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A Methodology to Qualitatively Select Upcycled Building Materials from Urban and Industrial Waste

Sara Parece [1,*], Vasco Rato [1], Ricardo Resende [1], Pedro Pinto [2] and Stefania Stellacci [1]

[1] ISTAR, Instituto Universitário de Lisboa (ISCTE-IUL), 1649-026 Lisboa, Portugal; vasco.rato@iscte-iul.pt (V.R.); ricardo.resende@iscte-iul.pt (R.R.); stefania_stellacci@iscte-iul.pt (S.S.)

[2] Dinâmia-Cet, Instituto Universitário de Lisboa (ISCTE-IUL), 1649-026 Lisboa, Portugal; pedro.pinto@iscte-iul.pt

* Correspondence: sara_parece@iscte-iul.pt

Abstract: The rising concern about climate change and other challenges faced by the planet led society to look for different design solutions and approaches towards a more balanced relationship between the built and natural environment. The circular economy is an effective alternative to the linear economic model inspired by natural metabolisms and the circular use of resources. This research explores how innovative strategies can be integrated for evaluating local urban and industrial wastes into sustainable building materials. A literature review is conducted focusing on circular design strategies, re-use, recycle, and waste transformation processes. Then, a methodology for the selection of upcycled and re-used building materials is developed based on Ashby's method. A total of thirty-five types of partition walls, which include plastic, wood, paper, steel, aluminium, and agricultural wastes, are evaluated using a multi-criteria decision aid (M-MACBETH). Among these solutions, ten types of walls show high-performance thermal and sound isolation, fourteen types are effective for coating, and two exhibit structural reliability. Regardless of their functional limitations, the proposed solutions based on waste materials bear great potential within the construction industry.

Keywords: circular economy; multi-criteria decision analysis; reuse; upcycle; industrial waste; urban waste

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1. Introduction

The Circular Economy (CE) has gained political and scientific significance in recent years as an alternative to the current mainstream industrial capitalism economic model [1]. CE is deemed an effective method to address social, economic, and ecological issues of the contemporary age and thus achieve the United Nations' Sustainable Development Goals (SDGs) [2].

The relationship between Planet Earth and the Global Economy will be truly sustainable when the supply of resources and the assimilation of waste considers the environmental limits of the planet [3]. World organisations estimate that production and consumption patterns exceed over 75% of the biocapacity [4]. While 92 billion tons of raw materials were extracted, 36 billion tons of waste were produced and collected in 2017, as stated in the Circularity Gap Report. Only 4.2% of these materials were reintroduced into the world economy [1]. These values reflect biodiversity loss, natural resources degradation, and the economic inefficiency of linear systems.

The extraction of virgin resources is predicted to double in the next thirty years [1] due to the growth and consumption patterns of the population. This trend will lead to a rupture in the supply chain and the volatility of trade prices, especially in the EU, where the industry is highly dependent on international markets. On the other hand, the amount of unrecovered waste illustrates lost economic opportunities in the order of USD 1000 billion per year [5]. The construction sector represents 10% of the European Union's (EU) GDP [6], accounts for the most significant consumption of virgin resources [7] and produces one-third of all generated waste [8]. The scientific community calls for a systemic change addressing the entire life cycle of buildings and the construction value chain based on energy efficiency, bio-efficiency, and material efficiency [9].

In this broader context, new strategies have been developed in the last few years, including bioclimatic architecture, disassembly construction techniques, and sustainable materials evaluation [10]. However, less importance has been given to the cascade recovery or the creative valuation of waste and by-products from other industries in the construction sector. Open-circuit resource management and industrial symbiosis represent effective methods to avoid loss of material and product value towards an overall economic and social stability. The main challenge presents offering construction solutions that are more flexible and cost-effective than traditional construction techniques. This is particularly important within European real estate markets when raw material stocks are falling, and the global materials supply chain is under pressure [11].

Advanced materials and techniques based on re-use/recycling are emerging on the current market, while designers need to identify the most viable solutions for each specific context. Various tools, e.g., building environmental product declaration (EPDs) and product certification schemes, provide standardised information about the environmental performance of products and materials essential to decision-making [12]. Many scholars have developed sustainable assessment criteria for selecting building materials [13,14] and evaluation criteria in line with the Circular Economy principles [15]. However, the literature does not yet support the selection of recycled and re-used materials derived from urban and industrial wastes.

Innovative strategies for converting local urban and industrial wastes into building materials and systems are discussed in this study. Our main purpose is to develop a methodology to guide designers' decision-making on upcycled and re-used building materials selection. The proposed methodology is based on the Ashby method followed by multi-criteria analysis in the software M-MACBETH (*Measuring Attractiveness by a Categorical-Based Evaluation Technique*) [16,17]. M-MACBETH can handle multiple results generated from qualitative expert judgments. In our case study, thirty-five construction solutions from post-consumer waste and by-products (plastic, wood, paper, steel, aluminium, and agricultural waste) are analysed and then tested and ranked in a case study in Lisbon (Portugal). This study aims to address the following questions:

- *How to compare a set of upcycled and re-used materials derived from local urban and industrial wastes?*
- *How efficient are these building systems based on urban and industrial wastes?*

The first section of the work presents a literature review on design strategies for the circular management of regional material flows in the construction sector. The second section identifies re-use and recycle typologies and waste transformation processes. The third section introduces a methodology for selecting upcycling materials and construction systems according to CE principles. This methodology is applied to evaluate thirty-five case studies. Finally, the results are discussed based on the sample analysis.

2. Design Strategies for Circular Management of Material Flows

A circular building is designed, constructed, managed, and constructed following the CE principles [9]. It can be adapted to the needs of users and the environment and function as a bank, or reservoir, where materials are identified, temporarily stored and released at the end of their life. As a result, this process leads to an optimisation of the entire value chain with new ownership and business models [18].

