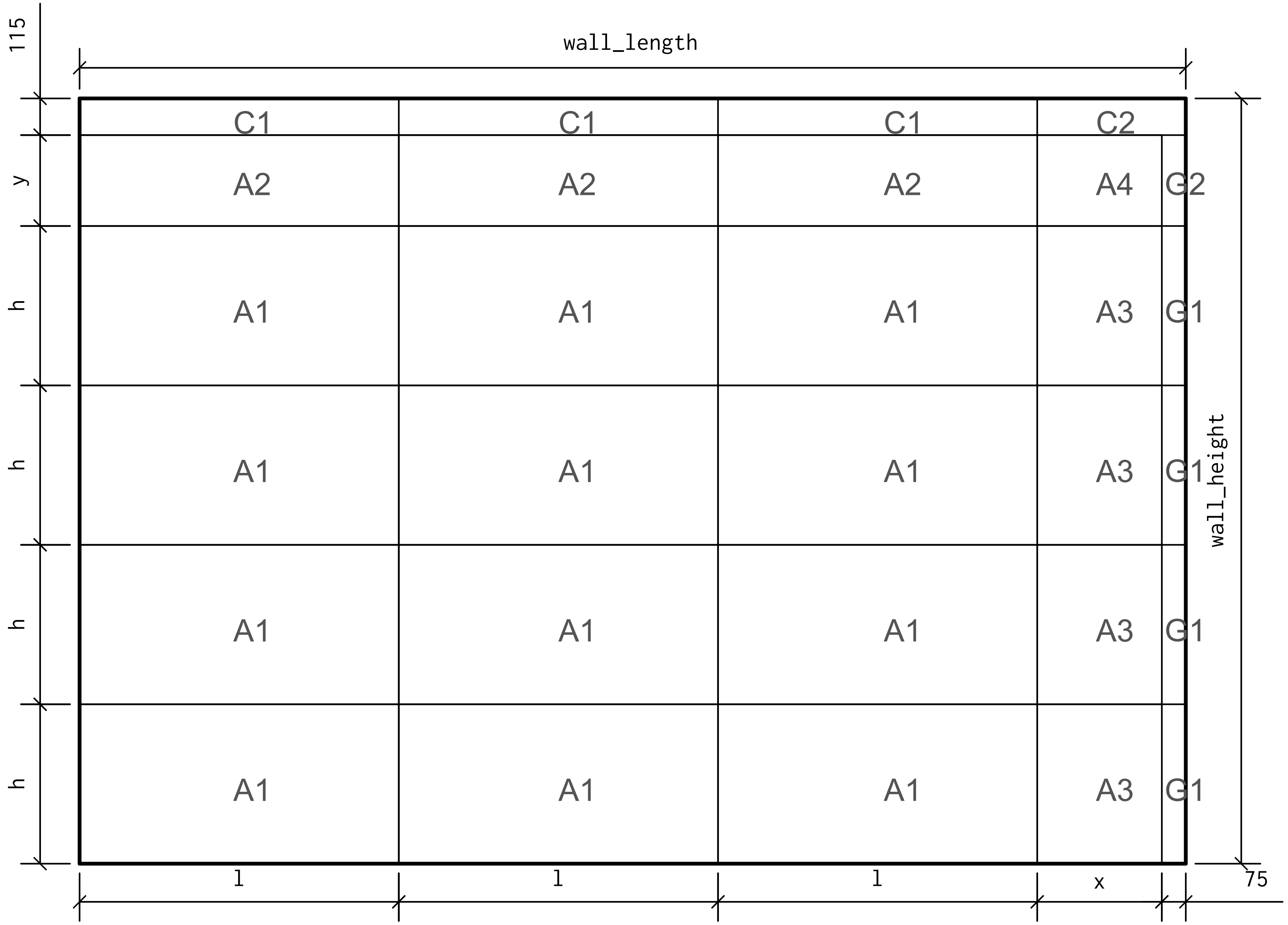
Project
ORW v2.0

Content
Type A component exploded axonometric view

Scale
no scale

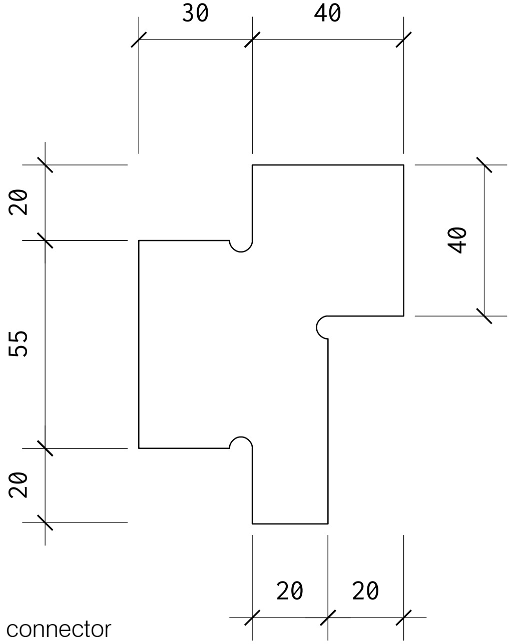
Code
ORW02_EX.002.00

Date
November 2017

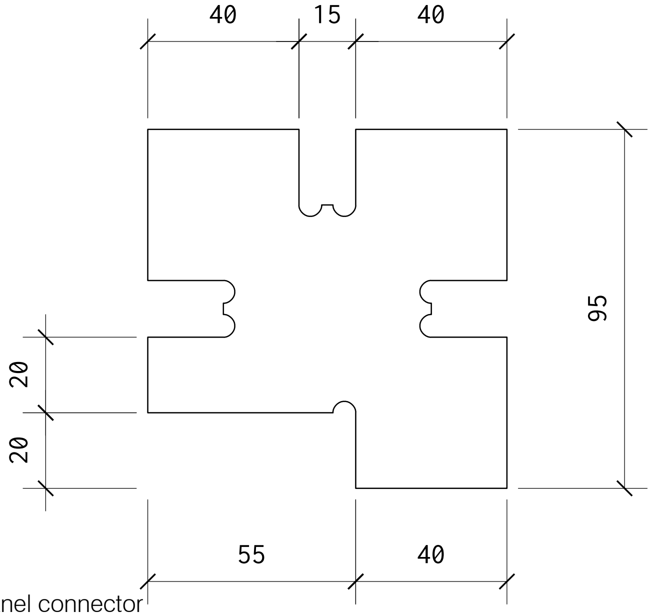


y = wall_height - 115 / h - Floor(wall_height - 115 / h)
x = wall_length - 75 / l - Floor(wall_length - 75 / l)
l_min = 165mm h_min = 150mm

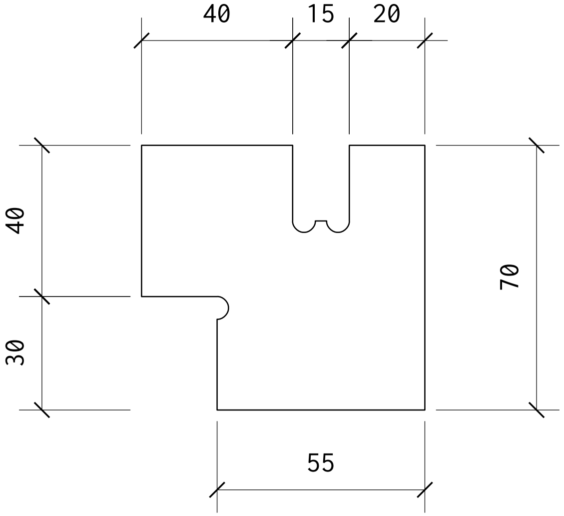
Author
Filipe Brandão, Arq
Project
ORW v2.0
Content
Functional and dimentional subdividion elevation
Scale
1/50
Code
ORW02_EX.003.00
Date
November 2017



Wall edge connector



Panel-to-panel connector



Floor edge connector

Author
Filipe Brandão, Arq

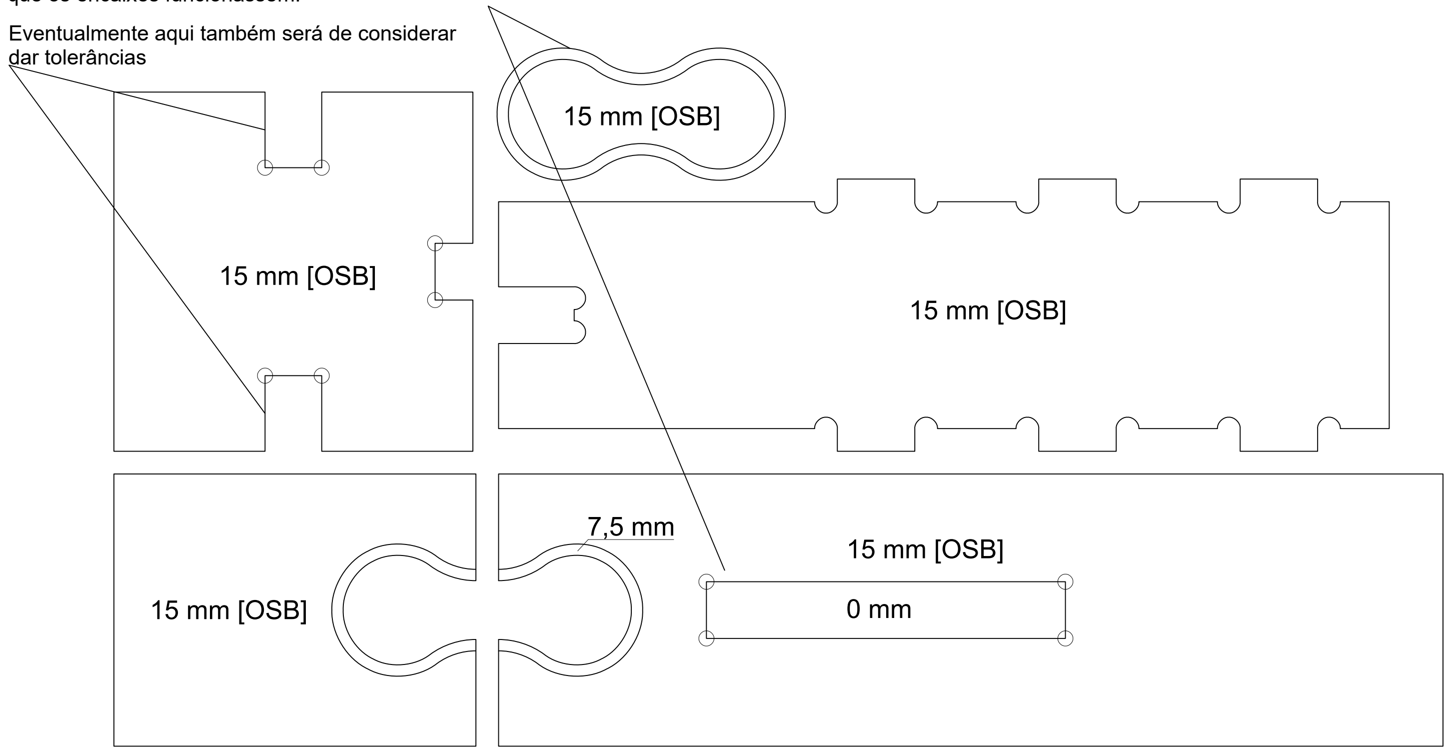
Project
CRW v2.0

Content
Connector details

Scale
1/2

Code
CRW02_EX.004.00

Date
November 2017



Não foram dadas tolerâncias o que aumentou o trabalho necessário para limpar as peças e permitir que os encaixes funcionassem.

Eventualmente aqui também será de considerar dar tolerâncias

Author
Filipe Brandão, Arq

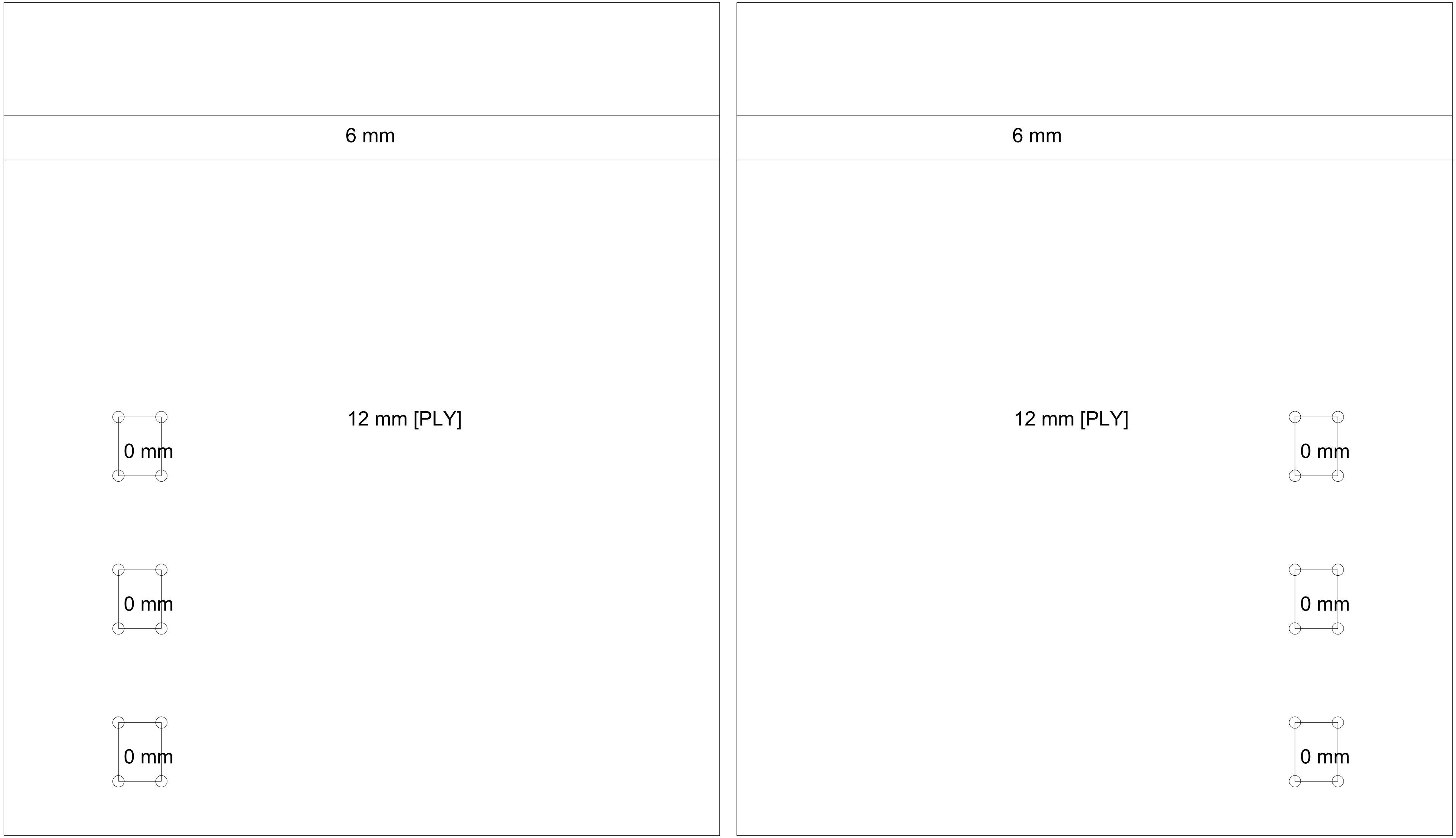
Project
ORW v2.1

Content
Production files: OSB 15mm joint tests

Scale
1/2

Code
ORW02_EX.005.01

Date
November 2017



Author
Filipe Brandão, Arq

Project
ORW v2.1

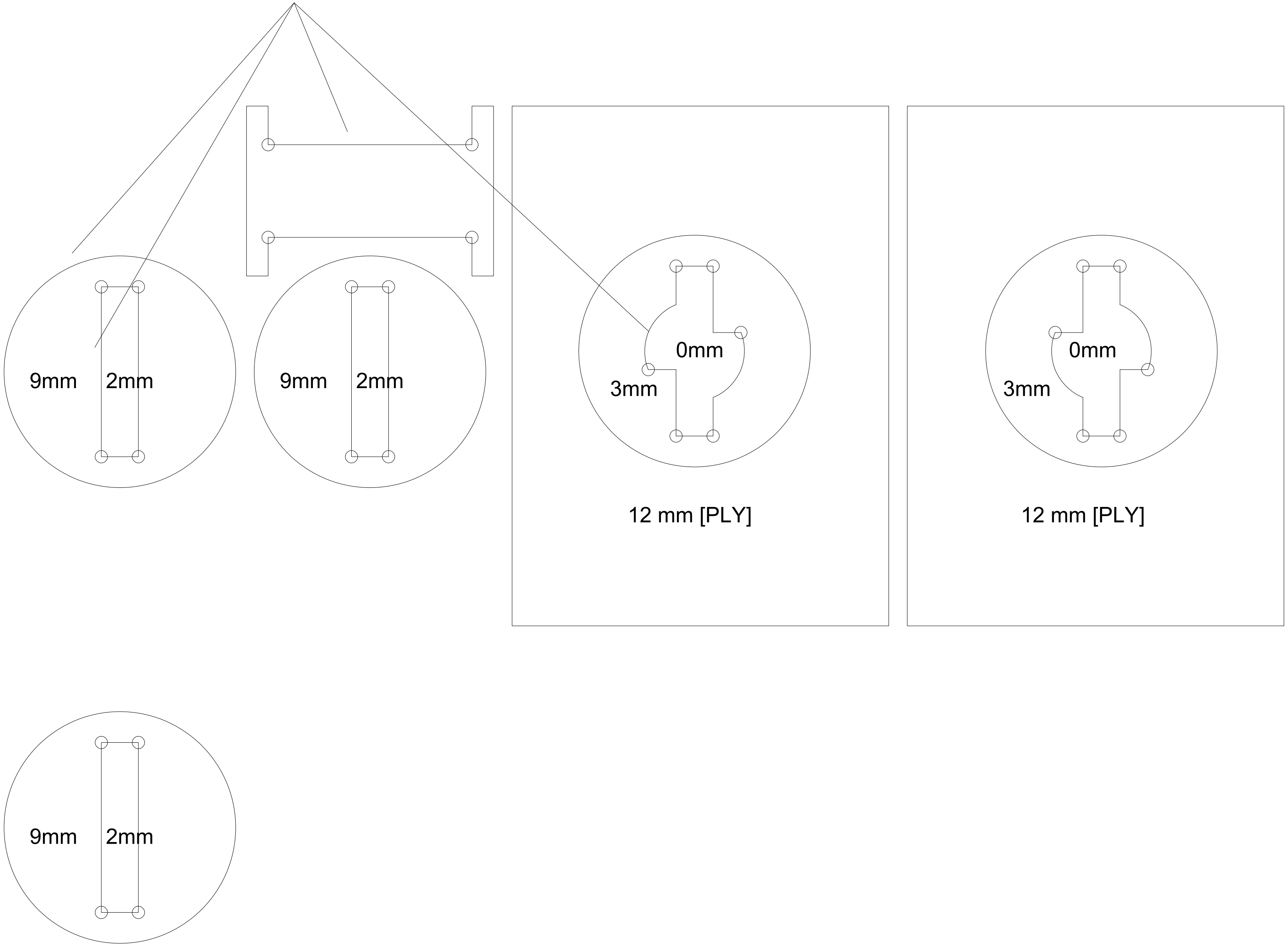
Content
Production files: Plywood 12mm panels

Scale
1/2

Code
ORW02_EX.006.01

Date
November 2017

Não foram dadas tolerâncias o que aumentou o trabalho necessário para limpar as peças e permitir que os encaixes funcionassem.



Author
Filipe Brandão, Arq

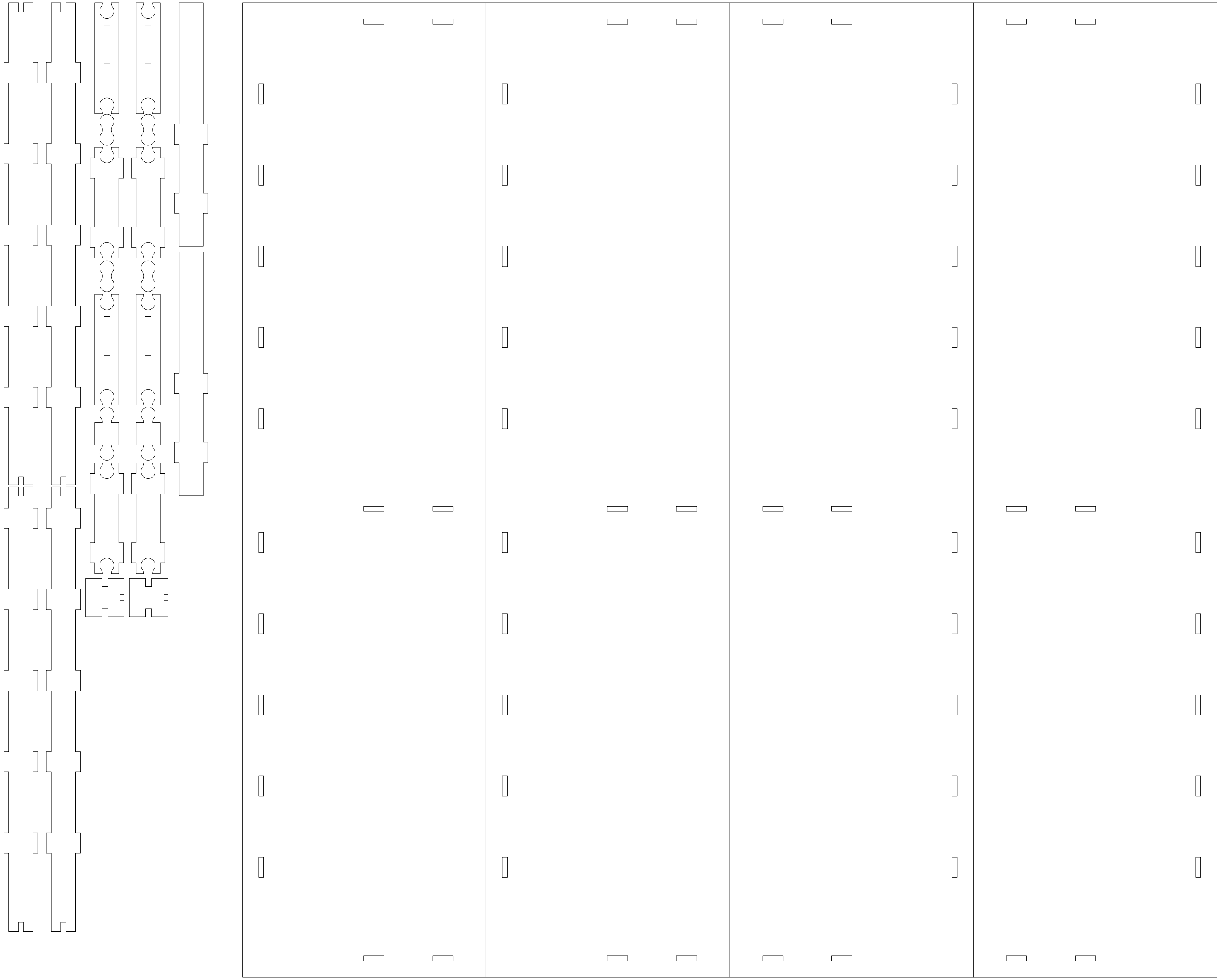
Project
ORW v2.1

Content
Production files: Plywood 12mm joint tests

Scale
1/2

Code
ORW02_EX.007.01

Date
November 2017



Author
Filipe Brandão, Arq

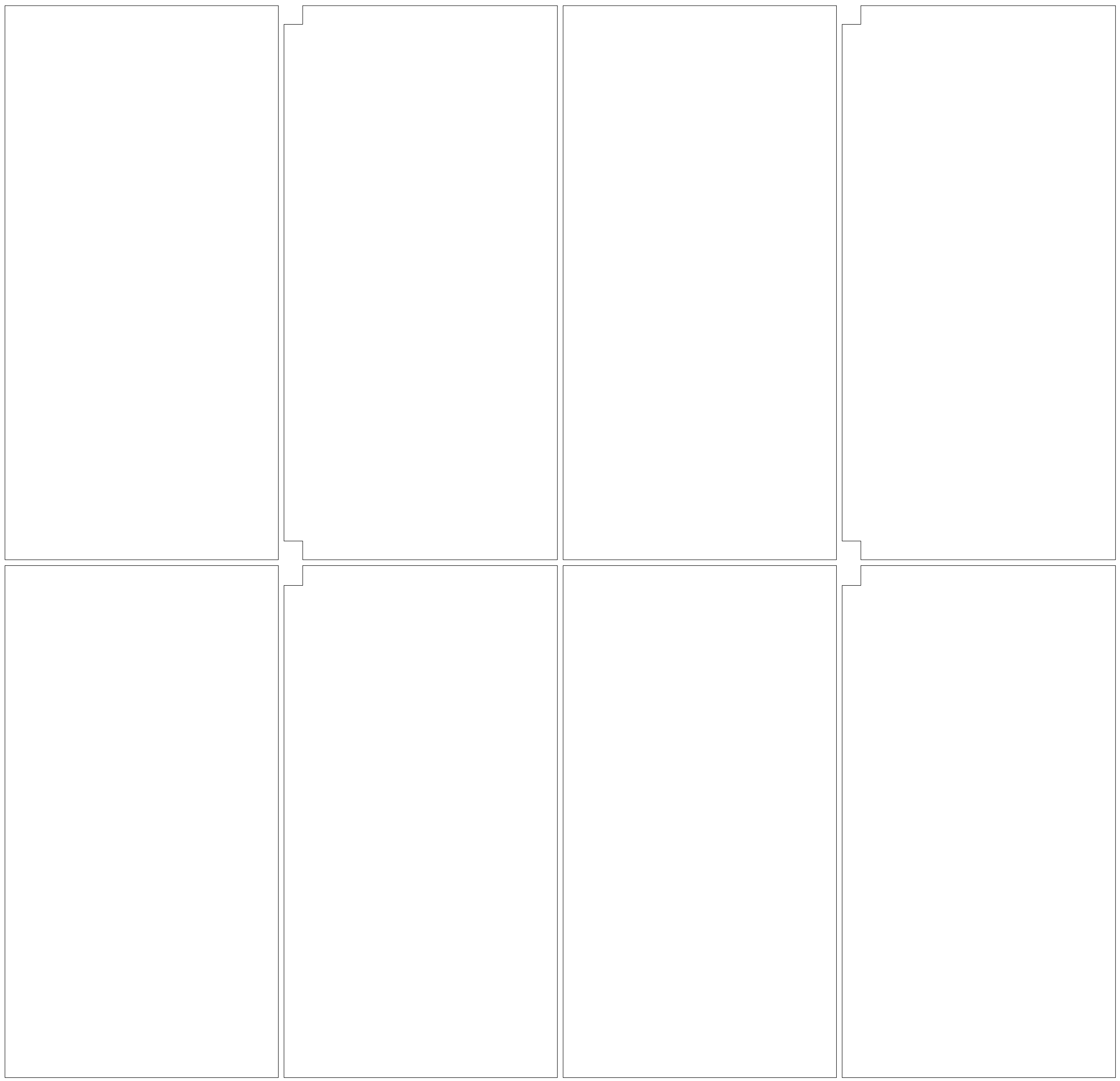
Project
ORW v2.1

Content
Production files: Laser cut scale model - cardboard parts

Scale
1/3

Code
ORW02_EX.008.01

Date
November 2017



Author
Filipe Brandão, Arq

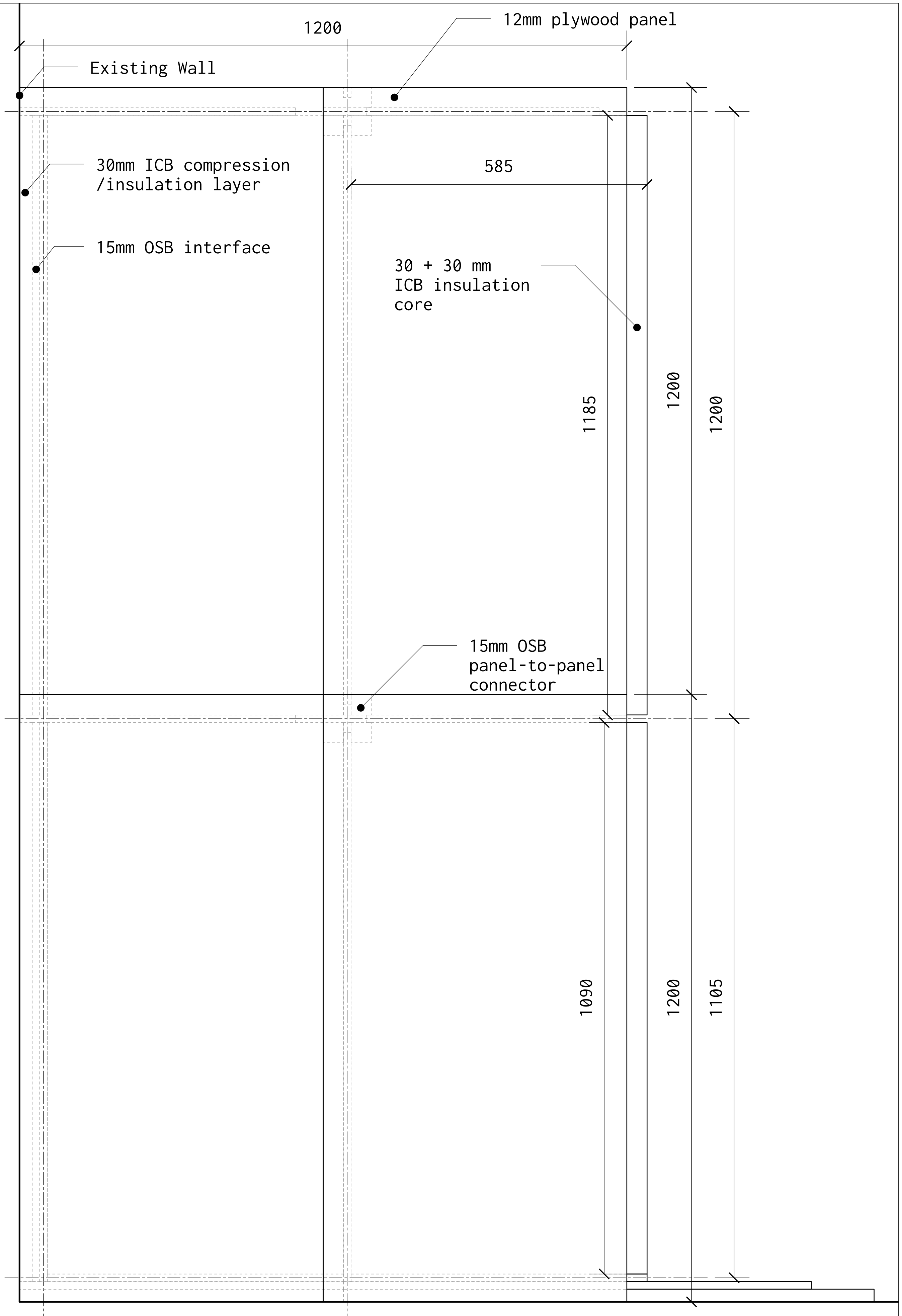
Project
ORW v2.1

Content
Production files: Laser cut scale model - cork parts

Scale
1/3

Code
ORW02_EX.009.01

Date
November 2017



Author
Filipe Brandão, Arq

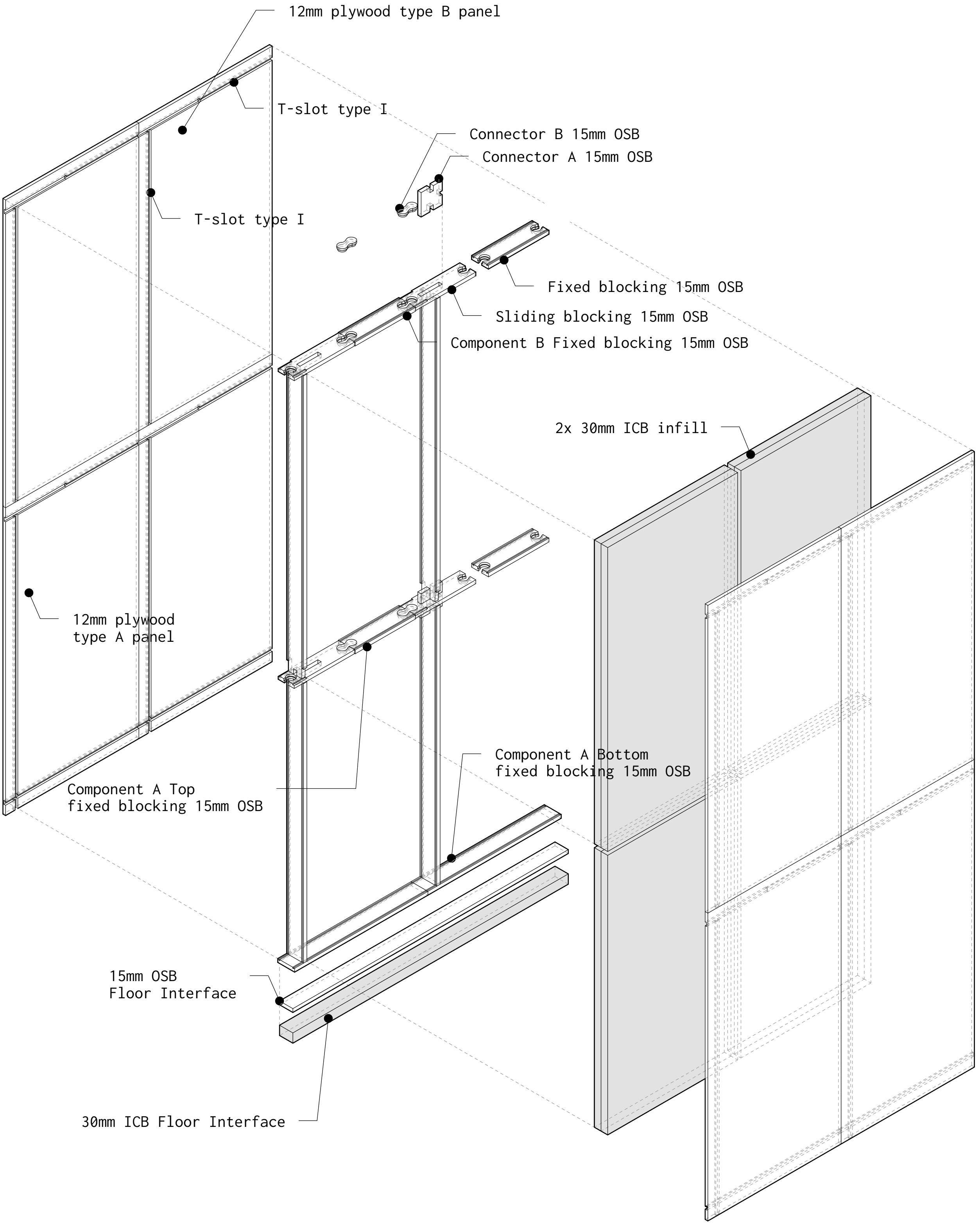
Project
ORW v2.1

Content
Assembled Component elevation detail

Scale
1/10

Código
ORW02_EX.010.01

Date
January 2018



Author
Filipe Brandão, Arq

Código
ORW02_EX.011.01

Project
ORW v2.1

Date
January 2018

Content
Type A and B components exploded axonometric

Scale
no scale

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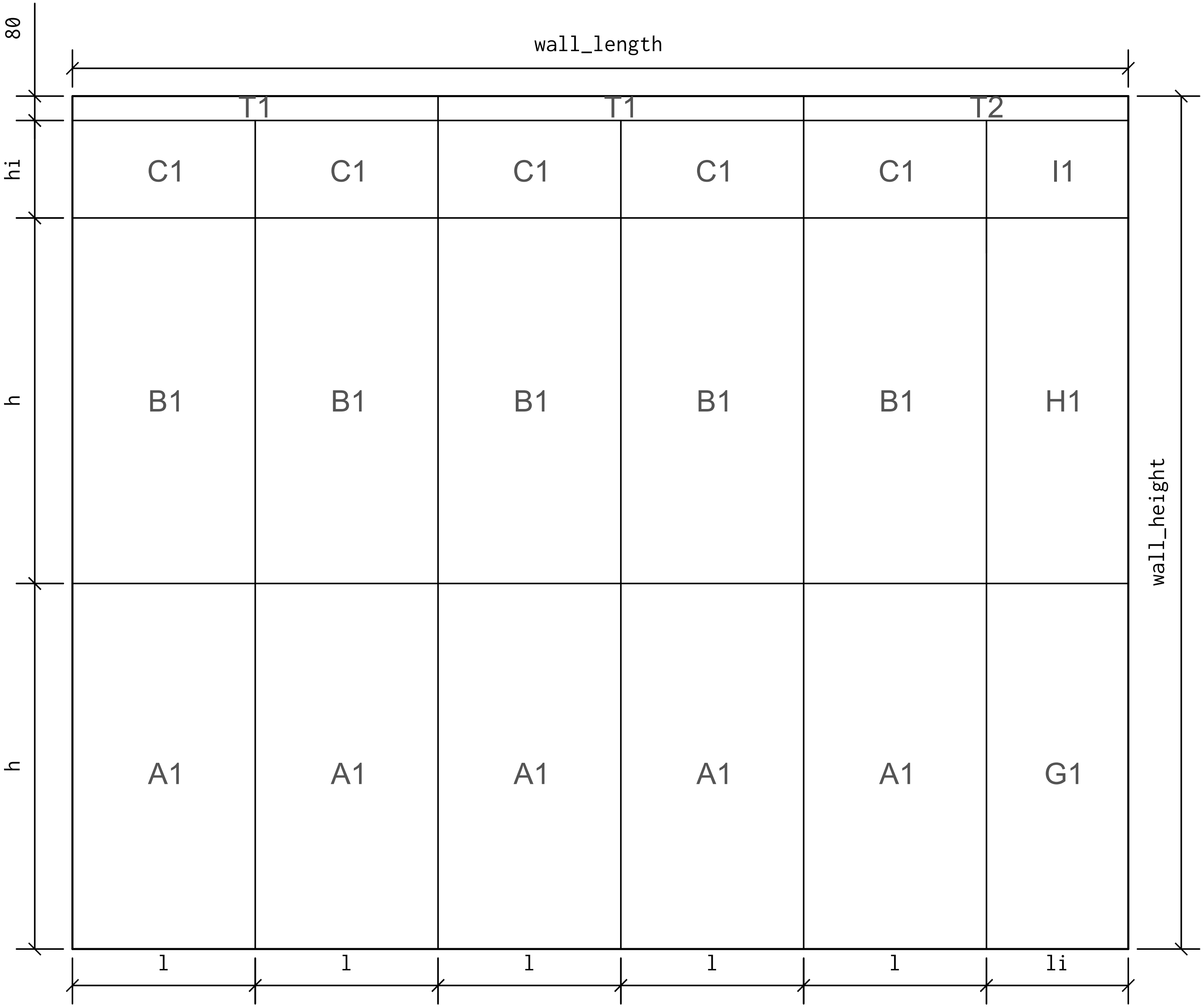
- Floor(wall_height - 80 / h)

li = wall_length/ l
- Floor(wall_length/ l)