This life cycle approach requires a transdisciplinary view and multiple-scale approach, the analysis of the connections between construction products, the built environment, and urban features, as well as the coordination of multiple stakeholders such as product manufacturers, service providers, and demolition/disassembly companies [19]. Due to this complexity, adopting systems thinking (i.e., understanding what the relationship of each part to the whole is and the relationship of the whole to each part in a system) facilitates the collaborative network in the value chain, where the architect assumes a central role [9,20].

Pomponi et al. (2017) propose CE strategies in the built environment through a system perspective that considers three following levels: macro- (national level, cities, general industry structure); meso (regional level/buildings/eco-industrial parks); micro- (product level, building components) [9]. However, this systematisation does not present a complete building analysis and understanding.

Buildings are long-lived entities, often interpreted as large static units but result as sets of various artefacts, each with its specific life cycle, grouped to respond to a series of requirements and constraints [21]. Consequently, buildings are not efficiently managed through their lifecycles as single manufactured products [6]. Indeed, the diachronic analysis of buildings reveals that they encompass a set of dynamic systems that can partially update themselves according to users' needs without becoming obsolete [22]. This phenomenon occurs because a building includes shearing layers (Site, Structure, Skin, Services, Stuff) responsible for its primary functions. Some of these systems can accommodate faster changes without compromising other systems being initially conceived as functional independent [23].

Designing a building in multi-layers may help approach each system according to specific rules and strategies [24]. Their independence allows a quick dismantling at the end of building life. However, a building transformation capacity depends not only on functional aspects but also on technical and physical ones. A façade may have a longer lifetime than the systems and components, and these may be incorporated in different technical or biological cycles [25]. Thus, their subcomponents and materials also require functional, technical, and physical independence allowing necessary transformations at the component and material levels. Within this perspective, the *Hierarchy of Material Levels* define the buildings as hierarchical system sets for building primary functions [21]. These systems, in turn, are composed of components, elements, and materials [26].

The compression of the buildings as a small piece of a city's metabolism, a living system composed of a series of logically and hierarchically assembled elements, helps organise circular design principles in a top-down approach and then achieve better management and a "wholly independent" and "exchangeable" design.

Regarding the *Hierarchy of Material Levels*, circular strategies are related to specific scales of intervention (Figure 1). Four design strategies that contribute to narrowing and slowing down regional material flows are identified in the literature [24,27,28]: (a) Design with local resources: analyses material flows in the geographic, economic, and social contexts of the city, affecting the choice of elements and materials. (b) *Design for adaptability* (*DfA*): evaluates the correlations between the building and their systems and *Design for disassembly* (*DfD*): assesses relationships between elements, components, and systems. (c) *Design with sustainable materials* focuses on materials and elements.

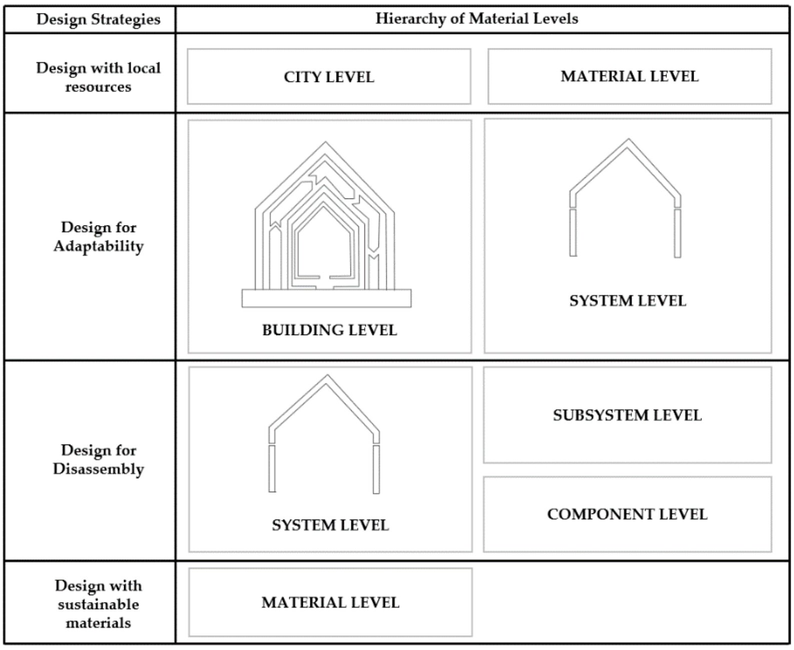


Figure 1. Relationship between Circular design strategies and the *Hierarchy of Material Levels*.

2.1. Design with Local Resources

As stated by Walker et al., the preliminary step in the design of a low environmental impact building is the inventory of locally available materials [29]. The use of local building materials reduces transport cost and impacts, supports regional development, and facilitates sustainable circular business models. The *Living Building Challenge program* defines as a requirement in the certificates of the building that at least 75% of the budget for building materials should come from within a 5000 km radius of the building site, of which 30% should be sourced within 1000 km and 20% within 500 km [30]. The LEED v4 in Material and Resource credits include the location valuation factor, which states that Products and Materials should be extracted, manufactured, and purchased within 160 km from the site location of the project [31].

SuperRuse Studios has pioneered the online platform *Harvest map*, an inventory of local used materials and their location, encouraging designers to explore resources and potential-used building products locally available [24]. Similarly, *REPAiR* project, and the *REFLOW* project, among others, introduce the *Activity-based Spatial Flow Analysis* (AS-MFA) [32]. This methodology connects the spatial, material, and social analyses relating to material flows and stocks from waste production. It determines the qualitative and quantitative waste flow specifications in content, space, and time. It also addresses the relations between managers and consumers, allowing the identification of extracted and manufactured resources, possible exchanges of by-products and wastes between industries (industrial symbiosis) and re-used recycling strategies [32].