li_min = 300mm

hi_min = 150mm



Author
Filipe Brandão, Arq

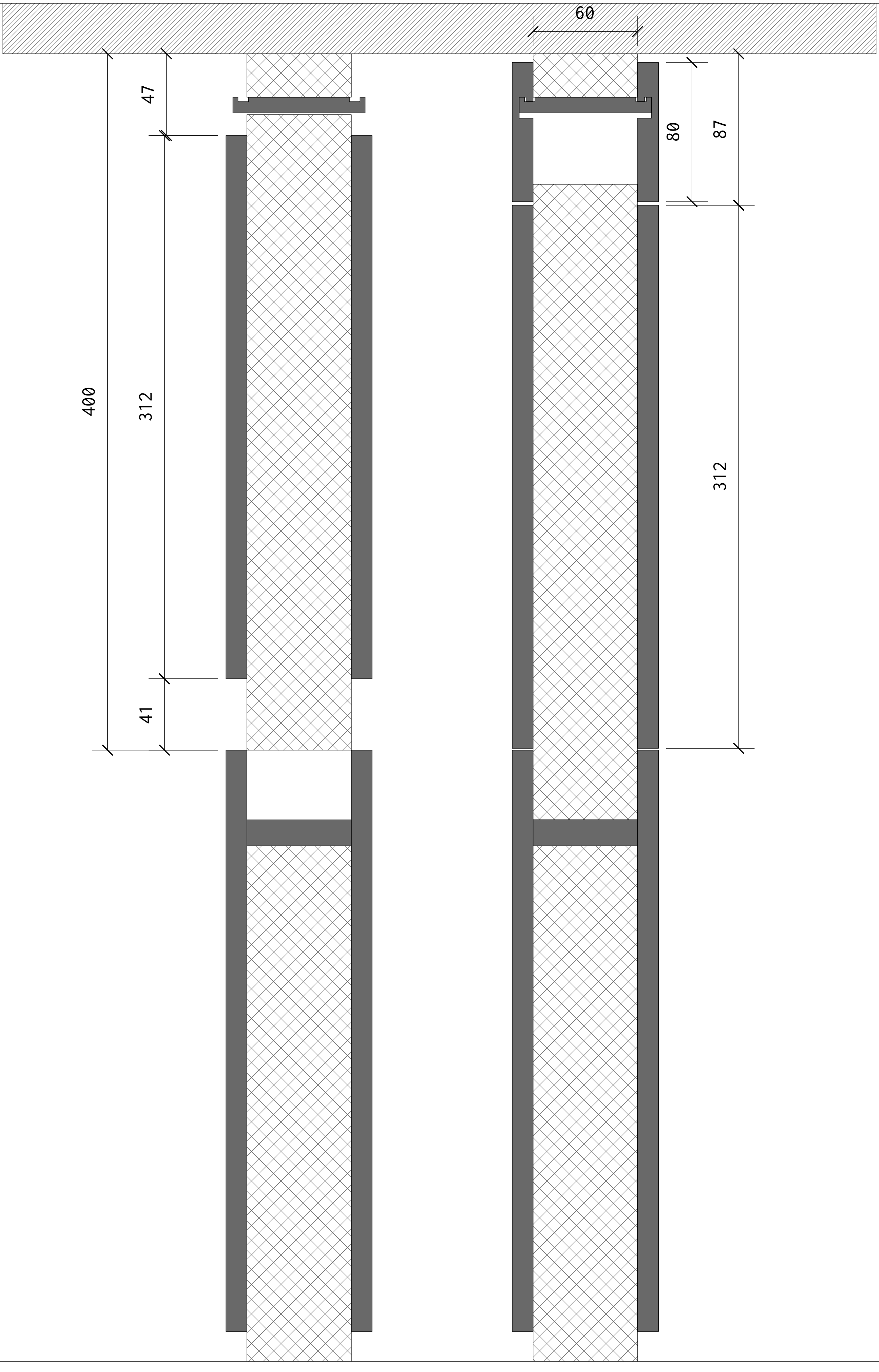
Project
ORW v2.1

Content
Functional and dimentional subdividion elevation

Scale
1/10

Code
ORW02_EX.012.00

Date
November 2017



Author
Filipe Brandão, Arq

Project
ORW v2.1

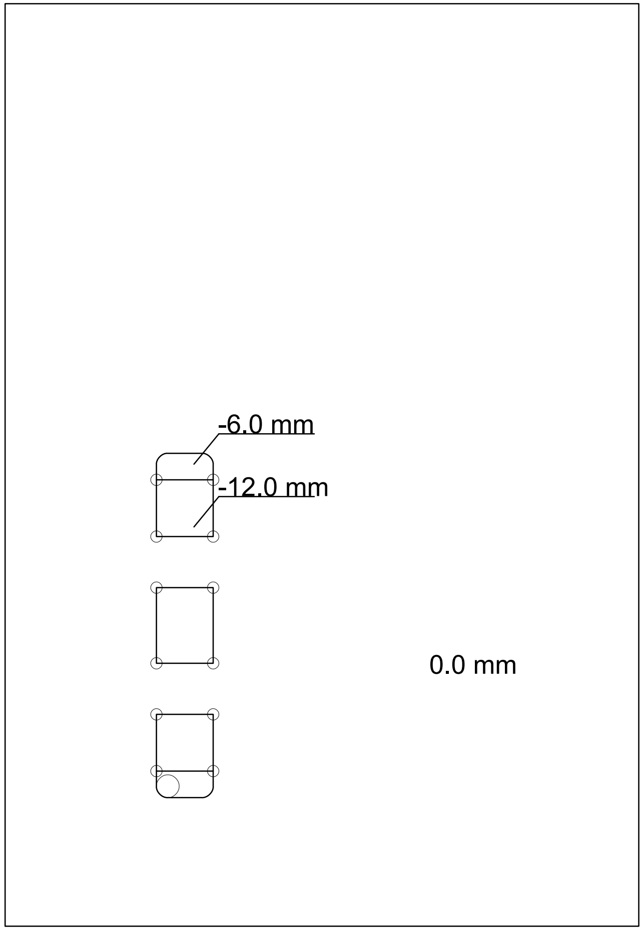
Content
Type C/I component assemby sequence

Scale
no scale

Código
ORW02_EX.013.01

Date
January 2018

ANNEX J – Open reWall v3



Author
Filipe Brandão, Arq

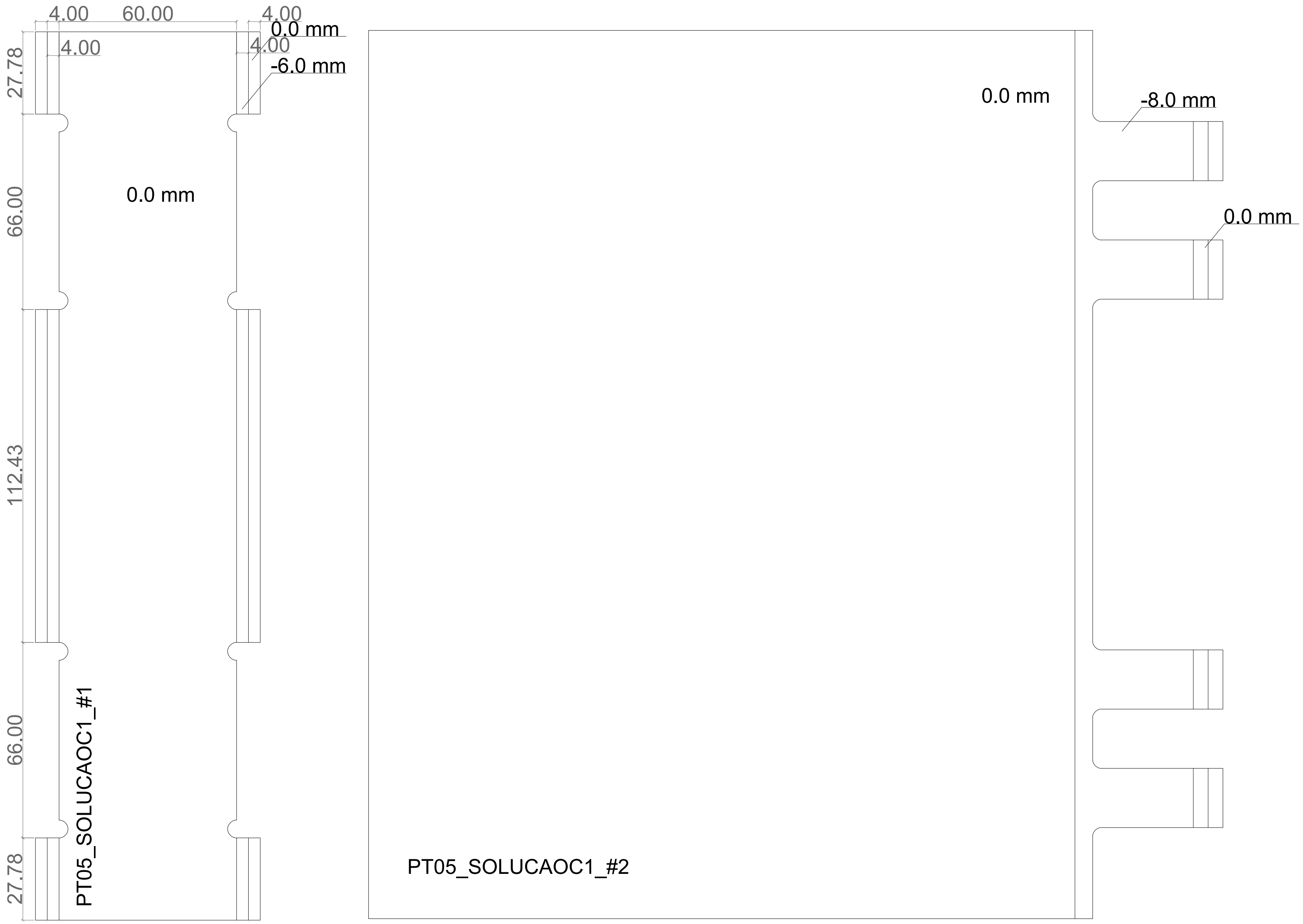
Project
ORW v3.0

Content
Production files: Plywood 12 mm panel with snap-fit joints

Scale
1/2

Code
ORW03_EX.002.01

Date
January 2018



Author
Filipe Brandão, Arq

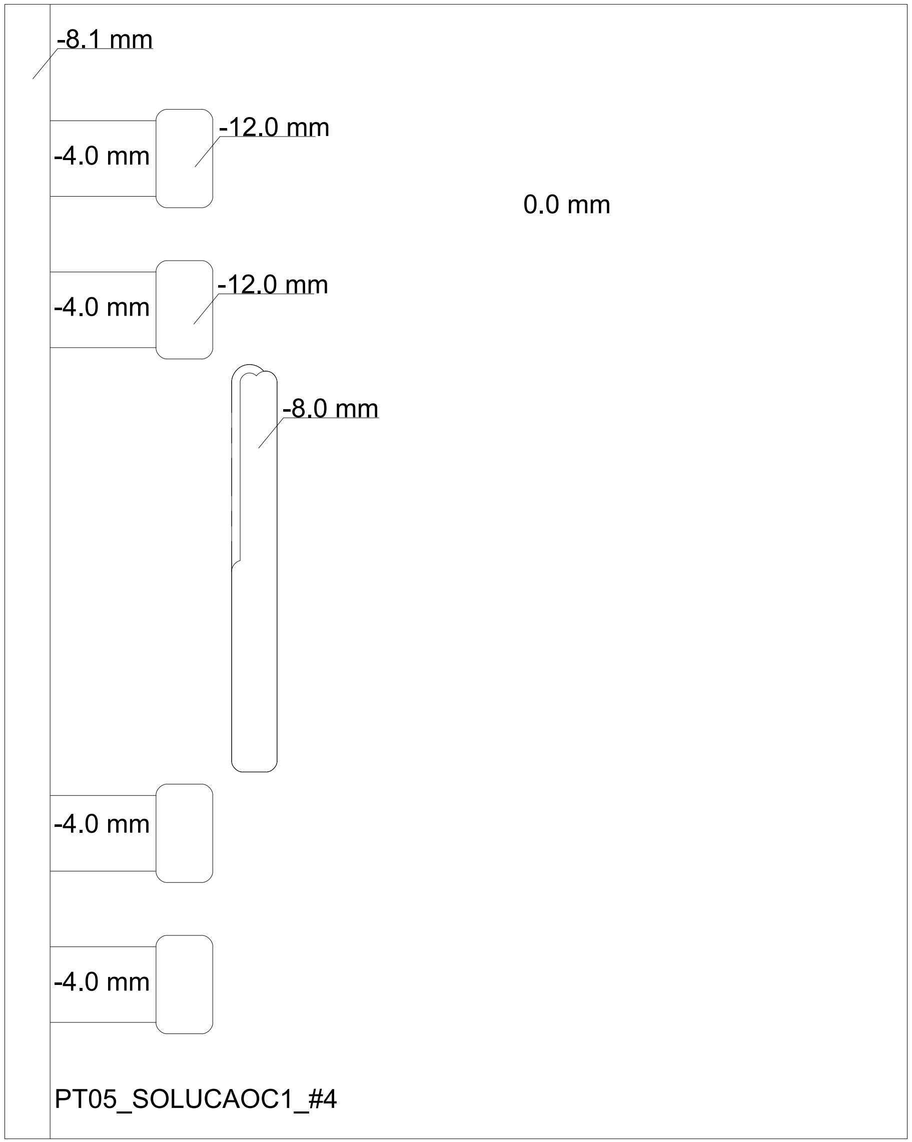
Project
ORW v3.0

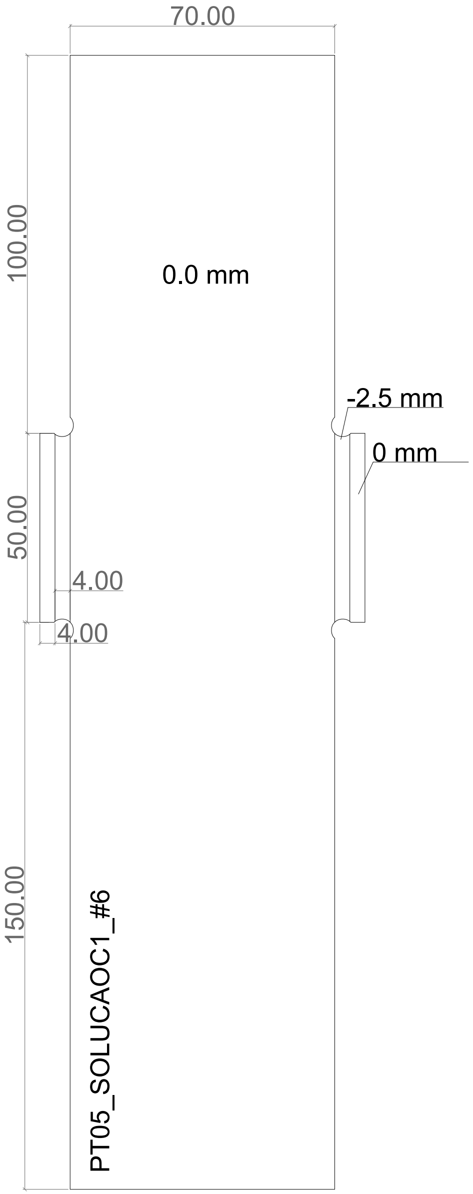
Content
Production files: Plywood 12 mm panel with snap-fit joints

Scale
1/2

Code
ORW03_EX.003.01

Date
January 2018





Author
Filipe Brandão, Arq

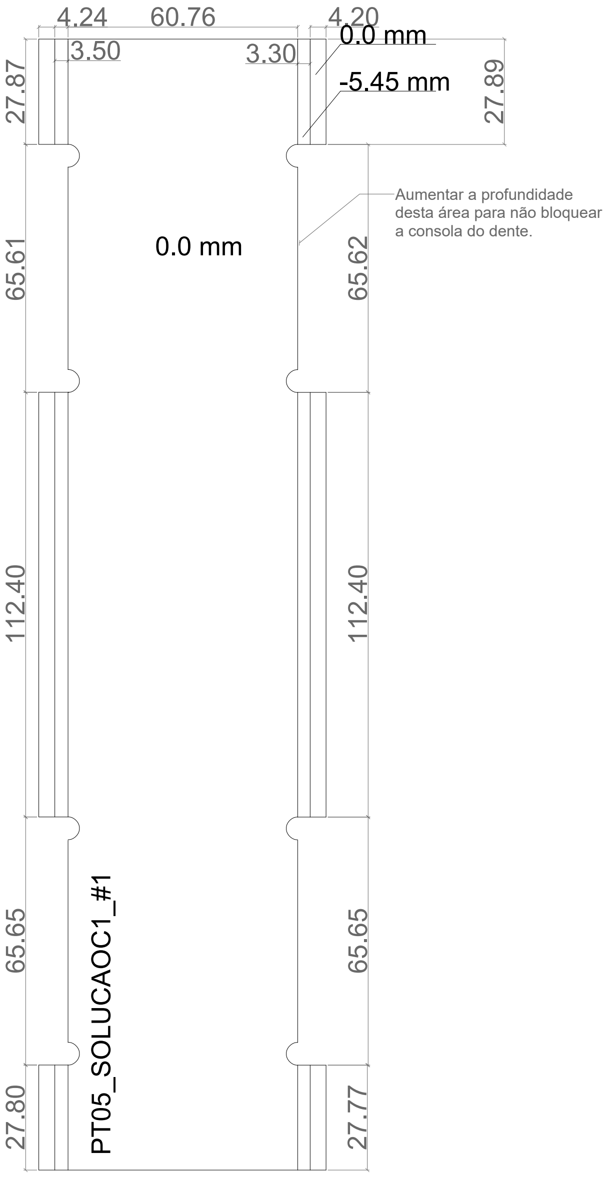
Project
ORW v3.0

Content
Production files: Plywood 12 mm panel w/snap-fit and T-slot joints

Scale
1/2

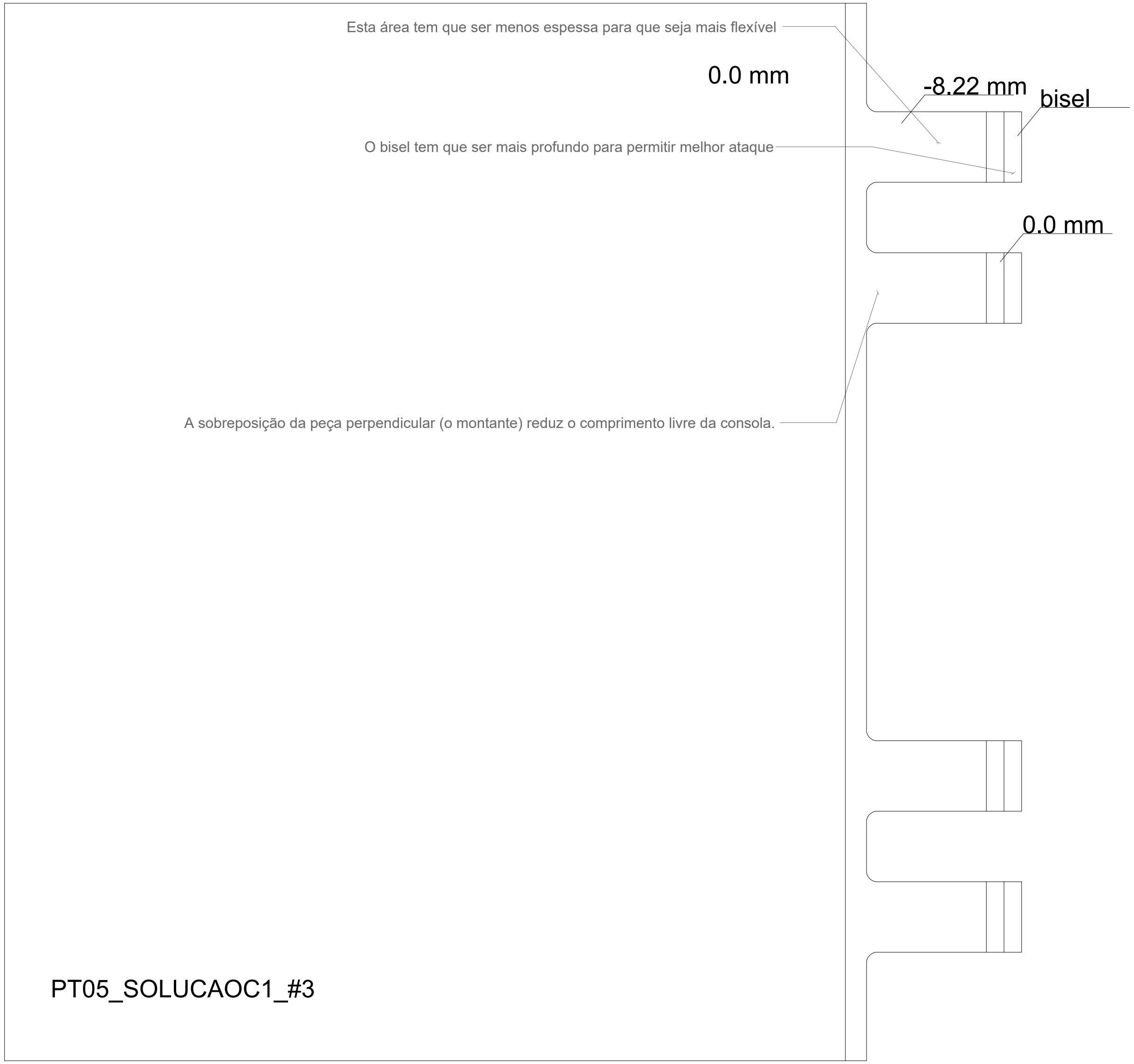
Code
ORW03_EX.004.01

Date
January 2018



Aumentar a profundidade desta área para não bloquear a consola do dente.

PT05_SOLUCAOC1_#1



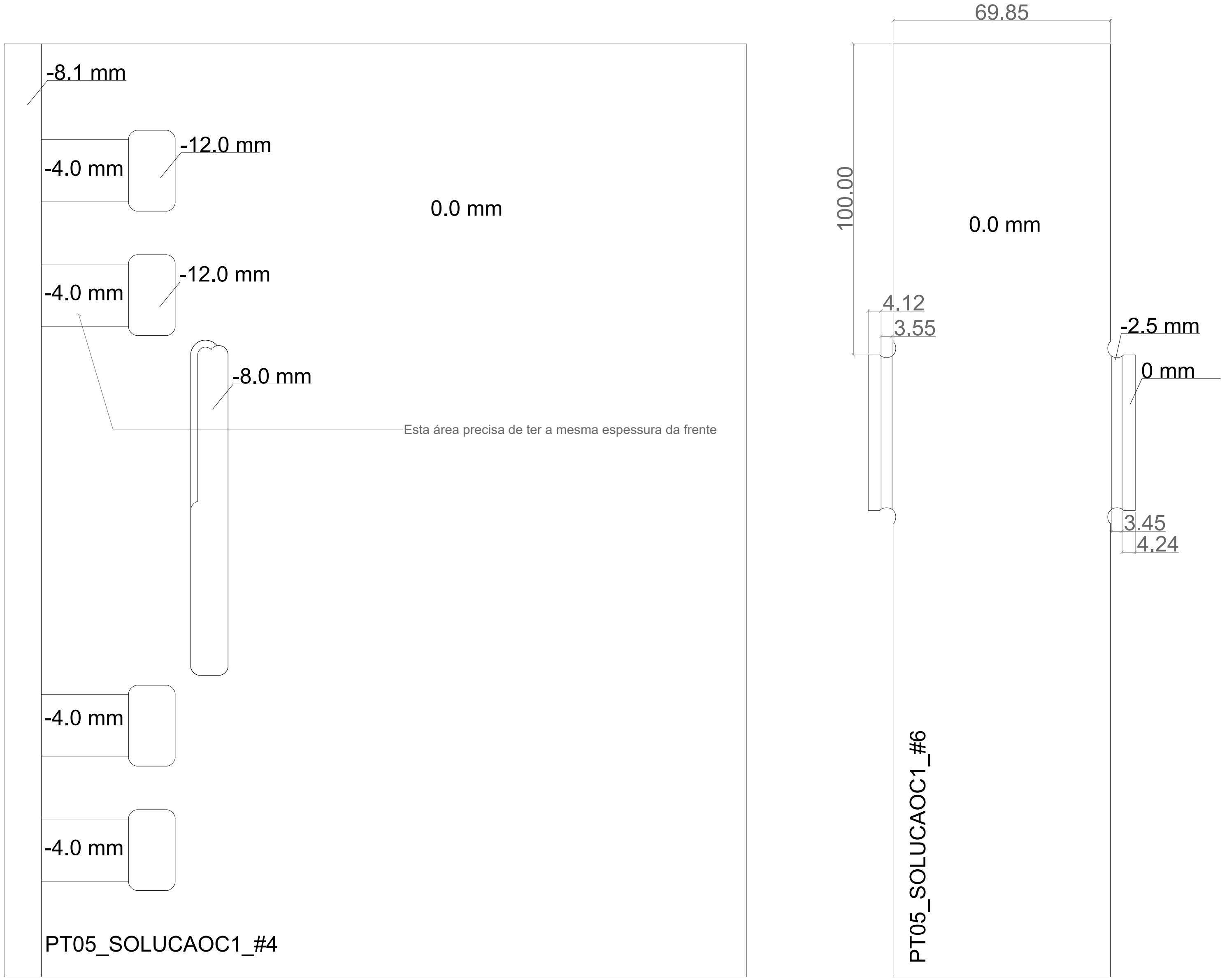
Esta área tem que ser menos espessa para que seja mais flexível

O bisel tem que ser mais profundo para permitir melhor ataque

A sobreposição da peça perpendicular (o montante) reduz o comprimento livre da consola.

PT05_SOLUCAOC1_#3

Author Filipe Brandão, Arq	Code ORW03_EX.005.01
Project ORW v3.0	Date January 2018
Content Post-production: Plywood 12 mm panel with snap-fit joints	Scale 1/2



Esta área precisa de ter a mesma espessura da frente

Author
Filipe Brandão, Arq

Project
ORW v3.0

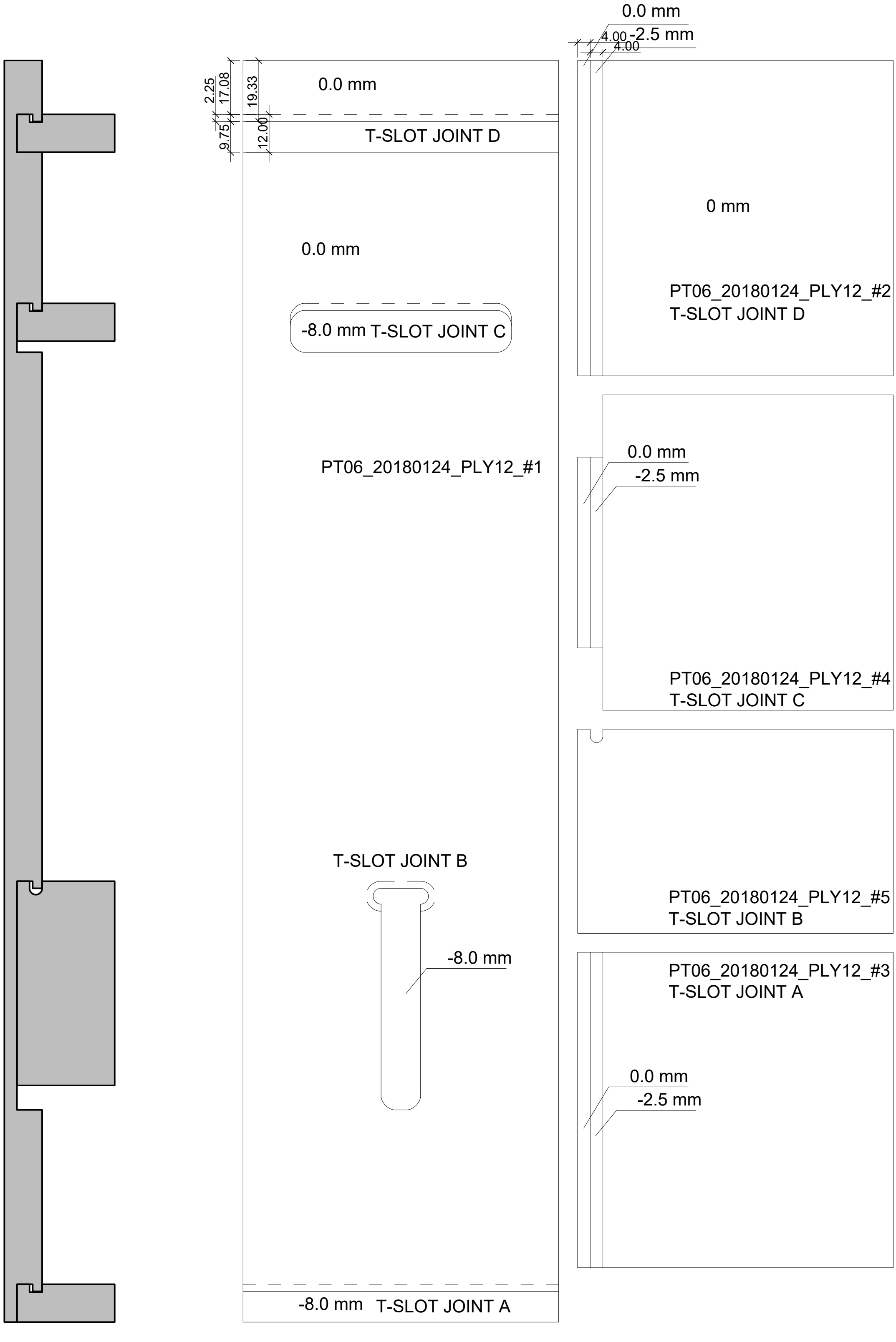
Content
Post-production: Plywood 12 mm panel w/snap-fit and T-slot joints

Scale
1/2

Code
ORW03_EX.006.01

Date
January 2018

ENVIADO PARA A MÁQUINA



Author
Filipe Brandão, Arq

Project
ORW v3.0

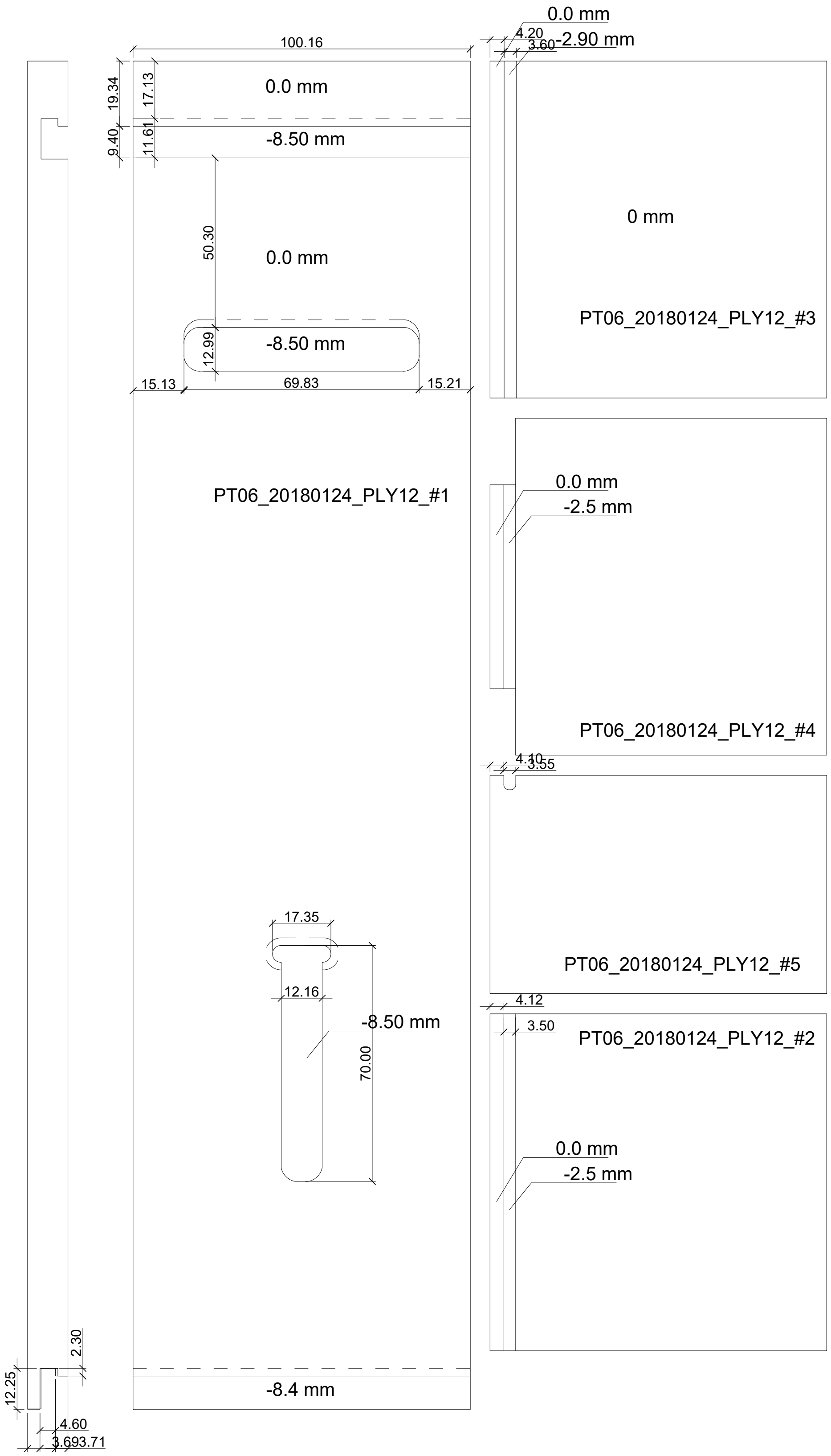
Content
Production files: T-slot joints tests

Scale
1/2

Código
ORW03_EX.007.01

Date
January de 2018

APÓS FABRICO E LIXAGEM



Author
Filipe Brandão, Arq

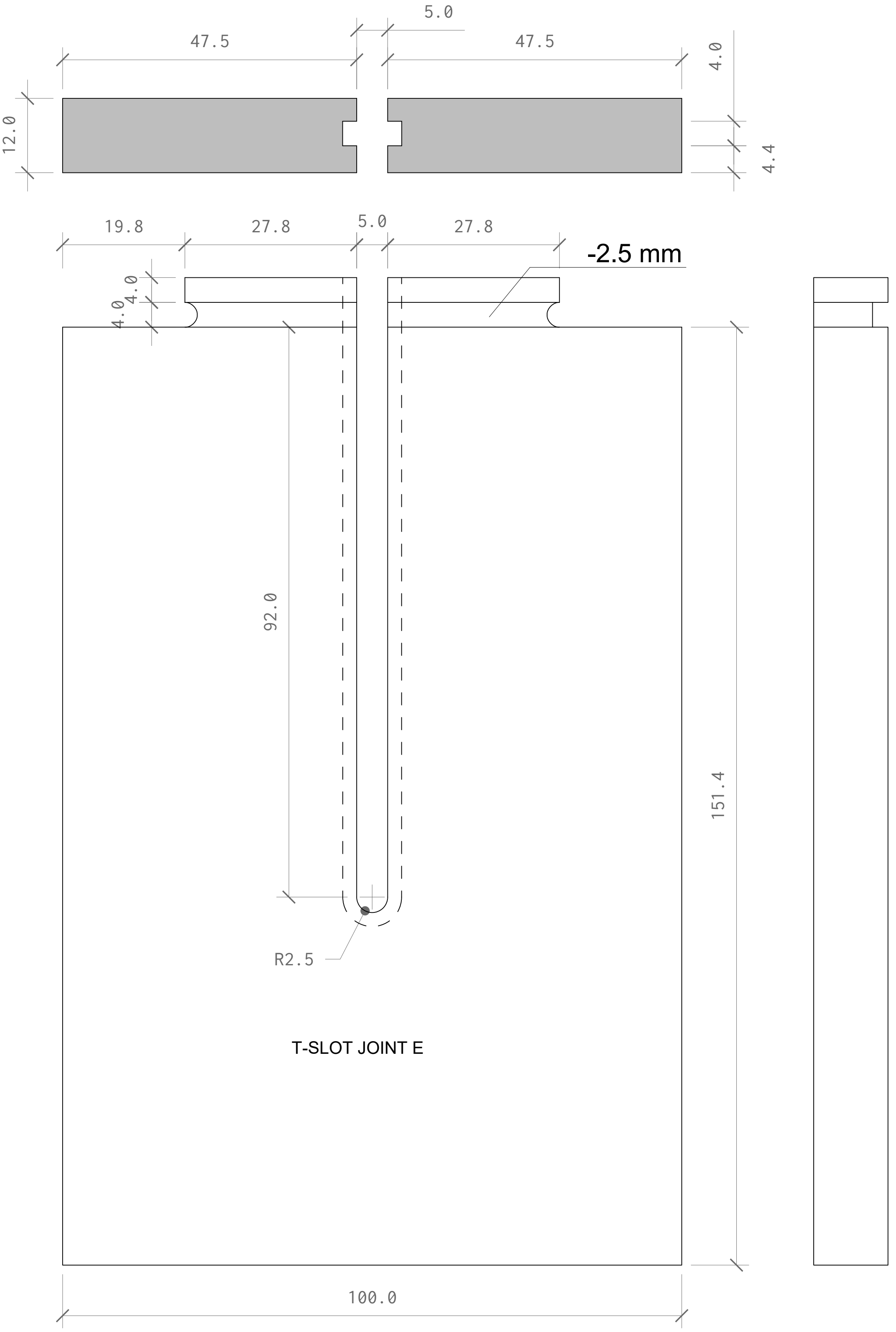
Project
ORW v3.0

Content
Post-production measurements: T-slot joints tests

Scale
1/2

Código
ORW03_EX.008.01

Date
January de 2018



Author
Filipe Brandão, Arq

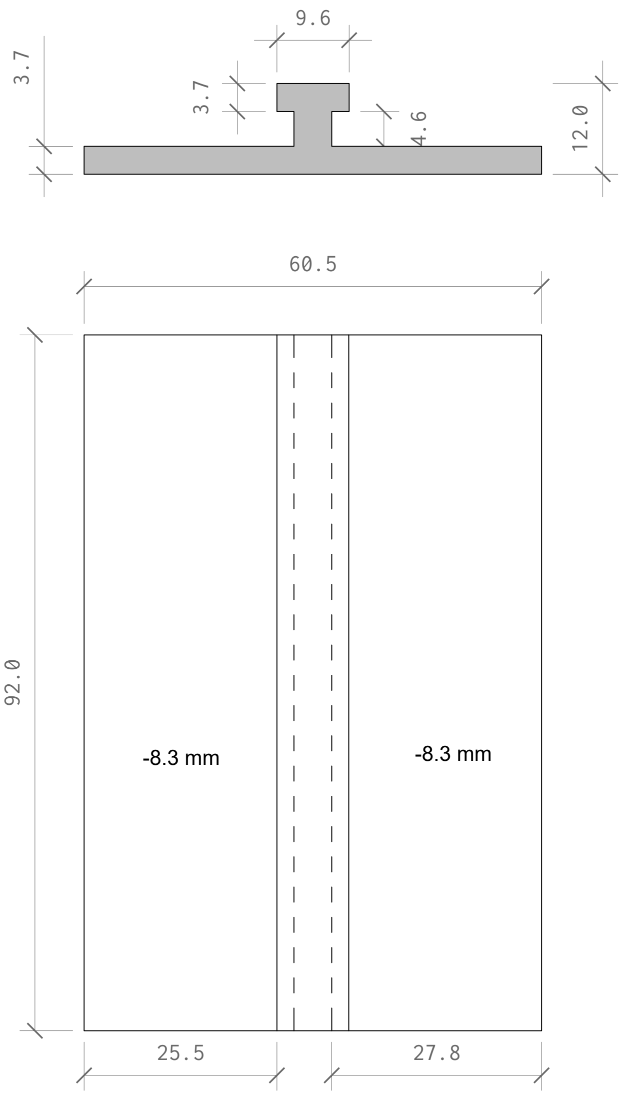
Project
ORW v3.0

Content
Production files: T-slot joint E

Scale
1/1

Código
ORW03_EX.009.01

Date
February de 2018



Author
Filipe Brandão, Arq

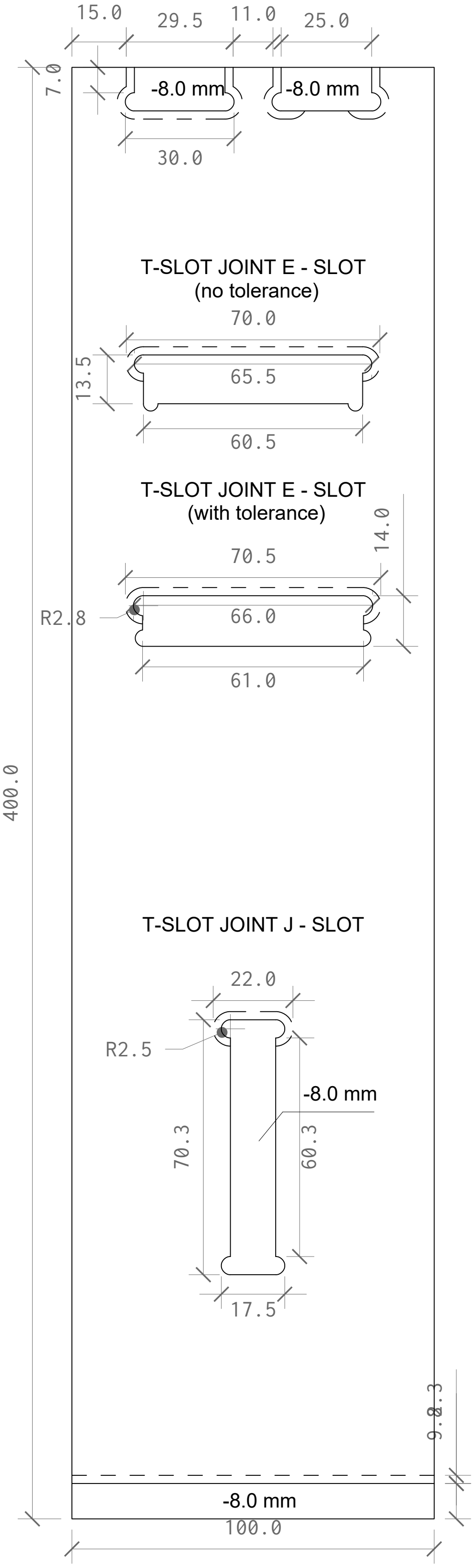
Project
ORW v3.0

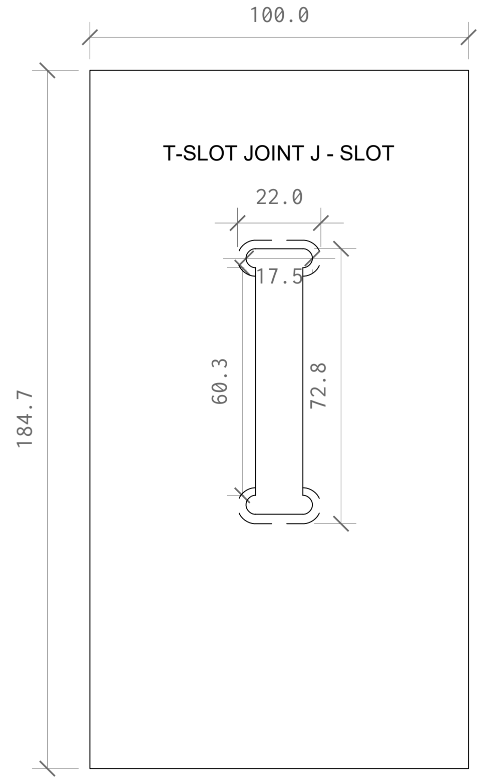
Content
Production files: T-slot joint E- Sliding lock