2.2. Design for Adaptability (DfA)

The *Design for Adaptability* (DfA) defines the need to conceive the buildings as adaptable living systems. They should be resilient and respond to multiple demands of the environment and the users [33]. The valuable life ends with its inability to accommodate changes [28]. Thus, the obsolescence of the building results from an incompatibility between demands and the capacity for transformation [33]. Considering the functional and social perspectives, there are three types of stakeholders: Society, Owners, and Users. Furthermore, when considering the capacity, influenced by technical and physical characteristics, Location, Building, Systems, and Components should be considered [34]. Schmidt III et al. propose a method for assessing structures according to six types of change, driven by the real estate market, performance, use, location, size, and space [33]. Other academics, e.g., Geraedts, developed key performance indicators for designers to assess the adaptive capacity of buildings [34].

2.3. Design for Disassembly (DfD)

The *Design for Disassembly* (DfD) regards the undamaged recovery of materials, components, and systems during and after the building lifetime, which is an effective alternative to building demolition [24,35,36]. In DfD, re-used systems have the highest rank and recycle materials the lowest (Figure 2) [36]. Thus, the hierarchical model prioritises the recovery (placing it at the highest levels) to preserve the embodied value of systems and components [28]. Durmisevic's Transformation Capability scheme introduces the fundamental assumptions for granting dynamic and dismountable structures [21]. It is necessary to consider the set of criteria regarding functional, technical, and physical decomposition. The functional decomposition evaluates the logical organisation of elements in an assembly and the functional autonomy of each element. The technical and physical decomposition evaluates the synchronous assembly of systems, the life cycle of components, the design of interfaces, and the connection types [21]. ISO 20887 standard on design for deconstruction and adaptability is an international tool to assess deconstruction [37]. Furthermore, research projects such as Buildings as Material Banks (BAMB) [38] offer essential support instruments.

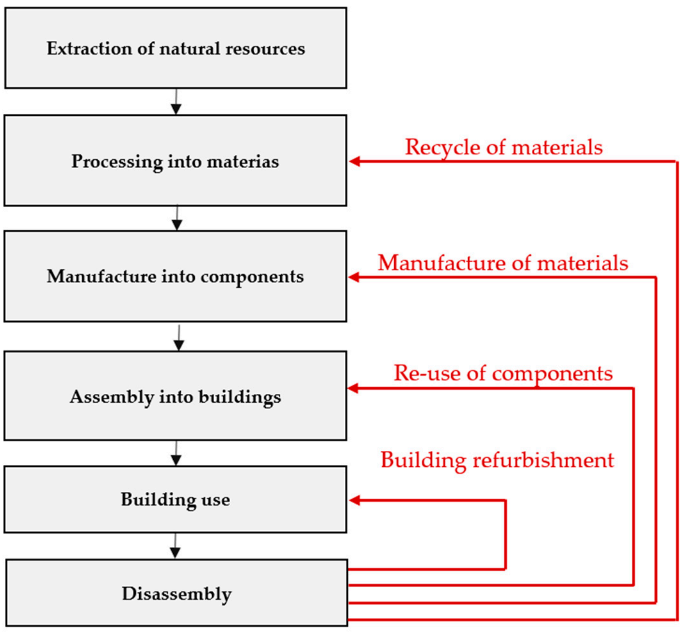


Figure 2. Building recycling hierarchy [36].

2.4. Design with Sustainable Materials

The selection of building materials that comply with sustainability standards reduces construction impacts and ensures that products circulate efficiently on healthy flows [2,39] with low social [40]. The CE distinguishes biological and technical materials. The former consists of natural resources free of toxic substances that can be absorbed by the biosphere, e.g., wood or sand [2]. The CE model proposes that biological materials can be 'cascaded' through various uses, e.g., solid timber can be transformed into panel products. The latter are manufactured resources that nature cannot assimilate, such as metals and plastics. Technological materials should be retained within industrial loops to ensure they are not discarded in the environment and lost to the economy but re-used and recycled [2]. The Cradle to Cradle (C2C) Certified TM product has four main categories to assess materials and circular products: the Material Health identifies the chemical ingredients of every material, avoiding chemicals harmful to humans and the environment present on the "Red

List"; the Material Re-Use evaluates if the design enables a safe return to nature or industry, and the Renewable Energy and Carbon Management promote renewable energy, and reduced CO_2 emissions; Water Stewardship safeguard clean water resources; and Social Fairness from contributing to equitable society [41].

3. Upcycling Waste and By-Products as Construction Materials

Since the European Waste Framework Directive (2008/98/EC) recently replaced by Directive 2018/851/EU-wastes have assumed a prominent role in manufacturing processes [42]. The rational use of natural resources as materials, components, and systems has progressively been prioritised. The Communication on resource efficiency opportunities in the building sector (COM (2014) 445 fin. l) and The Circular Economic Action Plan identify product design and product policies as one of the main enablers to implement CE. Furthermore, these long-term targets reduce landfilling and increase recycling and re-use [43,44].

Until the 20th century, many components were customised and designed by architects using local techniques and materials. The secondary materials market was the primary supplier due to the scarcity of resources available. Thus, many buildings were constructed with locally recovered materials, such as medieval constructions where masonry or bricks were employed from Roman ruins [45]. Even today, communities and informal settlements in developing countries are built with creative and wise solutions leveraging recycled materials. Throughout the 20th and 21st centuries, several architects have explored re-use and recycling through different creative processes. John Harbraken overcame the design limitation and the original function of products on re-use. Harbraken developed a beer bottle that could be re-used after consumption as an affordable house-building brick [46]. Michael Reynolds, back in 1972, built the Thumb House, the first of several homes built on throughout his career. This architect explores a new living concept focused on resource self-sufficiency (e.g., water, and energy) and uses waste from nearby landfills as construction materials [47]. Furthermore, research groups such as Vandkunsten Architects [48], Arup-Global Advisory, Design, Planning & Engineering [49], and from the University of Brighton [50] have been working on full-scale prototypes and new practices of flexible building components and materials.