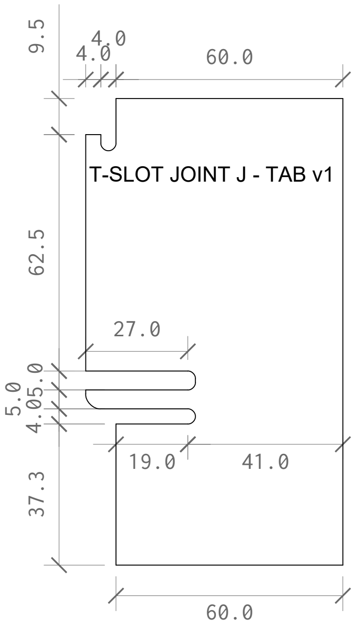
Scale
1/1

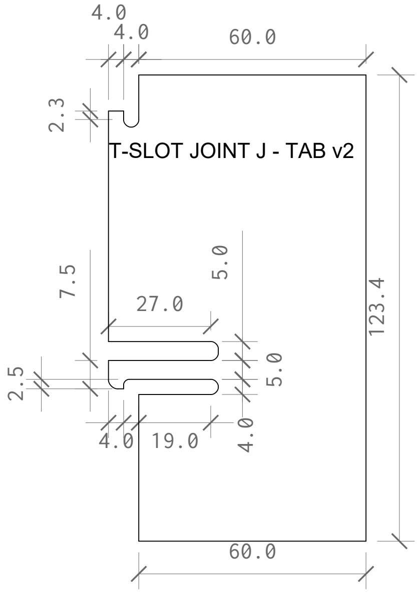
Código
ORW03_EX.010.01

Date
February de 2018









Author
Filipe Brandão, Arq

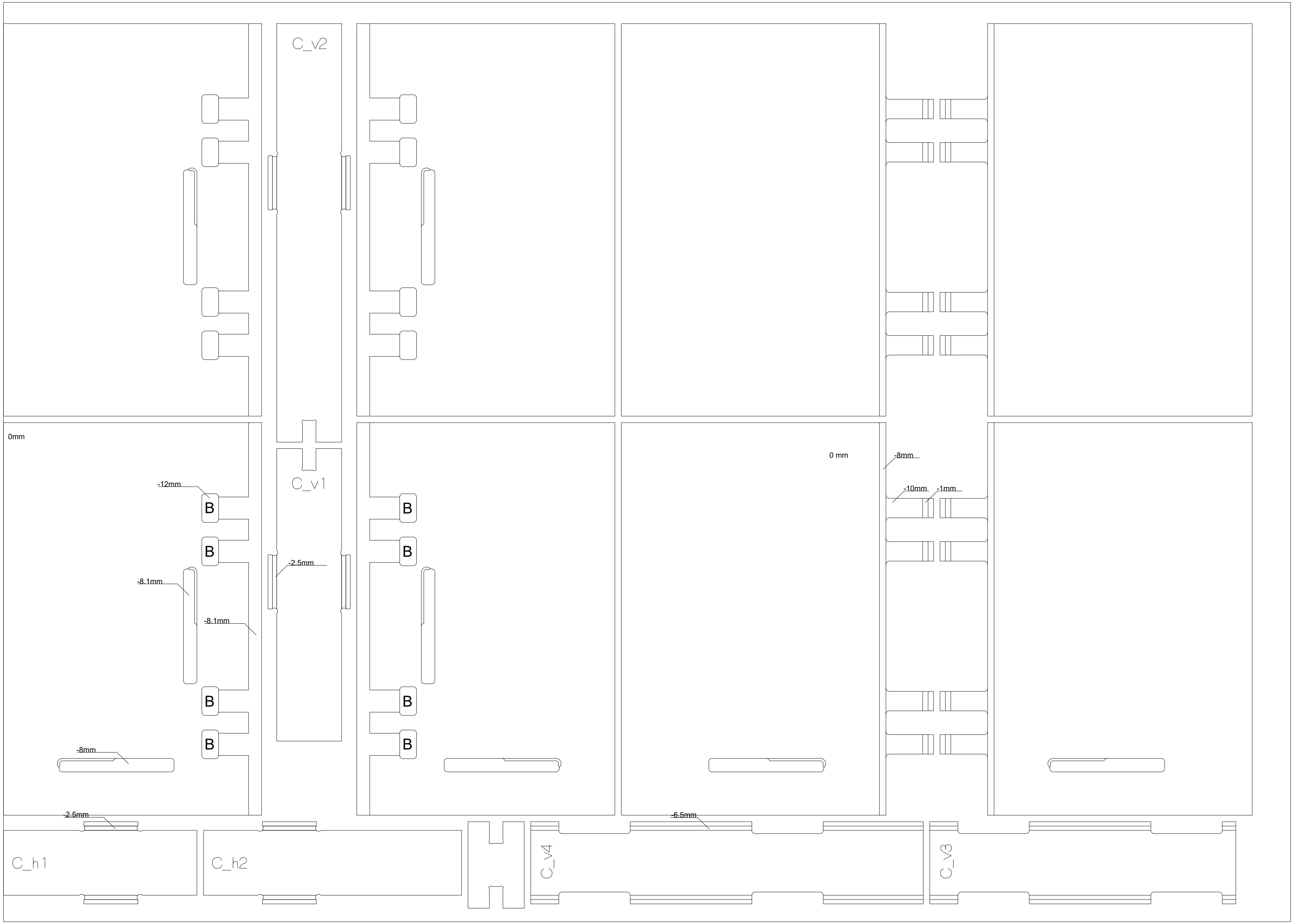
Project
ORW v3.0

Content
Production files: T-slot joint E and J

Scale
1/2

Código
ORW03_EX.011.01

Date
February de 2018



Author
Filipe Brandão, Arq

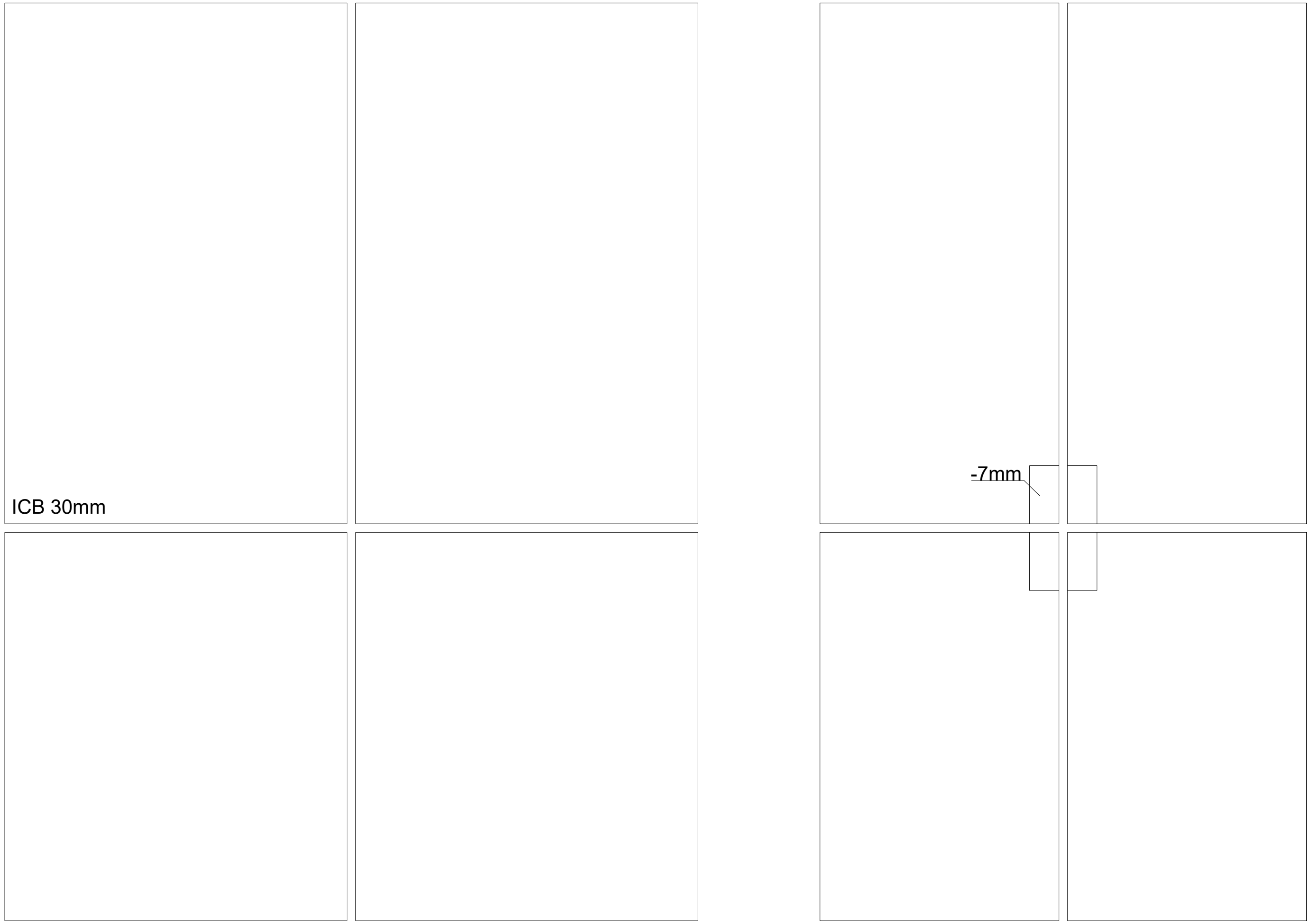
Project
ORW v3.0

Content
Production files: Plywood 12 mm panel with snap-fit joints

Scale
1/5

Code
ORW03_EX.012.01

Date
February 2018



Author
Filipe Brandão, Arq

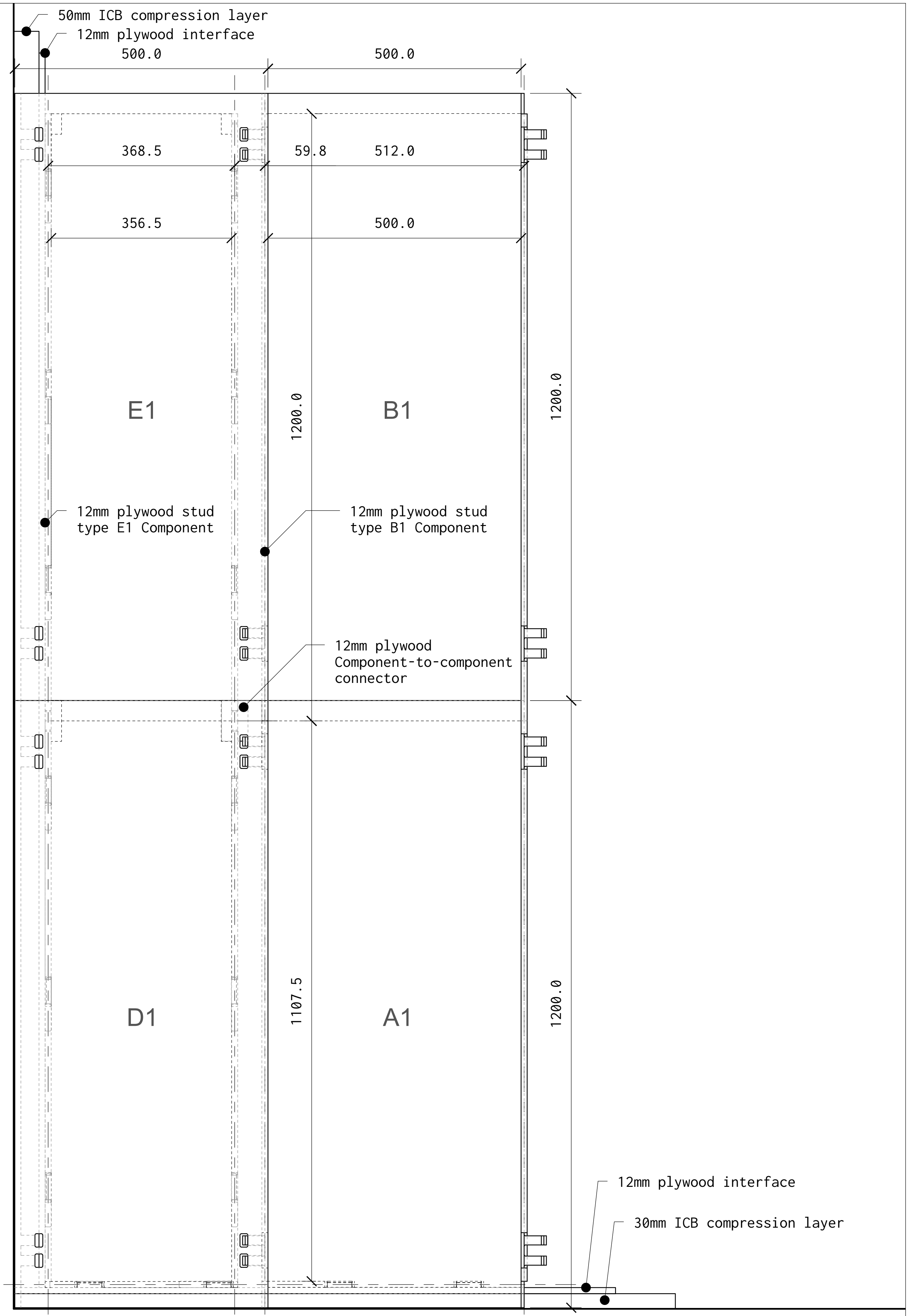
Project
ORW v3.0

Content
Production files: ICB 30 mm infill

Scale
1/5

Code
ORW03_EX.013.01

Date
February 2018



Author
Filipe Brandão, Arq

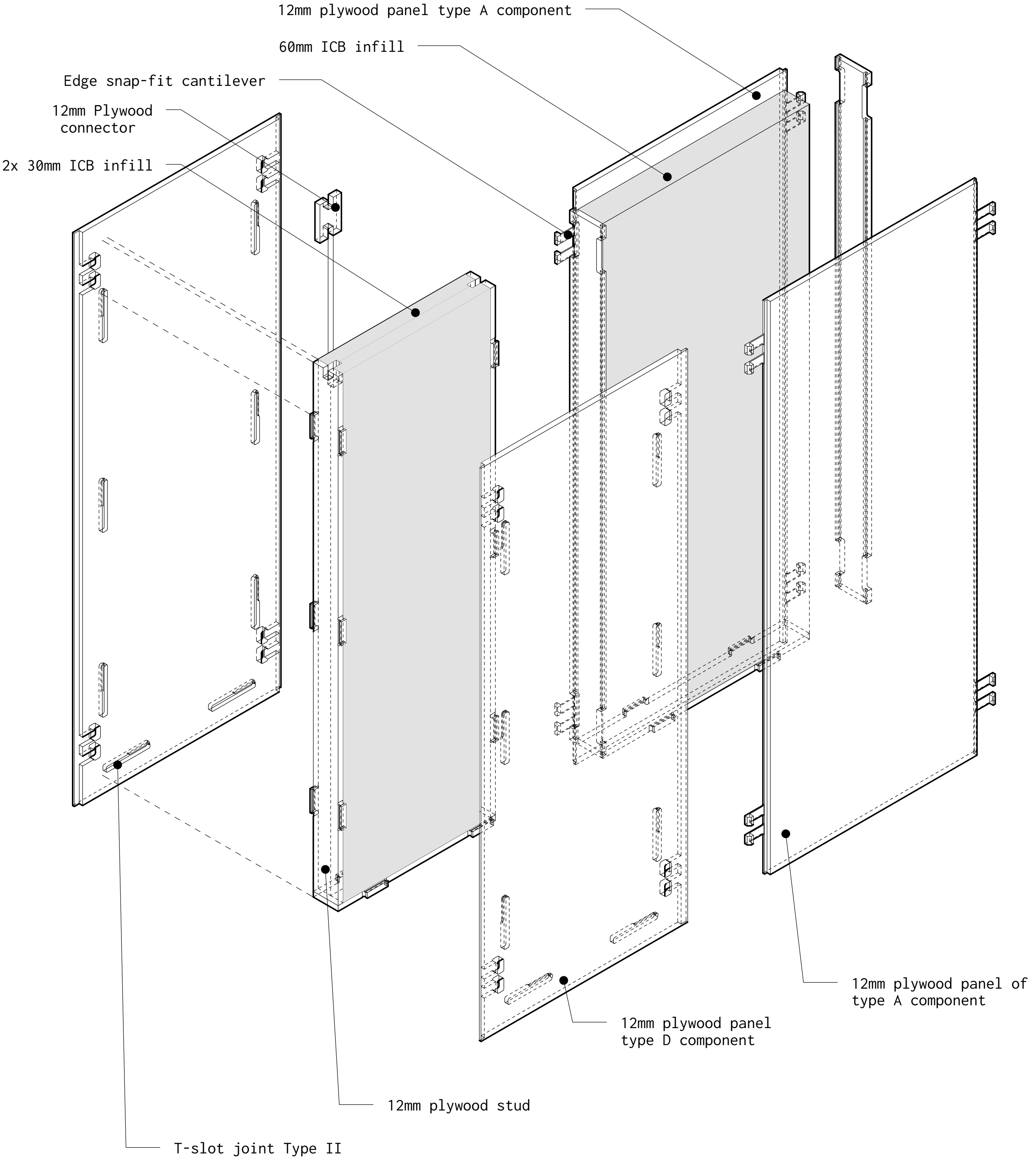
Project
ORW v3.0

Content
Assembled Component elevation detail

Scale
1/10

Código
ORW03_EX.014.01

Date
February 2018



Author
Filipe Brandão, Arq

Project
ORW v3.0

Content
Type A and D components exploded axonometric

Scale
no scale

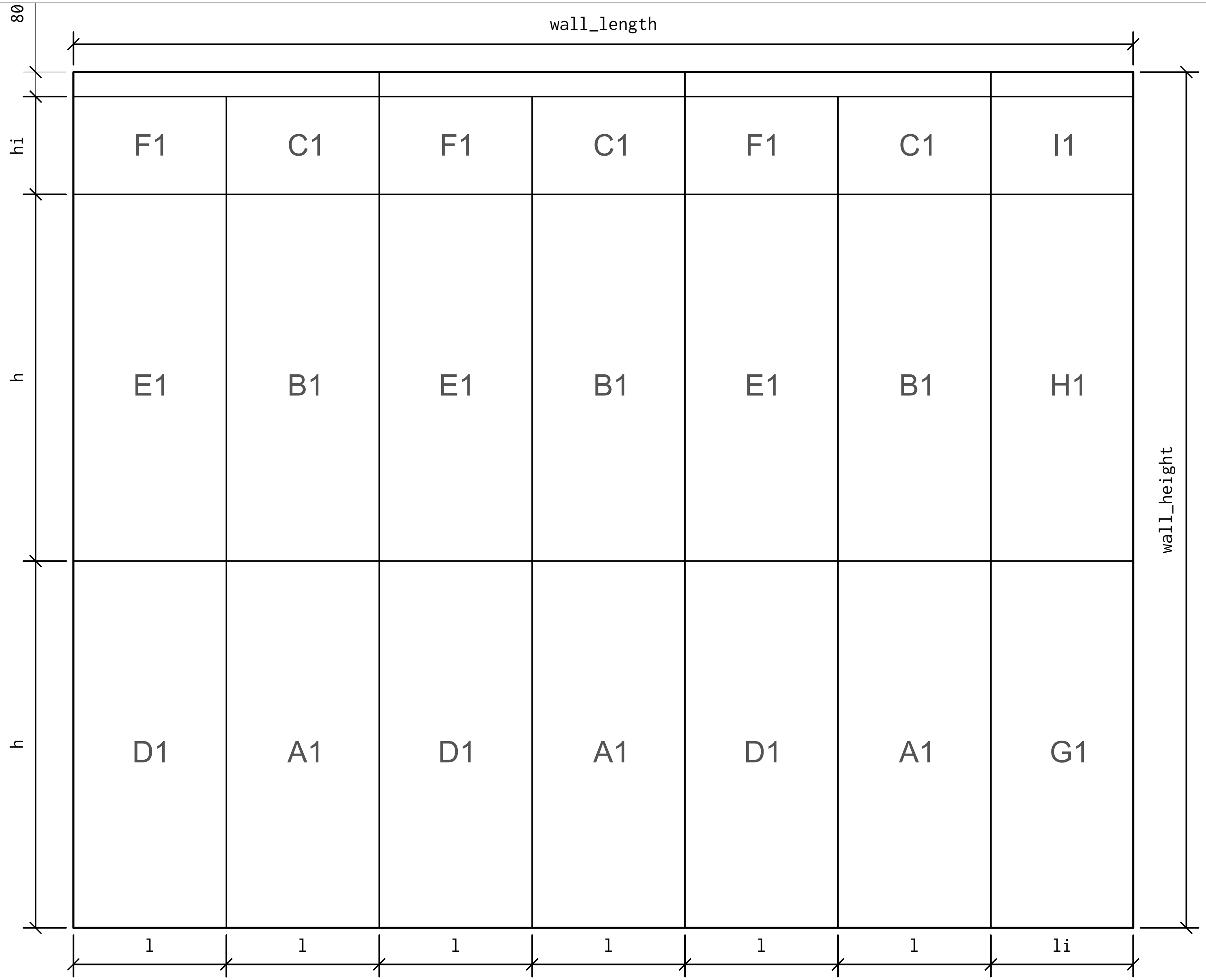
Código
ORW03_EX.015.01

Date
February 2018

hi = wall_height -80 / h
- Floor(wall_height -80 / h)

li = wall_length/ l
- Floor(wall_length/ l)