Re-use refers to the repeated use of a product, component, or material for the same or different purpose from its initial use. It includes minor changes that allow it to perform a function, e.g., a wooden structure is refurbished to be used again as a load-bearing structure or a cladding panel [51–53]. Superuse means recapturing the value of products when they have the lowest possible profit by providing new functions and reintroducing them into new cycles with creative design applications [54].

Recycle is the transformation process of a material so that it can be reintegrated into a new production line as raw material, marking the end of the cycle and the beginning of a new one [51]. The main distinction between re-use and recycle is irreversibility: the material does not return to its original form. Recycling can go in two ways: downcycle-the transformation resulting in a material with a lower value; and upcycle transformation into a material with a higher value than the initial one. To name an example, the ferrous blast-furnace slag (Fe-BFS), a by-product generated from siderurgic pyroprocesses to develop active ceramic anodes [55], and the composite material, which has as raw material adhesive and sticker printing waste produced by UPM Biocomposites, Lahti, Finland. The latter was used by Shigeru Ban for the furniture company Arteck Milan in 2007 [56]. Downcycle is the most widely used transformation process despite being the least beneficial loop in the waste management hierarchy. Re-use saves 88% of greenhouse gas emissions and optimises several tested environmental indicators compared to recycling [57,58].

Literature review and case study analysis render it possible to identify patterns and distinguish six variants in re-use and upcycle [56,59,60] (Table 1) as described below:

(a) *Simple Transformation Process*: A creative design process that gives new functional value to waste, including little changes such as cutting, polishing, painting, or screwing.

It can be executed on the construction site. The Resource Rows Apartments from Compenhaga Lendeger Group project is a remarkable example of creative re-use. The architects have developed an innovative system for re-using brick walls which involve cutting the walls into sections to deliver panels fitted into a steel structure and design different façade compositions [61].

(b) *Design Transformation Process*: The products never become waste, i.e., after their useful life, they are continuously re-used while maintaining their shape, properties, and composition over their life cycle, except for their function that can change drastically [52].

(c) *Densification Transformation Process*: Regards the compaction process of waste. In some specific cases, e.g., with some agricultural waste, the compression activates a specific potential that releases a natural glue under pressure. It can be an asset to produce straw panels, columns, or beams [56]. This process requires advanced industrial equipment or more rudimentary systems to compress the waste [56].

(d) *Cultivation Transformation Process*: The metabolism of cultivated materials enables natural recycle to be carried out locally with basic production techniques. Typically, they absorb carbon dioxide during growth, require controlled humid environments, and feed on other waste or materials. The growth process is halted when the material reaches the required density and strength [59]. The material developed by the University of Cape Town in 2018 is a relevant example of this process. Human urine was used to craft building blocks through microbial carbonate precipitation [62].

(e) *Reconfiguration Transformation Process*: Involves grinding, sewing, gluing, and changing the original form of the material. This process combines organic components, inorganic, or mineral adhesives; and can alter the material's density and aesthetic qualities by changing the size of each piece, the grinding, and the resins. It requires specific production processes and industrial equipment, which consume energy and release carbon dioxide. It cannot be executed in the proximity of the construction sites [56].

(f) *Molecular Transformation Process*: Involves the change of the molecular state of the waste. The process requires high-tech procedures involving, e.g., liquefaction or gasification of the original material. A relevant example regards the organic waste into bioethanol [56]. This process is carried out in specialised factories.

Table 1. Overview of practical examples of re-use and upcycle transformation processes.

Transformation Processes	Recycle or Re-Use	Practical Examples
Simple Transformation Process	Re-use	The Beehive project, Luigi Rosselli Architects, 2018, Sydney [63]; Resource Rows Apartaments, Compenhaga Lendeger Group [62,64].
Design Transformation Process		WaterBrick, Wendell Adams [65]
Densification Transformation Process		PHZ2, Dratz & Dratz Architects, Oberhausen, Germany [56]
Cultivation Transformation Process		Bio brick made from human urine, the University of Cape Town in South Africa [62]
Molecular Transformation Process	Upcycle	WasteBasedBricks®, StoneCycling [66]

4. A Methodological Framework for Evaluating Re-Used and Upcycled Building Materials

This research proposes a methodology for selecting re-used and upcycled building materials and systems from post-consumer waste and by-products. The methodology is applied to internal partition walls. It is based on the Ashby material selection approach [39]:

selecting materials involves seeking the best match between design requirements and the material properties. Ashby's method is based on four steps and shown in Figure 3.

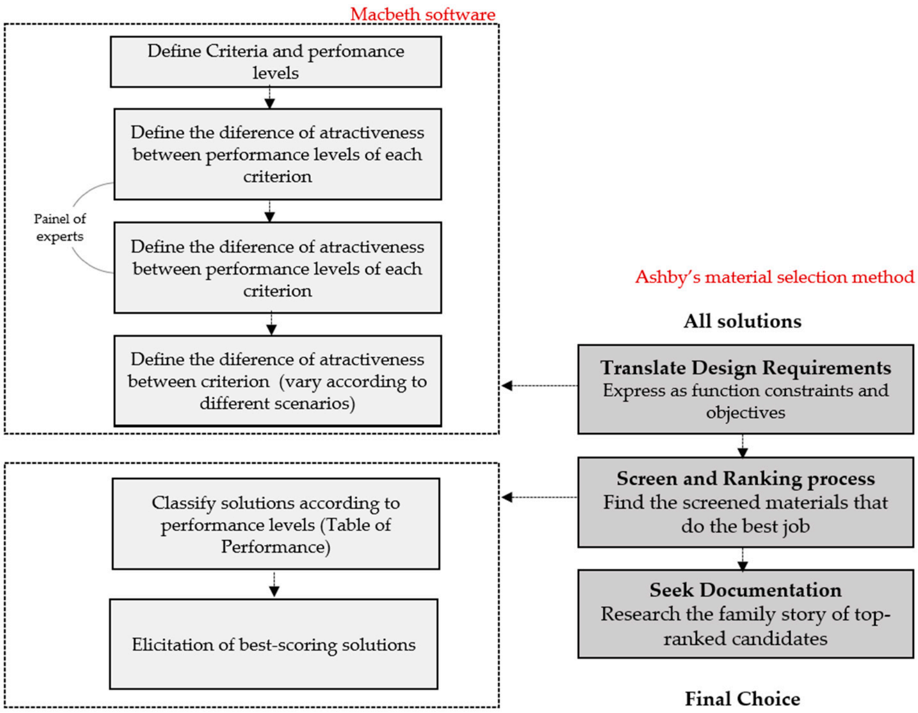


Figure 3. Methodology for evaluating building materials based on post-consumer waste and by-products, as proposed in this research.