li_min = 300mm
li_max = 500mm
hi_min = 150mm
hi_max = 1200mm



Author
Filipe Brandão, Arq

Project
ORW v3.0

Content
Functional and dimentional subdividion elevation

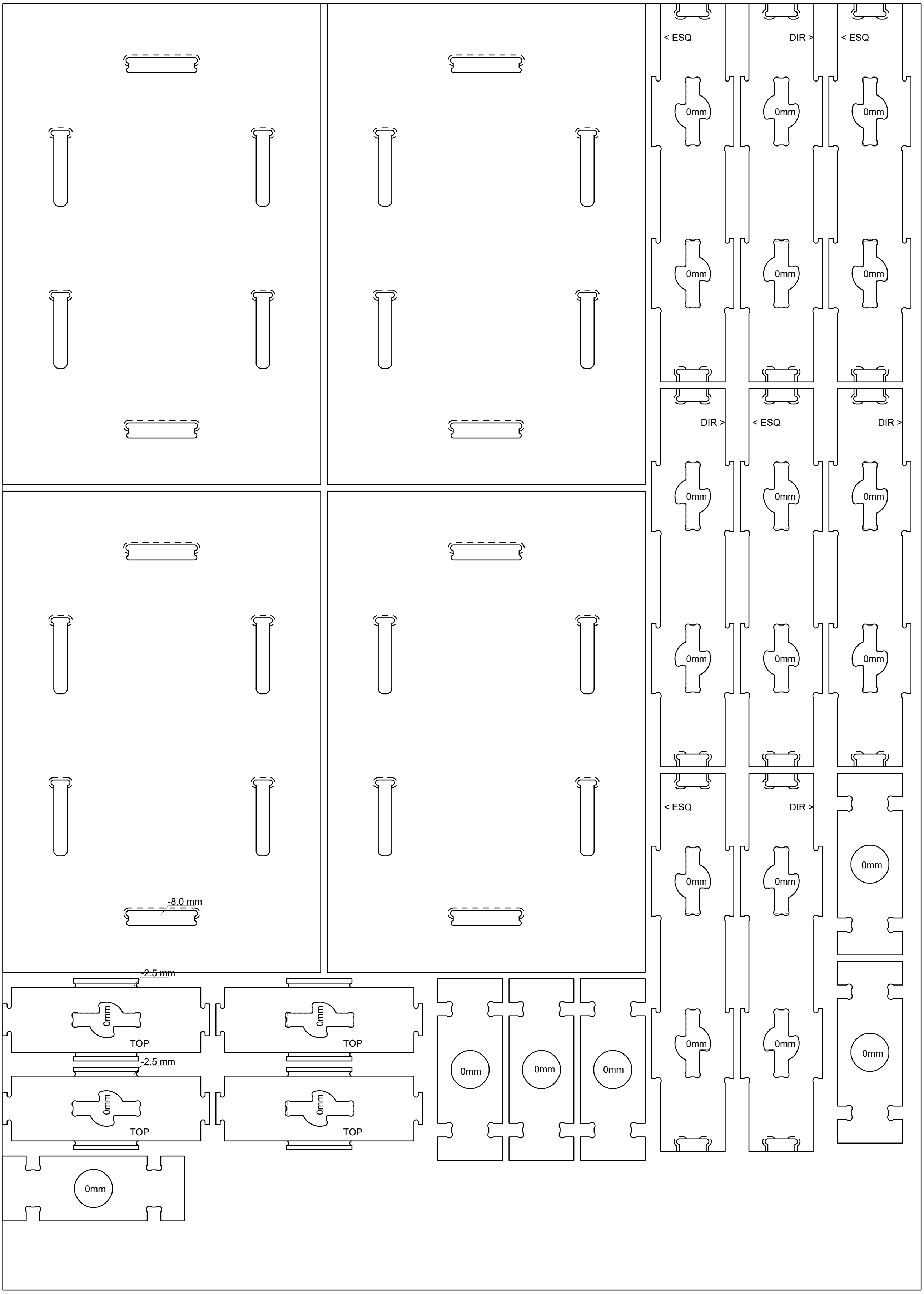
Scale
1/20

Code
ORW03_EX.016.00

Date
February 2018

ANNEX K – Open reWall v4

PLY 12MM



Author
Filipe Brandão, Arq

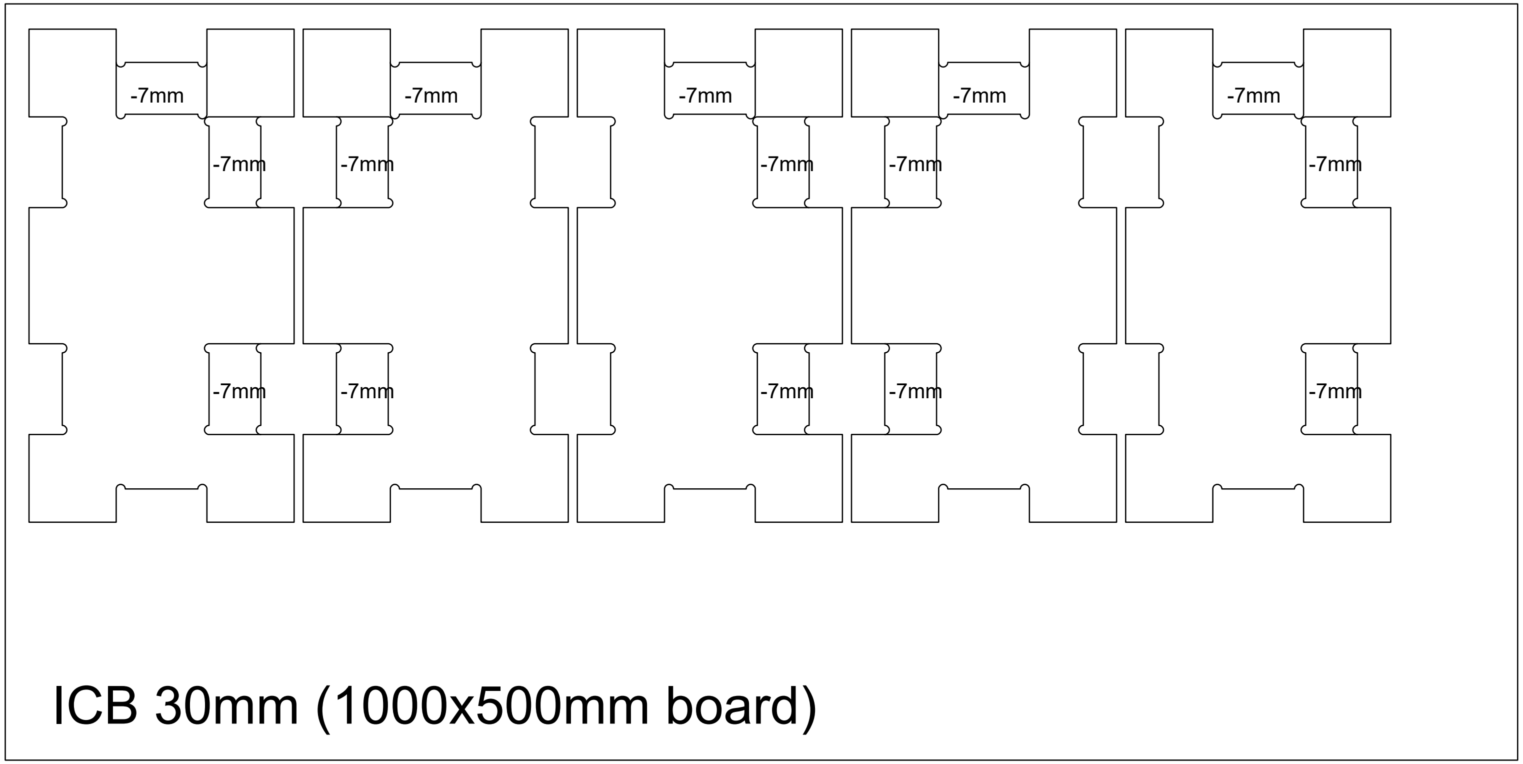
Project
ORW v4.0

Content
Production files: CRW v4.0 plywood parts

Scale
1/5

Código
ORW04_EX.001.01

Date
February de 2018



ICB 30mm (1000x500mm board)

Author
Filipe Brandão, Arq

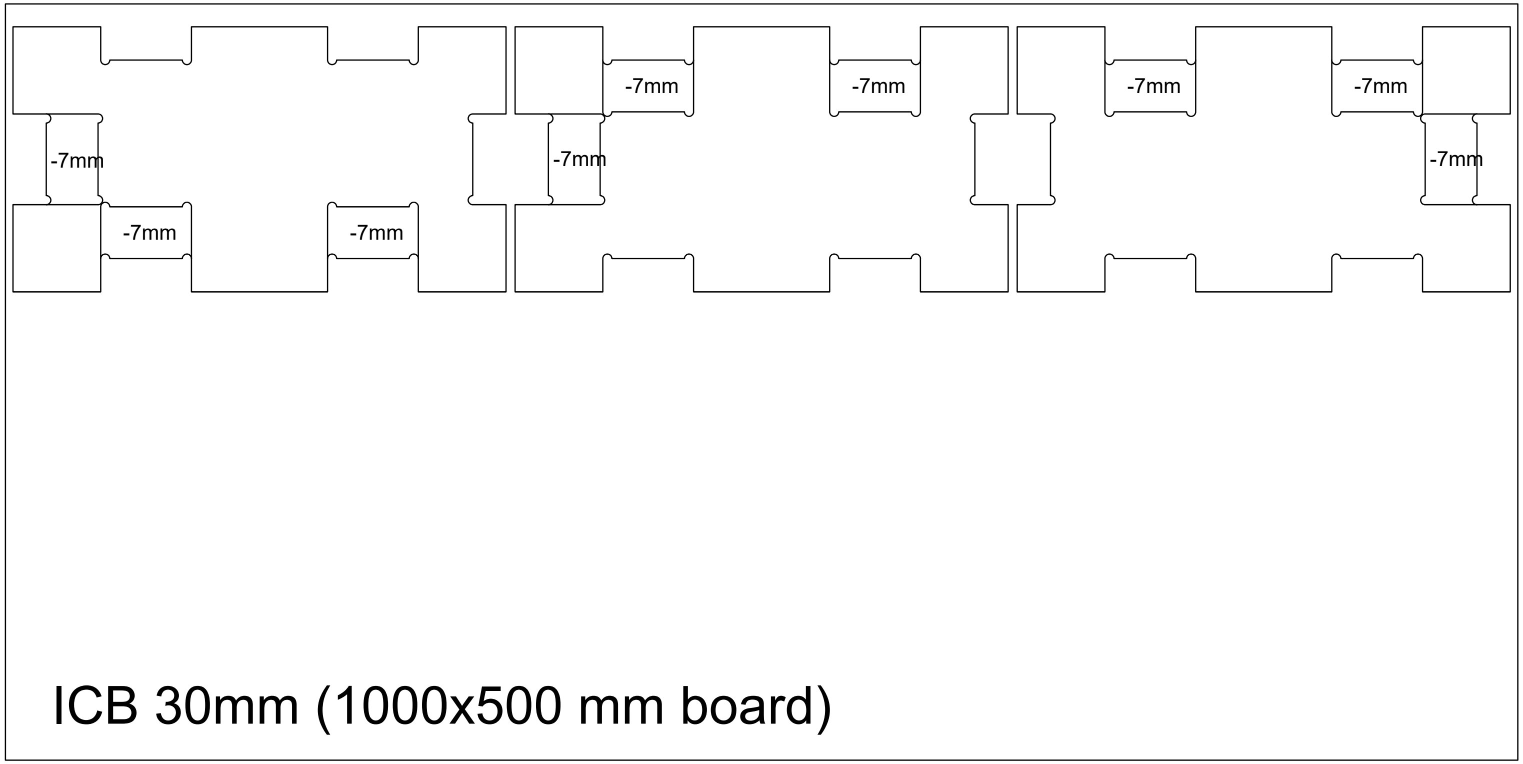
Project
ORW v4.0

Content
Production files: ICB 30 mm infill

Scale
1/5

Code
ORW04_EX.002.01

Date
February 2018



ICB 30mm (1000x500 mm board)

Author
Filipe Brandão, Arq

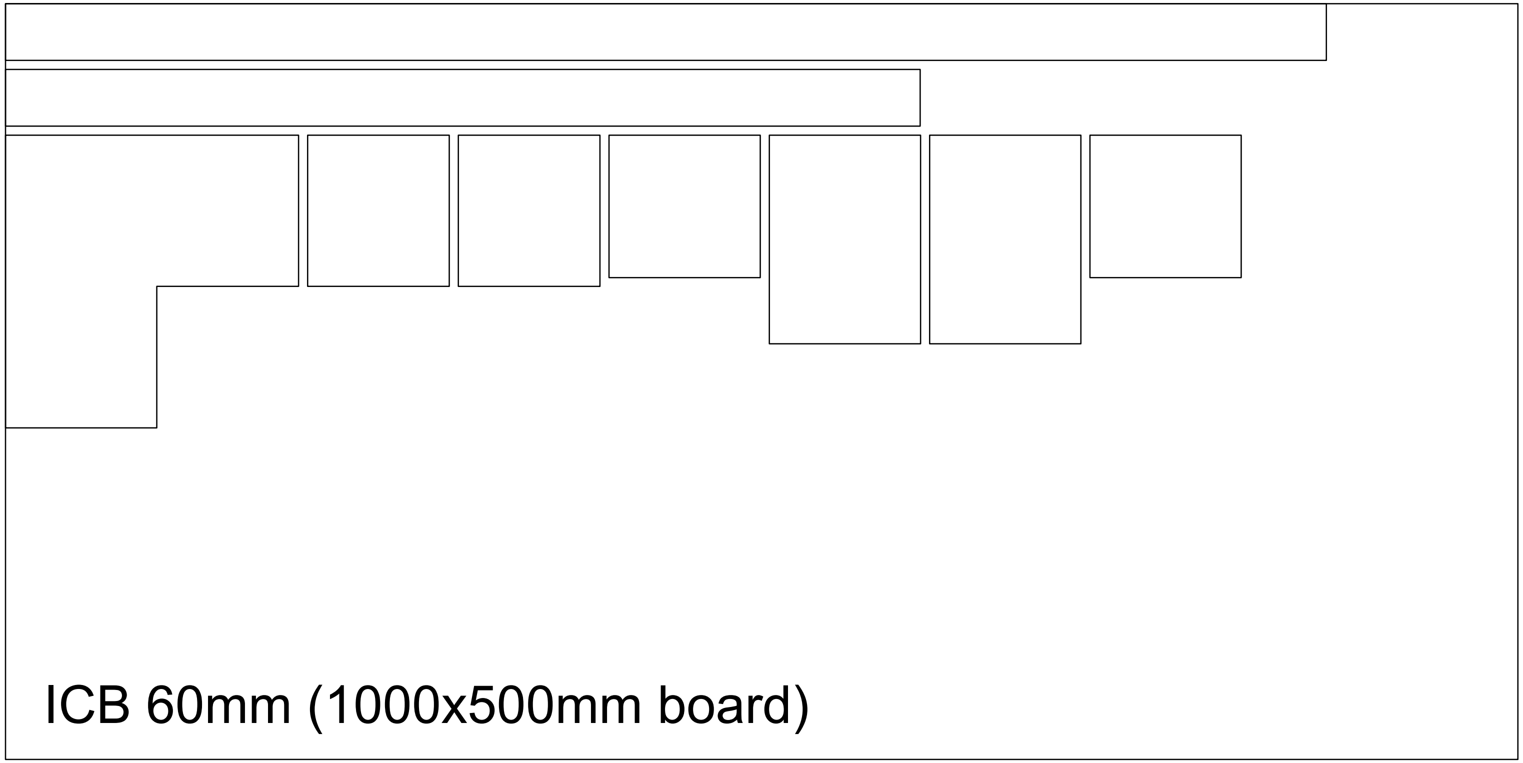
Project
ORW v4.0

Content
Production files: ICB 30 mm infill

Scale
1/5

Code
ORW04_EX.003.01

Date
February 2018



Author
Filipe Brandão, Arq

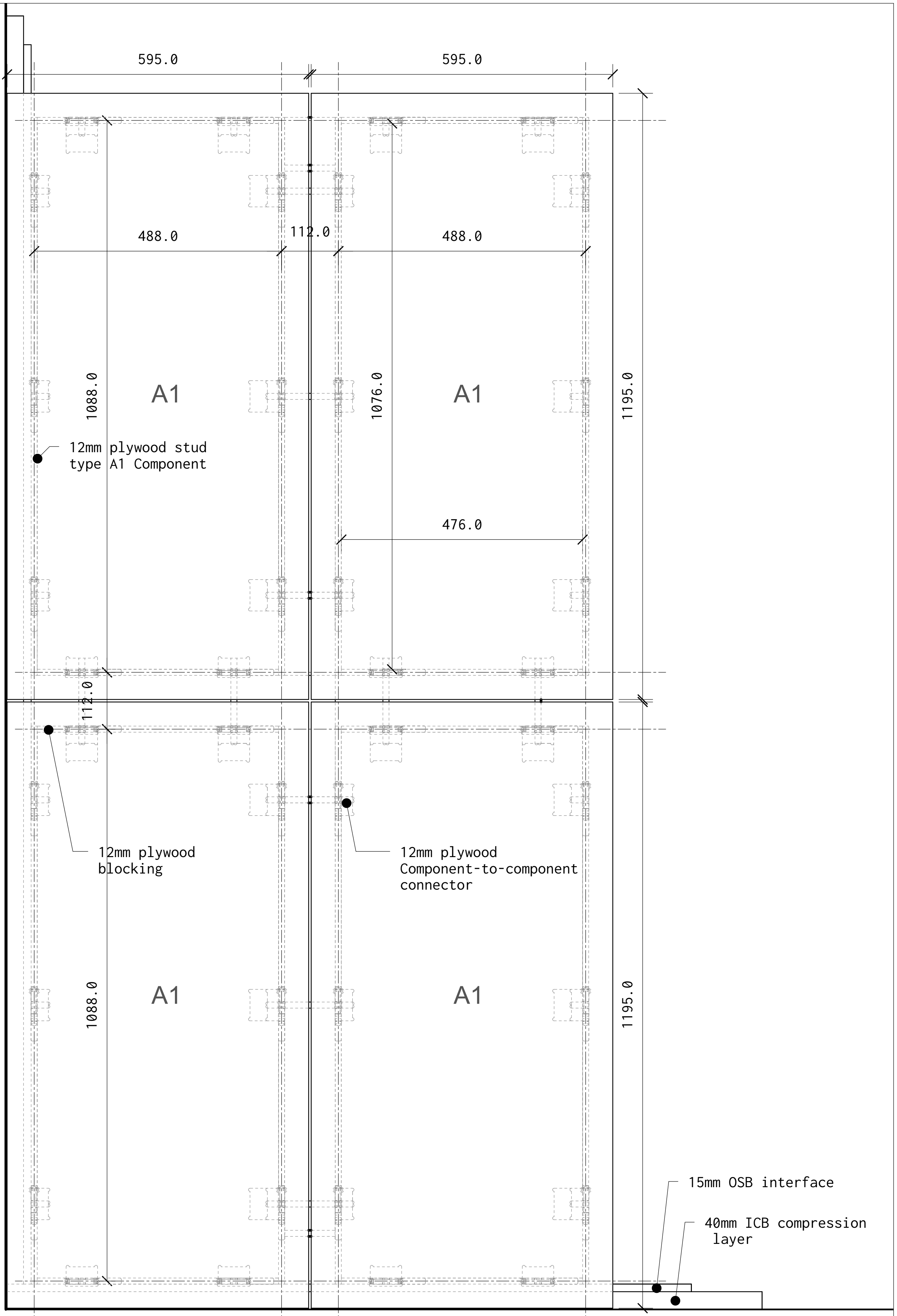
Project
ORW v4.0

Content
Production files: ICB 60 mm infill

Scale
1/5

Code
ORW04_EX.004.01

Date
February 2018



Author
Filipe Brandão, Arq

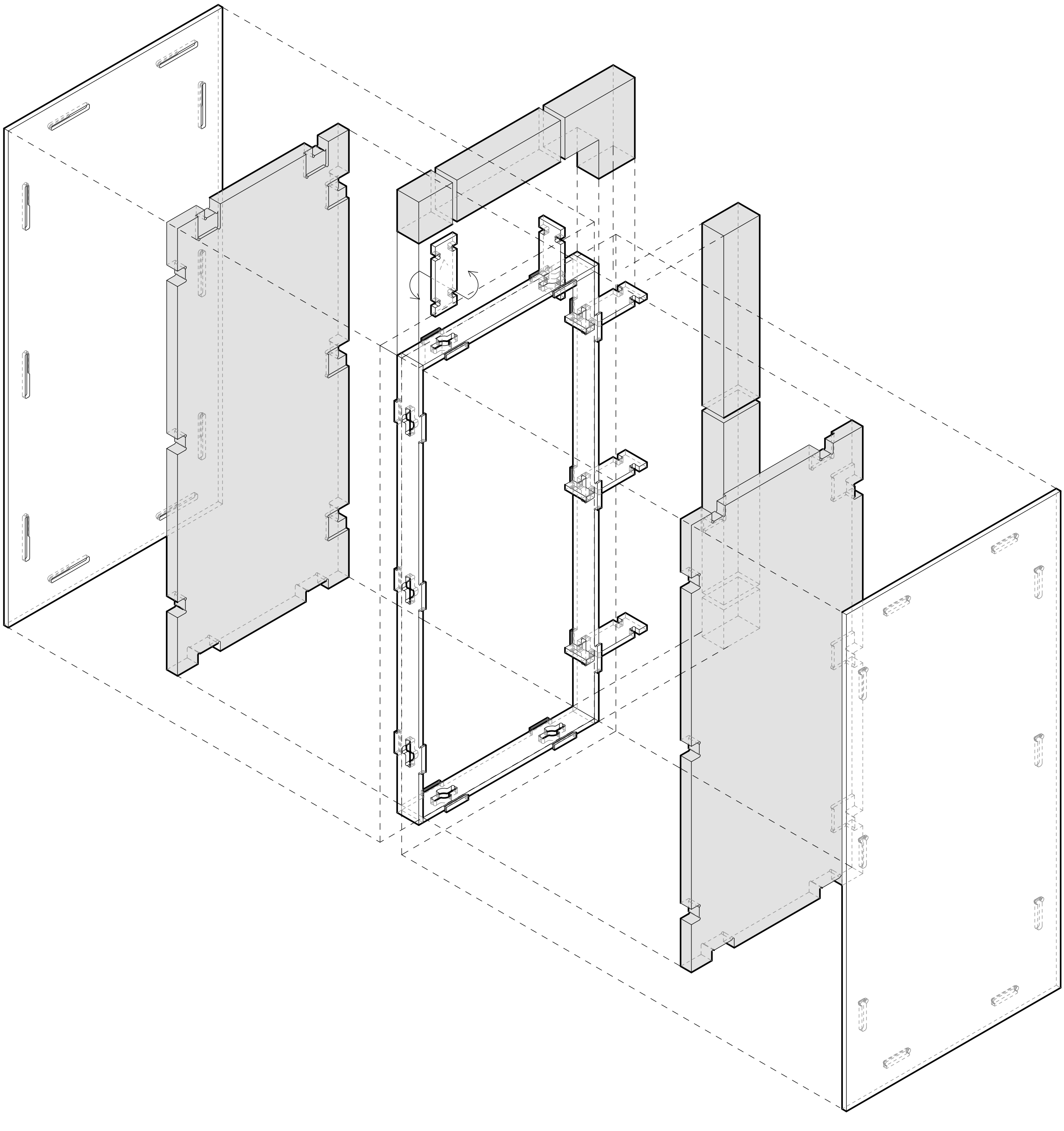
Project
ORW v4.0

Content
Assembled Component elevation detail

Scale
1/10

Código
ORW04_EX.005.01

Date
June 2018



Author
Filipe Brandão, Arq

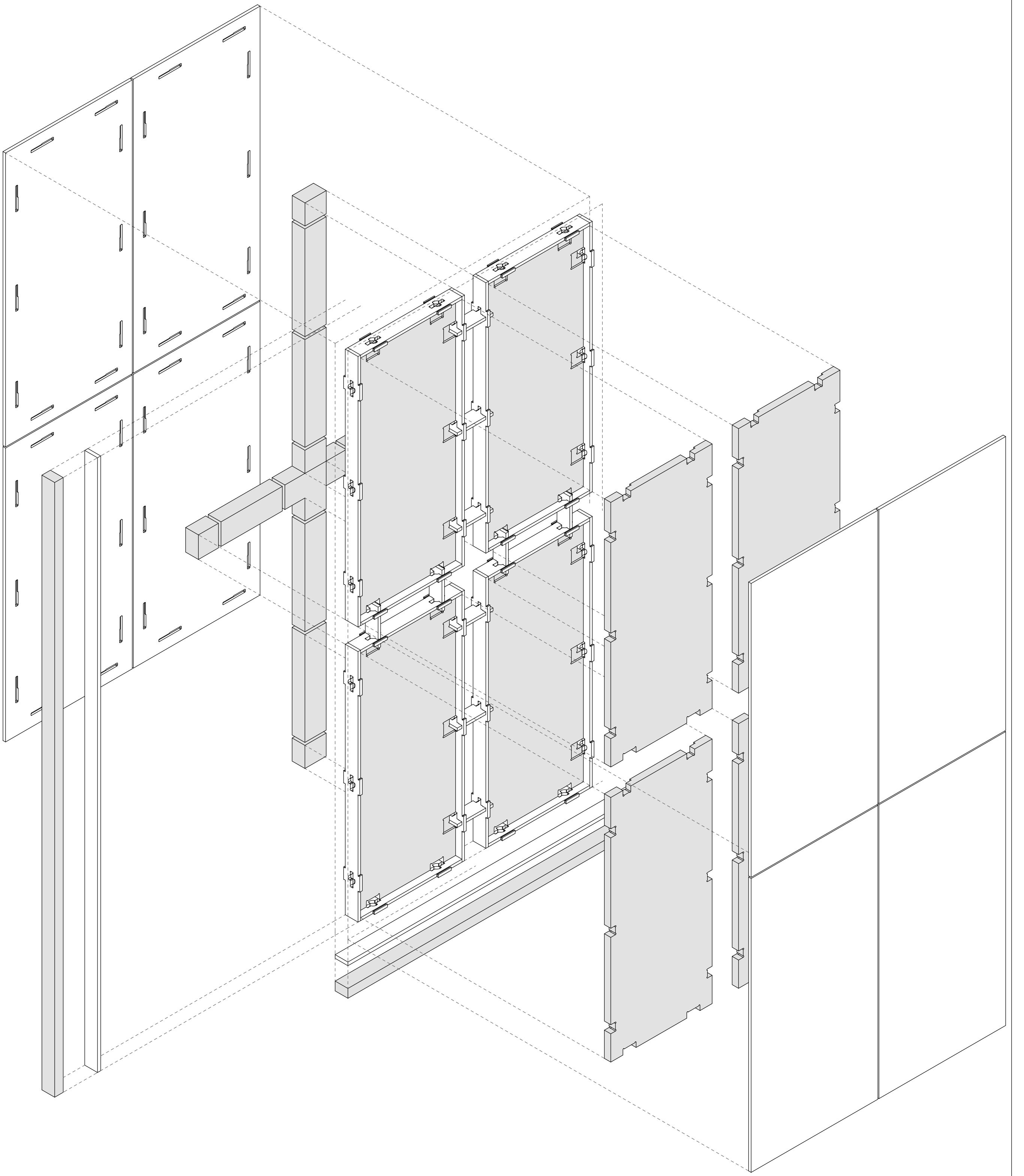
Project
ORW v4.0

Content
Type A component exploded axonometric

Scale
no scale

Código
ORW04_EX.006.01

Date
June 2018



Author
Filipe Brandão, Arq

Project
ORW v4.0

Content
Type A components exploded axonometric

Scale
no scale

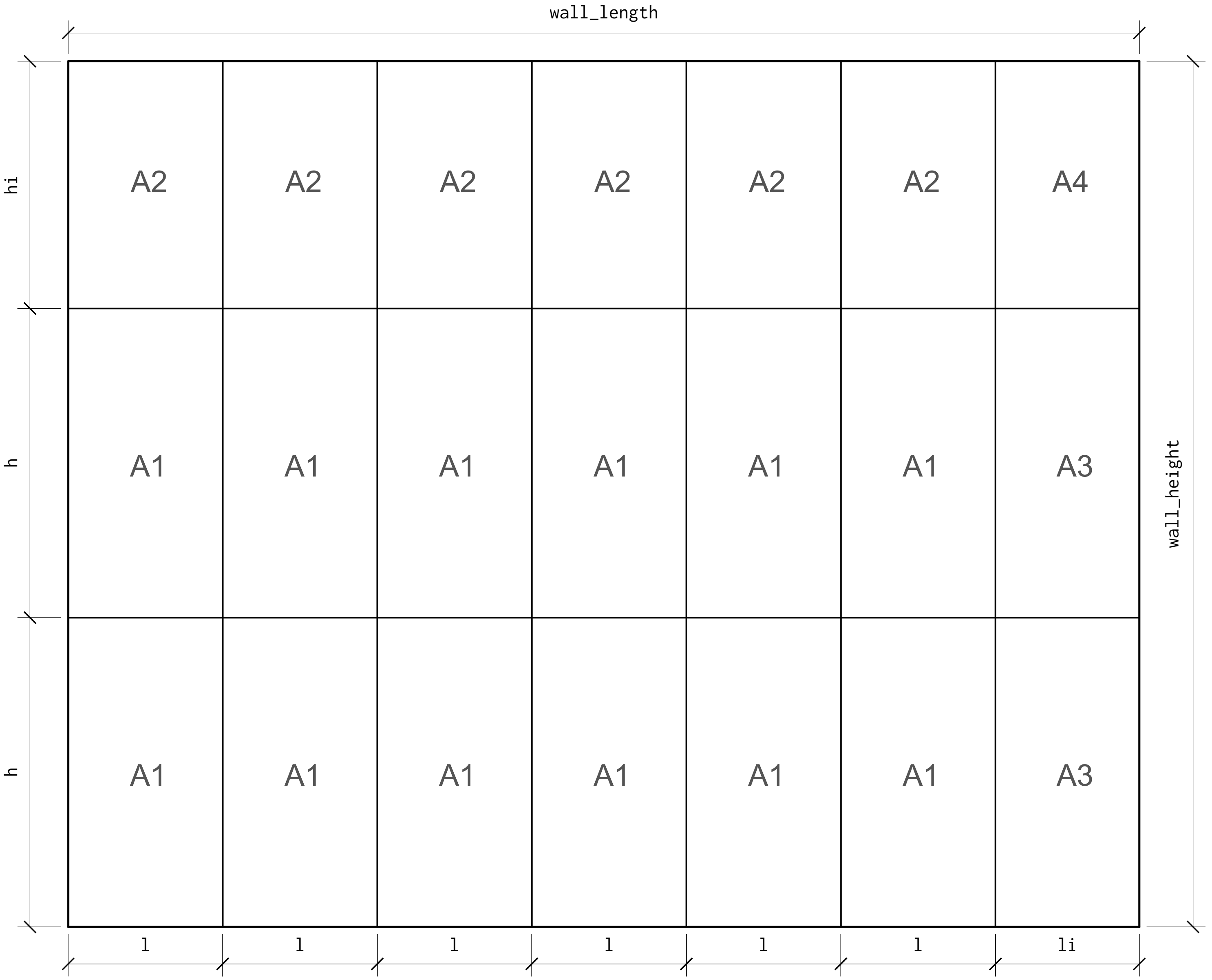
Código
ORW04_EX.007.01

Date
June 2018

hi = wall_height / h
- Floor(wall_height / h)

li = wall_length/ l
- Floor(wall_length/ l)