1. The *translation of requirements* defines the function of the material, the requirements necessary to achieve it, and identifies the non-negotiable ones.
2. The *screening process* involves the elimination of materials unable to meet the performance requirements. Each material is sorted considering its ability to meet the established requirements.
3. The *rank process* involves the evaluation of each material after the 2nd phase, with criteria of excellence.
4. The outcome of the steps is a ranked shortlist of candidates that meet the constraints and exhibit high scores. It is then necessary to collect the information, e.g., from handbooks, supplier datasheets, websites of environmental agencies, and other reliable sources.

In the first phase, to assess the sustainability and functionality of different solutions, it was necessary to synthesise the principles of the circular economy into performance requirements and criteria according to the function in the building.

Given the existence of multiple and heterogeneous criteria, the Multi-Criteria Decision Analysis (MCDA) is used to develop the screening process. The Macbeth (*Measuring attractiveness by a Categorical-Based Evaluation Technique*) method is adopted in this research for its ability to incorporate many preferences built through pairwise comparison judgments. It is a participative process based on an additive aggregation approach. It allows one to structure the problem and rank the options, considering qualitative indicators, performance levels, and different criteria weights [16,17].

After defining criteria and performance levels, a panel of experts (in this case, architects and civil engineers) judge the performance requirements for each sub-component of the wall. Then, they define the difference of attractiveness between the performance levels of each criterion and between different criteria. This set of criteria-wise is numerically ranked in terms of attractiveness. Then, all options (construction solutions) are classified according to the defined performance levels, and the software, through weighted average, delivers the ranking of all the options on a 0/100 scale.

In the following sections, we adopt these integrated methods (Ashby and Macbeth) to evaluate the performance of internal partition walls, using Lisbon as a case study. According to the concept of "shearing layers", partition walls are part of the Space Plan, with a life expectancy from 3 to 30 years [23]. Given its short life expectancy, the partition walls can be upgraded or replaced frequently. These systems require lower structural and weather resistance constraints than other building systems.

4.1. Translation of Functional Requirements

The functional performance defines the required level of material efficiency for each building component. Strength, deformability, and durability are fundamental parameters, especially in load-bearing elements [67]. The components of the façade system are waterproofing, hygrothermal properties, and so on. Table 2 shows the performance level of each criterion that are listed below:

- *Mechanical Resistance Capacity* defines the material behaviour subjected to mechanical stress. It refers to the ability to withstand an applied force without failing or excessive deformation.
- *Thermal performance* measures thermal properties (conductivity, specific heat) that ensure thermal comfort and building energy efficiency.
- *Acoustic performance* is the ability of a material to absorb or insulate sound.
- *Water-resistance* represents the ability of a material to maintain its properties when exposed to water. If a material absorbs water, it expands, thermal conductivity increases, and strength and durability are compromised.
- *Fire Resistance* characterises the behaviour of a material when exposed to fire, such as the release of toxic gases and emission. The classification of the material fire resistance is fundamental to guarantee the safety of the occupants in case of fire.
- *Durability* is the ability of a material to resist the combined action of physical, chemical, and biological factors. If the material is durable, it will have a longer service life and low maintenance.
- *Sensory Properties* identifies those sensory properties significant in finishing materials: texture, brightness, transparency, and odour.

Table 2. Performance levels for each functional criterion.

Mechanical Resistance Capacity	Thermal Performance	Acoustic Performance	Sensory Properties
High	High	High	
Medium	Medium	Medium	Texture; Brightness; Colour; Transparency; Odour
Low	Low	Low	
Water and moisture resistance	**Fire Resistance**	**Durability**	
Impermeable Hydrophilic water-resistant Hydrophilic non-water-resistant	Non-flammable materials Fire Retardant Materials Flammable materials	Durable Non-Durable	

4.1.1. Partition Walls Functional Requirements

The proposed methodology for selecting upcycled and re-used materials is applied to partition walls. The first step regards the identification of those functional parts that allow the components of a partition wall to work properly (Figure 4); the second step regards the translation of functional needs into requirements and constraints (Table 3).

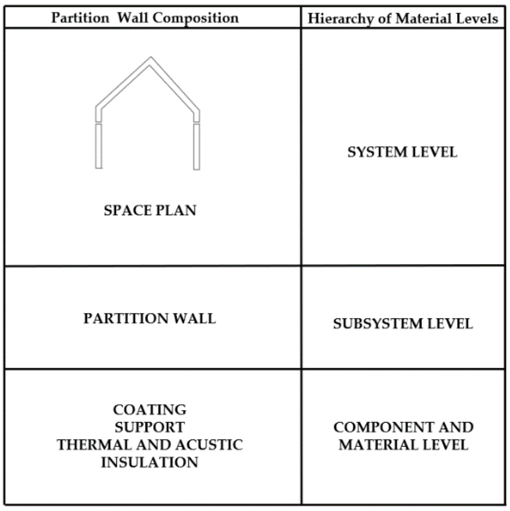


Figure 4. Identification of Partition Wall's main functions.

Table 3. Constraints and functions of partition walls.

Functional Parameters	Coating	Thermal Acoustic Insulation	Support
Mechanical Resistance Capacity	Not relevant	Not relevant	High
Thermal performance	Not relevant	high	Not relevant
Acoustic performance	High	High	High
Water and moisture resistance	not relevant		Hydrophilic water-resistant or impermeable
Fire Resistance	Non-flammable or fire retardant	Non-flammable or fire retardant	Non-flammable or fire retardant
Durability		High	
SensoryProperties	Relevant *	Not relevant	Varying *

* It should achieve aesthetic and functional consistency.

The requirements and constraints necessary to achieve all functional demands were qualitatively identified according to the need to respond to the functional parameters that were previously defined (Table 3).

4.1.2. Environmental Requirements and Parameters According to CE Principles

Environmental performance requirements are essential for evaluating the potential of re-used and upcycled materials. The following requirements are listed in Table 4:

- The *type of waste* identifies the nature of the waste. Post-consumer waste is composed of urban waste, i.e., waste of domestic origin generated during daily activities. Industrial waste or by-products result from advanced production processes or waste from a specific industry, e.g., fly ash from the steel industry or wood scraps.
- The *complexity of the Transformation Process* allows sorting by order of complexity of the transformation processes. The more complex the transformation processes are, the more energy, carbon, and labour are required to produce new materials and new building systems. The simplest transformation processes can be executed at a construction site, eliminating the need for production and transport processes, whereas complex processes require a specific production line.
- The *toxic content* identifies harmful substances that may compromise human and environmental health. The materials used in the circular building must not contain the substances present in Building Industry Red Lists [68]. No prohibited products or materials (e.g., epoxy resin) can be employed.

- The *Potential for Reintegration into the Biological and Technological Cycle* allows the identification of the capacity that materials, at the end of the useful life of the building, to be re-used in cascade, eliminated by nature in biological nutrients, or recycled without losing value in technological nutrients [69]. Each transformation process is evaluated considering the potential contribution of the building material to a global continuous material flow.
- The *Availability and Local Proximity* parameters can be defined at various scales according to the city's political and social geographic context. Three radii of geographical proximity with a centre in Lisbon can be defined for this analysis: High proximity: Radius of 10 km; Medium proximity: 25 km radius; Low proximity: Radius of 40 km radius of the centre of the intervention area (Figure 5). Different types of waste were identified and divided into five groups according to their nature: plastic, paper, wood, steel/aluminium, and agricultural waste. The relevant stages in managing this waste, the actors involved, and the potential places to obtain this waste in Lisbon were also identified within the defined radius.

Table 4. Performance levels for each criterion based on experts' judgments.

Type of Waste (Tw)	Potential for Reintegration into the Biological and Technological Cycle (CTR)	Availability and Local Proximity (PRC)
Urban Waste Industrial Waste	Null Low High	10 km radius 25 km radius 40 km radius
Complexity of the Transformation Process (ALP)	**Toxic Content (TC)**	
Simple Transformation (Reuse) Design Transformation Densification Transformation Reconfiguration Transformation Cultivation Transformation Molecular Transformation	High Low Null	

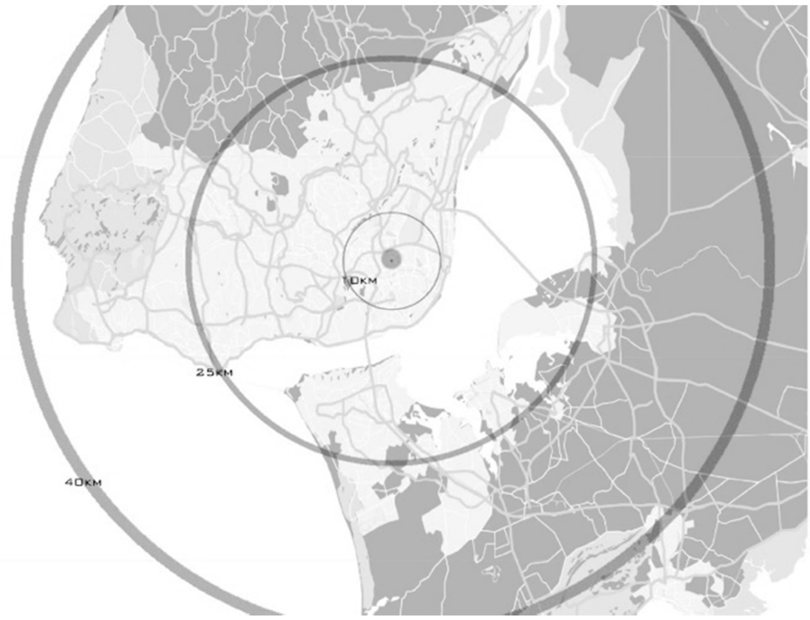


Figure 5. Lisbon map.

4.2. Weighting of Environmental and Functional Performance Levels

After defining the environmental and functional performance levels, a panel of experts establish the distances between each performance level to obtain overall cardinal values. The experts define the difference in attractiveness between two performance levels by selecting the most appropriate adjective from seven semantic categories defined in the Macbeth method: *no, very weak, weak, moderate, strong, very strong, or extreme* (Figure 6). For example, the complexity of the difference in attractiveness between *Simple Transformation Process* (S) and *Design Transformation Process* (D) ratings is *very weak*. In contrast, the difference of attractiveness between *the Cultivation Transformation Process (C) and Reconfiguration Transformation Process (R)* is *strong*. A similar process is undertaken to define the weights of each criterion for each partition wall component. Then, three design scenarios are defined when the dominant criterion is thermal and acoustic insulation, cladding, and load-bearing materials (Figure 7).