li_min = 295mm
li_max = 600mm
hi_min = 295mm
hi_max = 1200mm



Author
Filipe Brandão, Arq

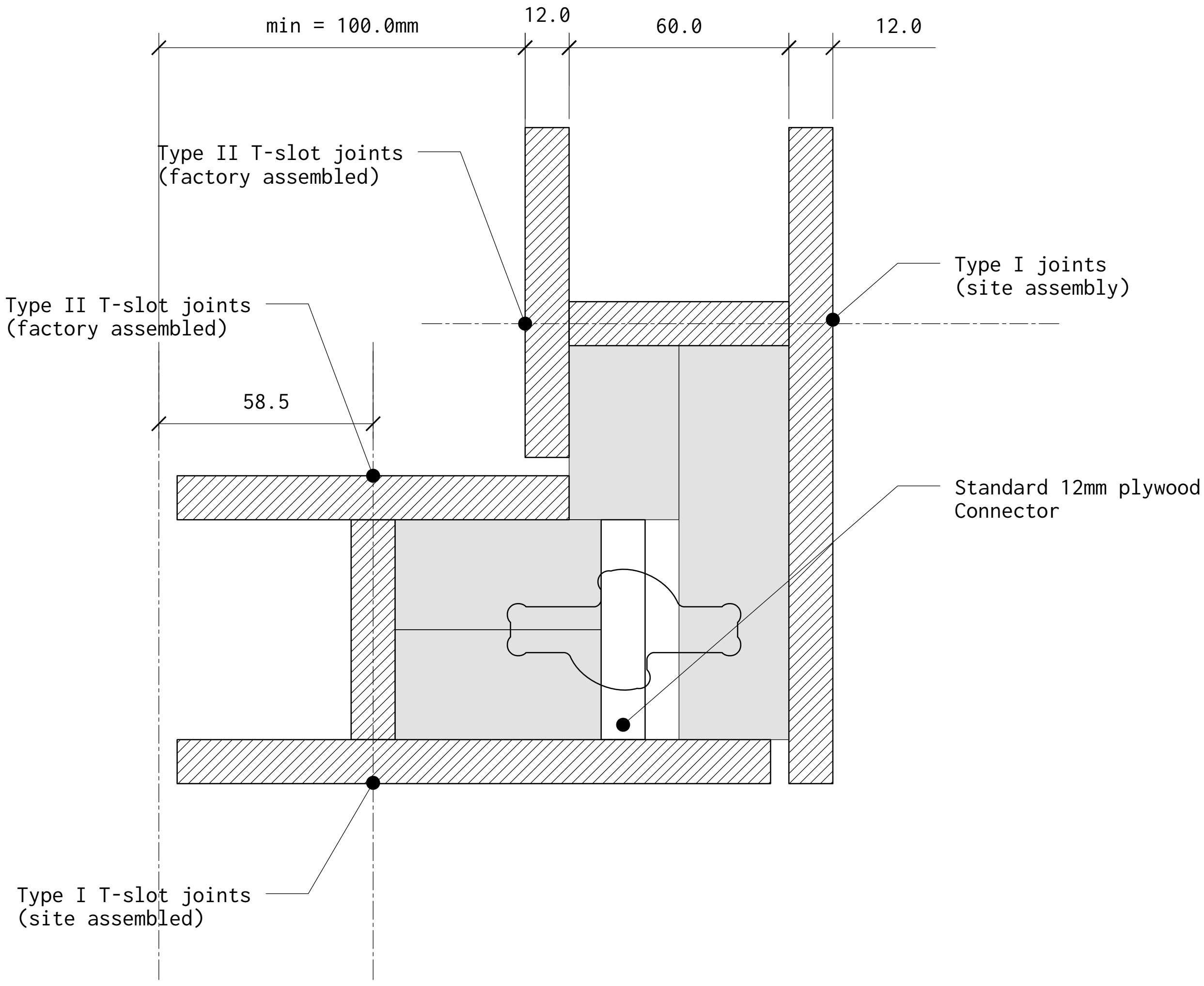
Project
ORW v4.0

Content
Functional and dimentional subdividion elevation

Scale
1/10

Code
ORW04_EX.008.00

Date
June 2018



Author
Filipe Brandão, Arq

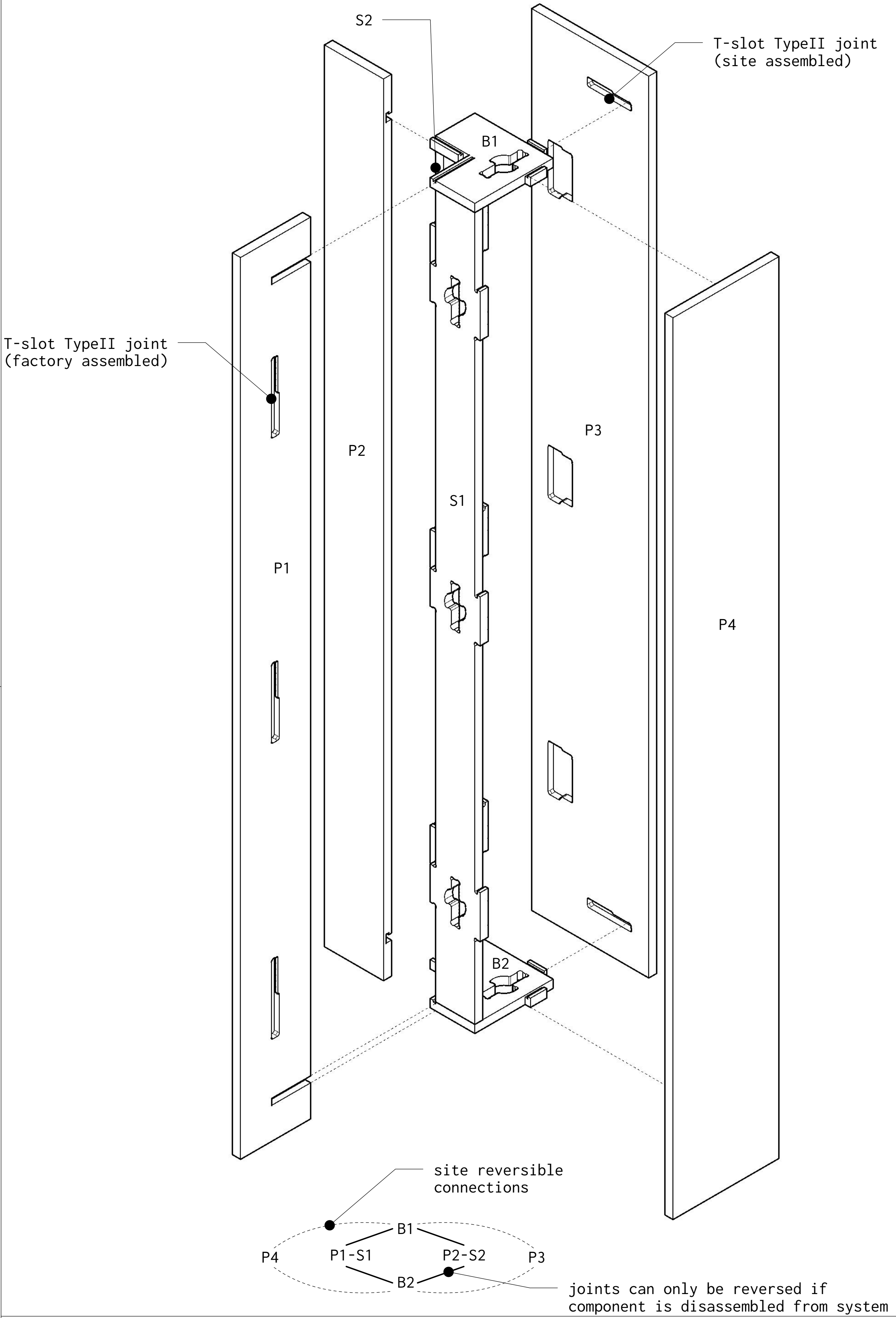
Project
ORW v4.2

Content
2-wall orthogonal intersection component

Scale
1:2

Código
ORW04_EX.009.01

Date
June 2018



Author
Filipe Brandão, Arq

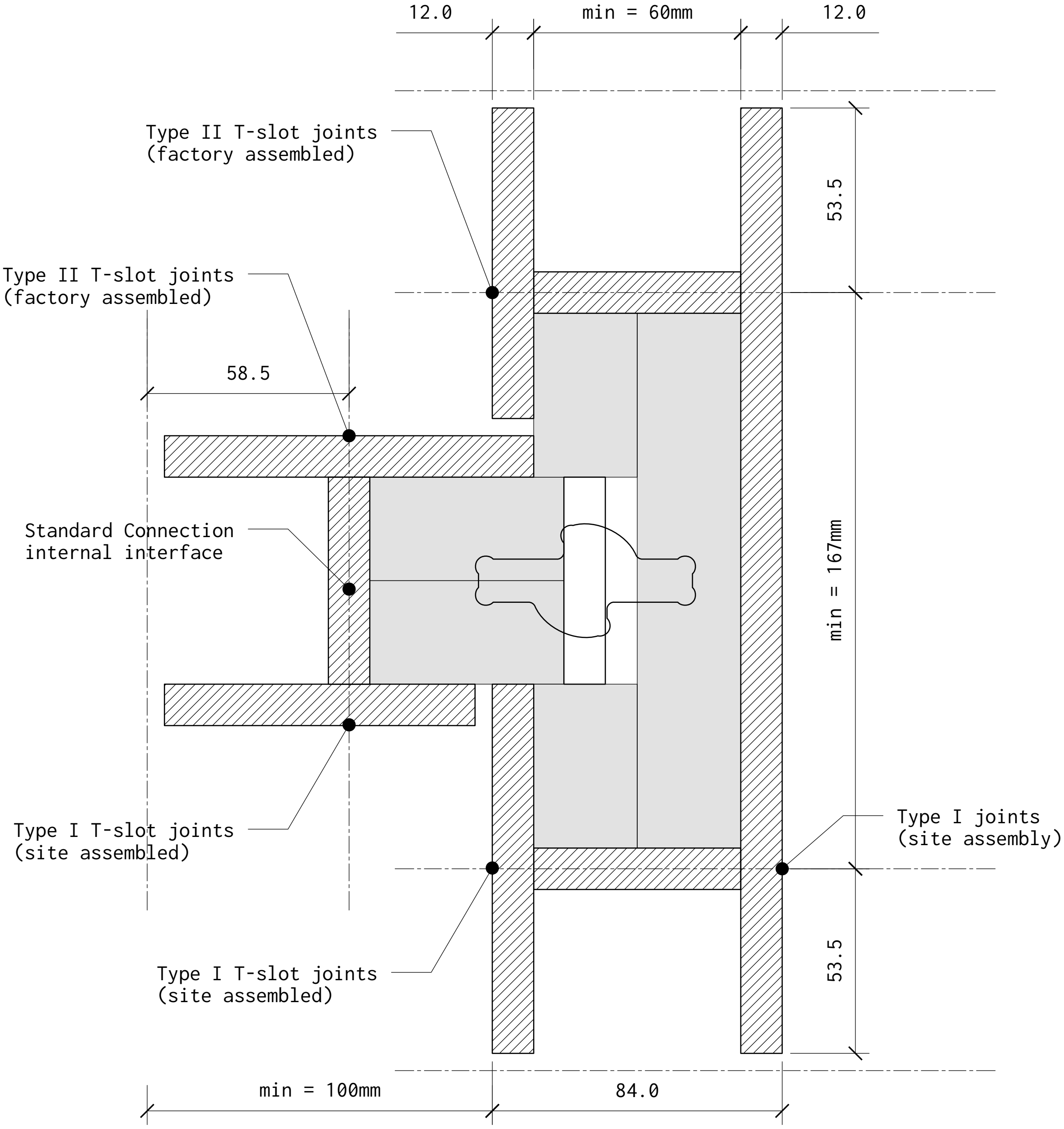
Project
ORW v4.0

Content
2-wall orthogonal intersection component exploded axonometry

Scale
no scale

Código
ORW04_EX.010.01

Date
June 2018



Author
Filipe Brandão, Arq

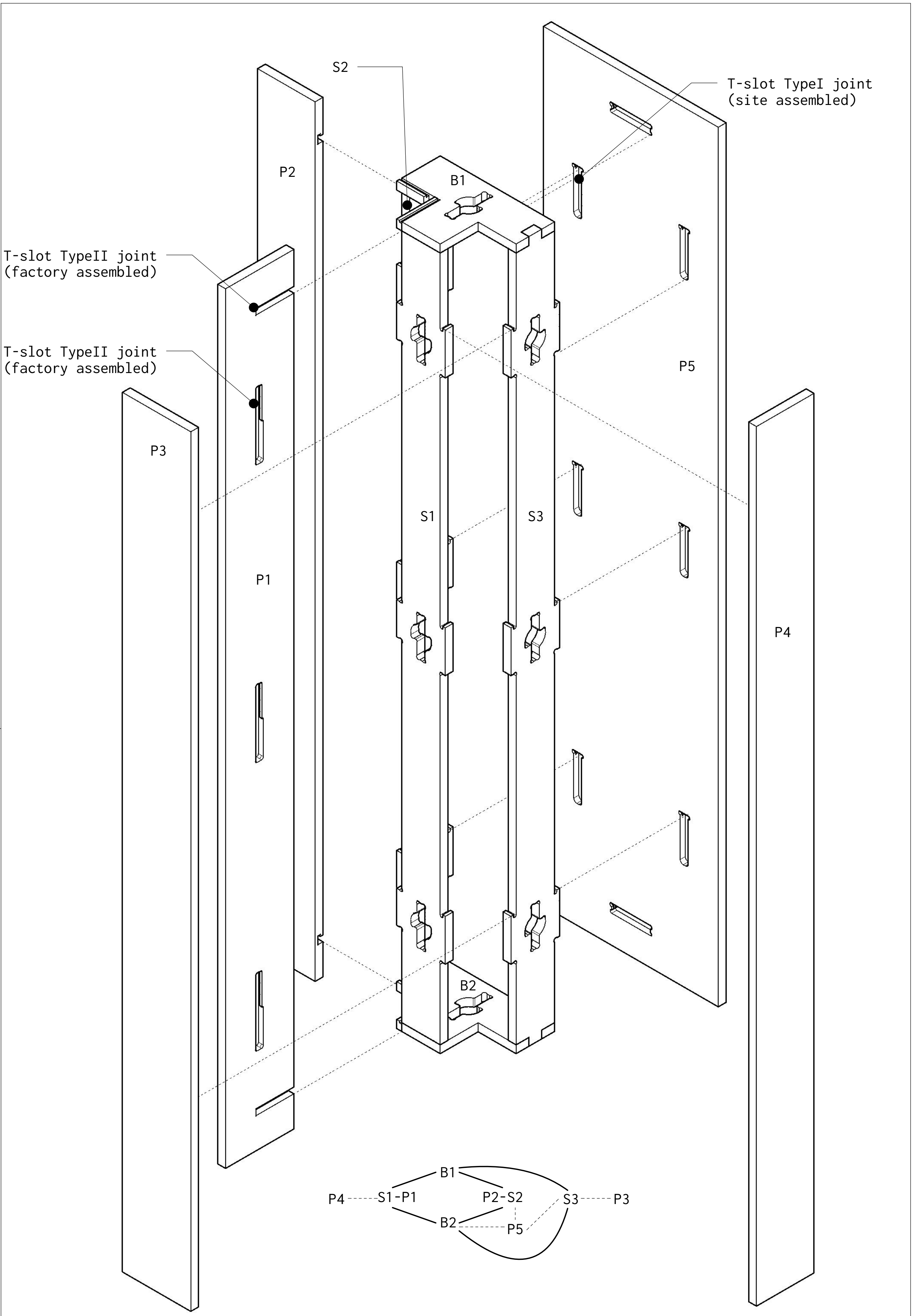
Project
ORW v4.0

Content
3-wall orthogonal intersection component

Scale
1:2

Código
ORW04_EX.011.01

Date
June 2018



Author
Filipe Brandão, Arq

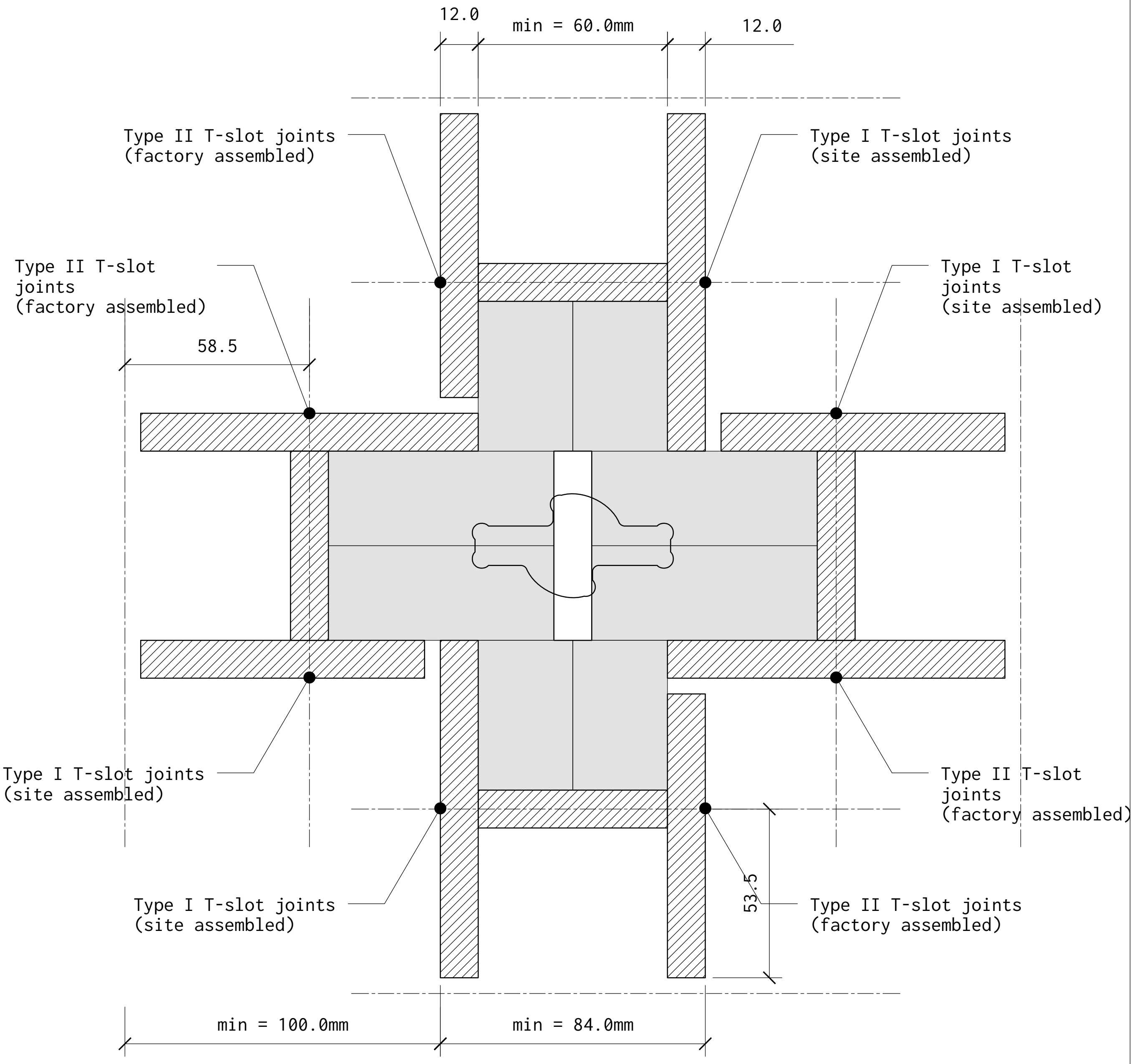
Código
ORW04_EX.012.01

Project
ORW v4.0

Date
June 2018

Content
3-wall orthogonal intersection component exploded axonometry

Scale
no scale



Author
Filipe Brandão, Arq

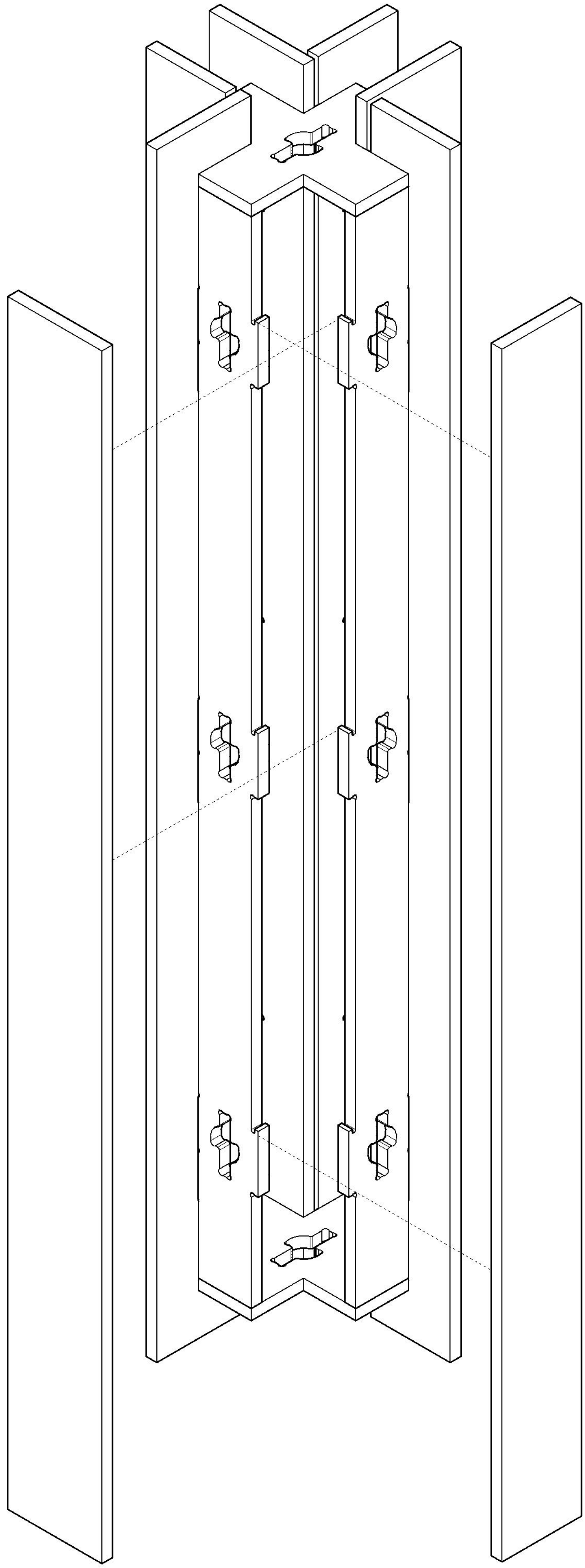
Project
ORW v4.0

Content
4-wall orthogonal intersection component

Scale
1:2

Código
ORW04_EX.013.01

Date
June 2018



Author
Filipe Brandão, Arq

Project
ORW v4.0

Content
4-wall orthogonal intersection component exploded axonometry

Scale
no scale

Código
ORW04_EX.014.01

Date
June 2018

ANNEX L - RoomSurveyor Grasshopper plugin

RoomSurveyor is a plugin for the visual programming environment Grasshopper for Rhino 6 and 7 developed during this thesis with the aim of providing a low-key survey workflow to be used on the web and integrated with design configurators.

The first version, 0.6.0, was released on Food4Rhino on June 3rd 2020, and was compatible with the macOs or Windows versions of Rhino. The first version contained RoomSurvey5 and RoomSurveyStrict interactive triangulation algorithmic workflows which can be used to assist users to survey rooms, either orthogonal or non-orthogonal, and automating the drawing of the as-is survey.

Besides the core triangulation components RoomSurveyor contains several other auxiliary components for processing polygons. These components are tools that have been useful for testing, analyzing, and developing the semi-automated survey workflows.

1. ArePointsLeft/IsPointLeft – Determines if the provided points are left or right of the directed infinite line from P0 to P1 in bidimensional space.
2. IsCx – Verifies if an input polygon is convex.
3. IsIn – Verifies if a given point is inside an input polygon using the Winding Number algorithm. It returns a positive integer if the polygon is CCW oriented, a negative integer if the polygon is CW oriented and zero if the point is outside the polygon.
4. IsOrtho – Returns true if the input polygon is orthogonal.
5. Polygon Angles – Returns the internal and reflex angles of the input polygon at each vertex.
6. Orient Polygon – A component that orients a polygon in CCW direction and verifies if the polygon is simple.
7. ShiftStartPoint – Shifts the starting point of the polygon by a given number of steps.
8. Valid Diagonals – Returns the internal diagonals of a given polygon ordered by corner and without repetition and a list of indices of the end points of each diagonal.
9. Room Turtle – Creates and ortho-polygonal chain from a list of dimensions and a list of turns.
10. RandomConvexPoly – Generates a random convex polygon. A C# version of the algorithm implemented in Java by Sander Verdonschot (Verdonschot, 2017),

based on Pavel Valtr's (Valtr, 1995) proof of the probability of convexity of a random point set.

11. Polygon Corner Properties – It returns some morphological properties of the polygon that may be used for comparisons between polygons.
12. RandomOgonGen - Random Ogon Generator - CutPaste. This algorithm generates a random orthogonal polygon by cutting or pasting rectangles to a seed rectangle. Is follows a similiar approach to one described by Tomas and Bajuelos (Tomás & Bajuelos, 2004a, 2004b) InflatePaste and InflateCut algorithms, with some improvements to adapt it to floating point and reduce the likelyhood of failure in cuts. It implements one rule to prevent generating features that are smaller than a given dimension. This algorithm may fail if a point is outside the bounding box of the ogon or in certain interior very particular points.
13. DeOgonizer (v4) – This algorithm randomly transforms an ogon into a non-orthogonal polygon. It does it by randomly moving a corner along the infinite line of the previous edge line segment, back or forth by half the length of the segment. It implements a few methods to prevent transformations that may generate self-intersecting polygons.

RoomSurveyor version 0.7.0 was released on 21st February 2021 on Food4Rhino and was mostly focused on providing some improvements to the functionality and bug fixes. It is the first version of RoomSurveyor that is supported on ShapeDiver platform. Yet, there were some API breaking changes to the IsPointLeft and ArePointsLeft component APIs.

The new version of the IsPointLeft component has 4 inputs (3 points and 1 plane) and 4 outputs (1 integer and 3 points). The plane is the XY plane by default, so the component may be used as previously. The 3 added outputs return the input points projected to the provided plane. Similar changes were made to ArePointsLeft component.

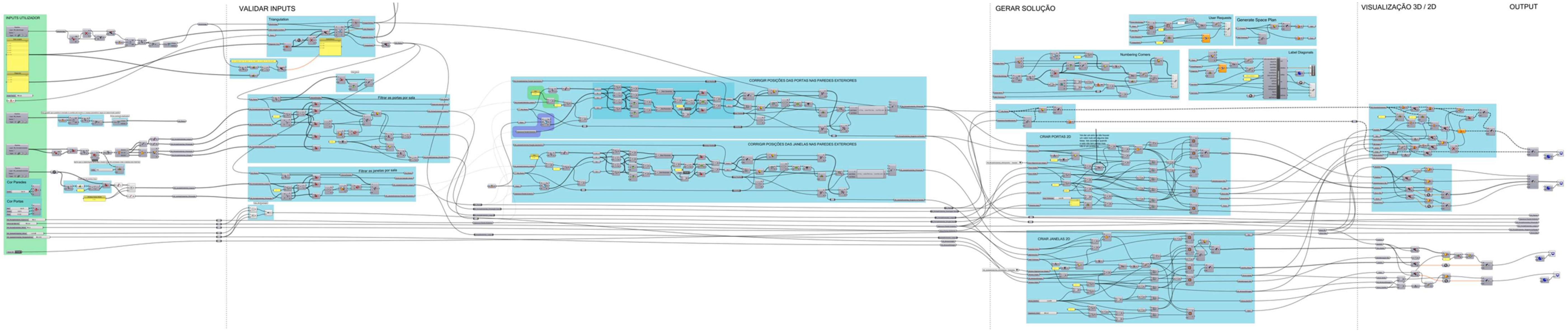
The plugin code with all the described algorithms is available on github[35] and zenodo[36].

---

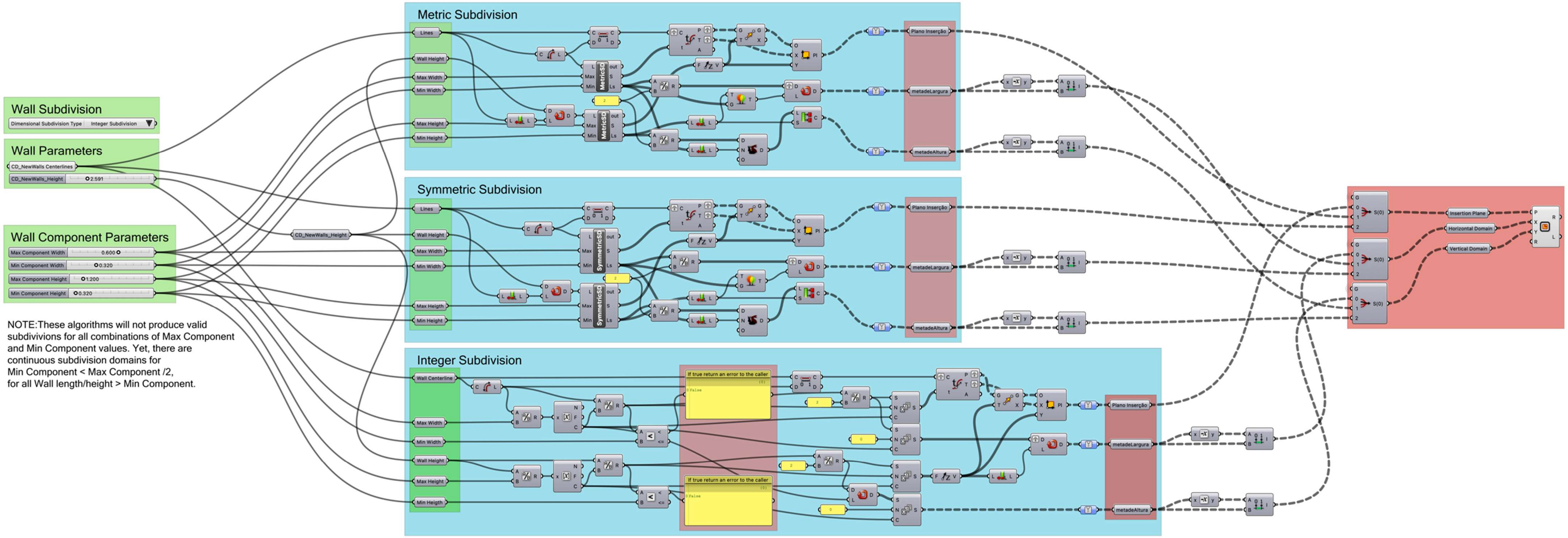
[35] https://github.com/filipejsbrandao/roomsurveyor/

[36] filipejsbrandao. (2022). filipejsbrandao/roomsurveyor: RoomSurveyor v0.7.2 (v0.7.2). Zenodo. https://doi.org/10.5281/zenodo.6930251

ANNEX M – Low key survey workflow



ANNEX N – Dimensional Subdivision algorithms



NOTE:These algorithms will not produce valid subdivivions for all combinations of Max Component and Min Component values. Yet, there are continuous subdivision domains for
Min Component < Max Component /2,
for all Wall length/height > Min Component.