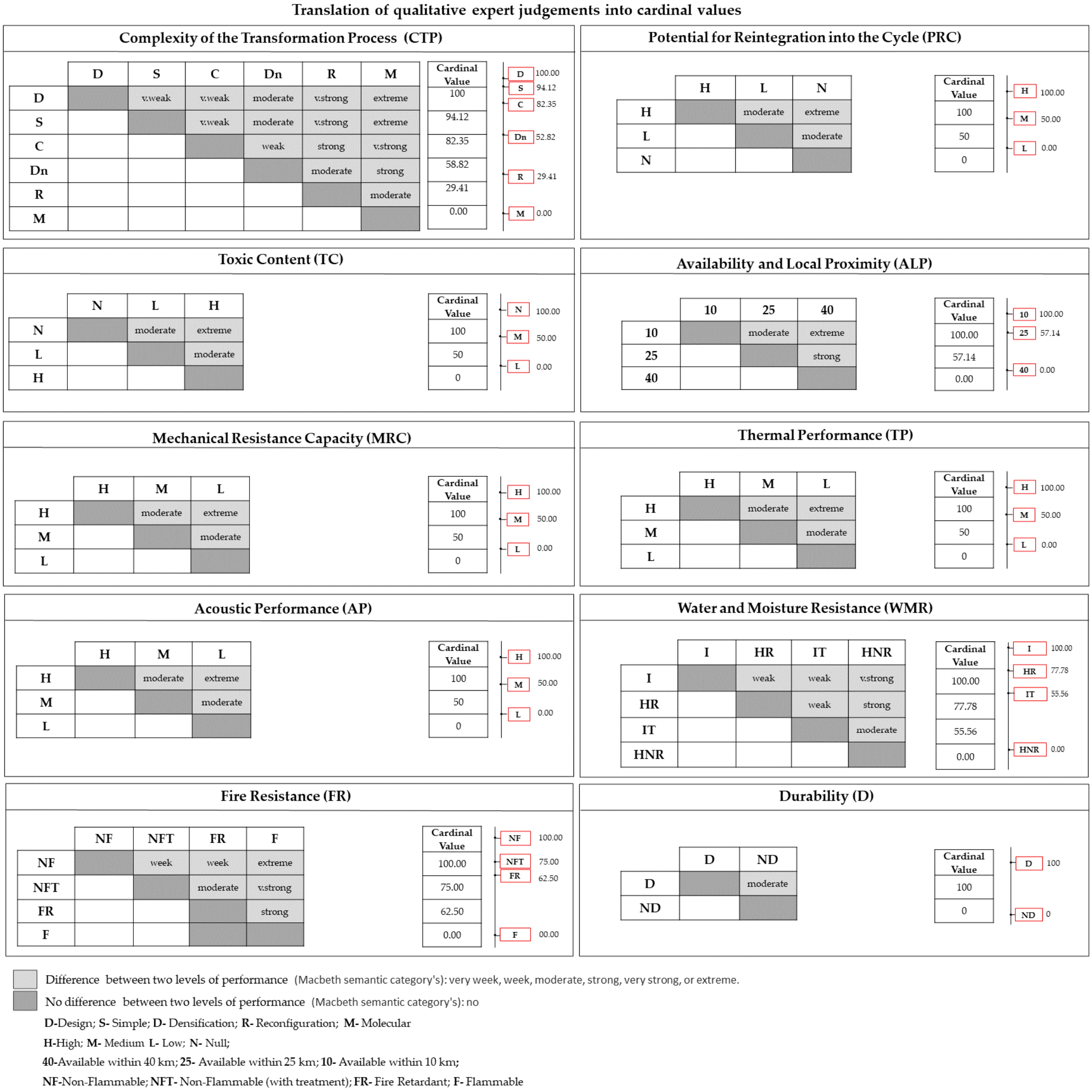
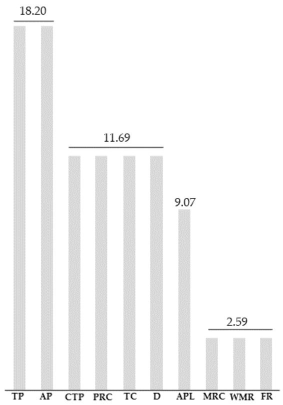


Figure 6. Macbeth judgment matrices related to the attractiveness difference between the performance levels.

Translation of qualitative expert judgements into cardinal values

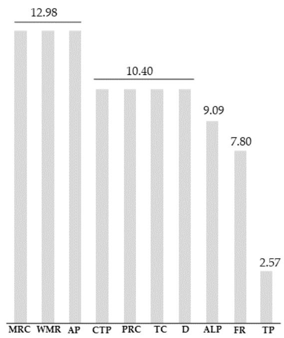
1st Scenario: Thermal and Acoustic Isolation

	TP	AP	CTP	PRC	TC	D	APL	MRC	WMR	FR	Cardinal Value
TP			strong	strong	strong	strong	v.strong	extreme	extreme	extreme	18.20
AP			strong	strong	strong	strong	v.strong	extreme	extreme	extreme	18.20
CTP							weak	v.strong	v.strong	v.strong	11.69
PCR							weak	v.strong	v.strong	v.strong	11.69
TC							weak	v.strong	v.strong	v.strong	11.69
D							weak	moderate	moderate	moderate	11.69
APL								moderate	moderate	moderate	9.07
MRC											2.59
WMR											2.59
FR											2.59



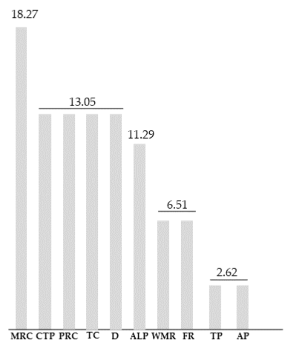
2st Scenario: Coating

	MRC	WMR	AP	CTP	PRC	TC	D	ALP	FR	TP	Cardinal Value
MRC				weak	weak	weak	weak	moderate	moderate	extreme	12.98
WMR				weak	weak	weak	weak	moderate	moderate	extreme	12.98
AP				weak	weak	weak	weak	moderate	moderate	extreme	12.98
CTP								v.strong	v.strong	strong	10.40
PRC								v.strong	v.strong	strong	10.40
TC								moderate	moderate	strong	10.40
D								v. weak	moderate	strong	10.40
ALP									v. weak	strong	9.09
FR										strong	7.80
TP											2.57



2st Scenario: Support

	MRC	CTP	PRC	TC	D	ALP	WMR	FR	TP	AP	Cardinal Value
MRC		weak	weak	weak	weak	moderate	strong	strong	v.strong	v.strong	12.98
CTP						v. weak	moderate	moderate	strong	strong	12.98
PRC						v. weak	moderate	moderate	strong	strong	12.98
TC						v. weak	moderate	moderate	strong	strong	10.40
D						v. weak	moderate	moderate	strong	strong	10.40
ALP							weak	weak	moderate	moderate	10.40
WMR									v. weak	v. weak	10.40
FR									v. weak	v. weak	9.09
TP											7.80
AP											2.57



Difference between two levels of performance (Macbeth method): very week, week, moderate, strong, very strong, or extreme.
No difference between two levels of performance (Macbeth method): no

CTP-The Complexity of the Transformation; Process **PRC**-The Potential for Reintegration Into The Biological and Technological Cycle; **TC**-The Toxic Content **ALP**-The Availability and Local Proximity; **MRC**-The Mechanical Resistance Capacity; **TP**-The Thermal Performance; **AP**-The Acoustic Perfomance **WMR** - The Water and Moisture Resistance **Fr**-The Fire Resistance **D** -The Durabilityz

Figure 7. Macbeth judgment matrices related to the attractiveness difference between each criterion (three scenario models were developed according to the different components of partition walls).

4.3. Classification Process

A total of 35 materials are collected in this study comprising materials and construction systems upcycled or re-used from post-consumer and industrial waste. These were divided into five groups: plastic, paper, wood, steel/aluminium, and agricultural waste, (Tables 5–9).

Table 5. Performance levels of the materials and construction solutions from plastic waste.

Sample	Ref.	Environmental Parameters								Functional Parameters			
		Tw	CTR	PRC	TC	ALP	MCR	TP	AP	WMR	FR	D	SP
1-14 ARTEK PAVILION, Shigeru Ban Architects, Paris, France	[56]	Tw1 Sticker Printer Waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Low	Low	Impermeable	B1 Fire Retardant	Durable	Smooth, Spleen, Colour Gray, Transparent,
1-14 BYFUSION BYBLOCK, UPM Bio composites, Lahti, Finland	[70]	Tw1 plastic waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Flammable	Durable	Irregular Texture, Spleen, Opaque, Odourless
1-14 POLLI-BRICK MINIWIZ, Taipei, Taiwan	[71]	Tw1 PET Bottles	Design	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Non-Flammable	Durable	Geometric Pattern, Glossy Translucid, Colour Gray, Odourless
1-14 RECY BLOCKS, Gert de Mulder	[56]	Tw1 Plastic Bags	Reconfiguration	High Technological Cycle	Null	10 km	Low	Low	Low	Impermeable	Flammable	Durable	Smooth, Spleen, Colour Gray, Transparent, Odourless
1-14 Bima's Microlibrary, Indonesia, SHAU Bandung	[72,73]	Tw1 Ice Cream Boxes	Simple	High Technological Cycle	Null	10 km	Medium	Medium	Low	Impermeable	Flammable	Durable	Texture with Geometric Pattern, Glossy, Translucid, White, Odourless

Table 5. *Cont.*

Sample	Ref.	Environmental Parameters					Functional Parameters						
		Tw	CTR	PRC	TC	ALP	MCR	TP	AP	WMR	FR	D	SP
1-14 Pet Pavilion, Project.DWG e LOOS.FM, The Netherlands	[74]	Tw1 PET Bottles	Simple	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Flammable	Durable	Texture Smooth, Glossy, Translucid, Blue and White, Odourless
1-14 PET WOOL, SupaSoft Insulation UK	[75]	Tw1 PET Bottles	Reconfi guration	High Technological Cycle	Null	10 km	Low	High	High	Hydrophilic water-resistant	Non-Flammable	Durable	Irregular Texture, Glossy, Opaque, White, Odourless

Preferable	Medium	Less Preferable

Table 6. Performance levels of the materials and construction solutions from paper wastes.

Sample	Ref.	Environmental Parameters					Functional Parameters						
		Tw	CTR	PRC	TC	ALP	MCR	TP	AP	WMR	FR	D	SP
1-14 Corrugated Cardboard Pod, Rural Studio, Auburn University, Newbern, AL, USA	[56]	Tw1 Cardboard waste	Densification	High Technological Cycle	Null	10 km	Low	High	High	Impermeable with treatment	Fire Retardant	Not Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
1-14 PHZ2, Paper recycling facilities, Oberhausen, Germany	[56]	Tw1 Cardboard waste	Densification	High Technological Cycle	Null	10 km	Low	High	High	Impermeable with treatment	Fire Retardant	Not Durable	Irregular Texture, Dull, Opaque, Coloured, Odourless

Table 6. *Cont.*

Sample	Ref.	Environmental Parameters					Functional Parameters						
		Tw	**CTR**	**PRC**	**TC**	**ALP**	**MCR**	**TP**	**AP**	**WMR**	**FR**	**D**	**SP**
1-14 PAPER TILE VAULT, BLOCK Research Group, ETH Zurich, Switzerland	[56]	Tw1 Cardboard waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	High	Impermeable	Non-Flammable	Not Durable	Texture Irregular, Dull, Opaque, Beige, Odourless
1-14 Newspaper Wood, Mieke Meijer with Vij5, Eindhoven, The Netherlands	[76]	Tw1 Newspapers	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Non-Flammable	Durable	Irregular Texture, Spleen, Opaque, Coloured, Odourless
1-14 TUFF ROOF, Daman Ganga Paper Mill, Gujarat, India	[56]	T1 TetraPack Packaging	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Fire-retardant	Durable	Irregular Texture, Glossy, Opaque, Coloured, Odourless
1-14 REMATERIALS ROOF PANELS, Hasit Ganatra and Swad Komanduri,	[56]	T2 Paper Packaging and Agricultural Waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Low	Impermeable	Flammable	Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
1-14 ECOR, Robert Noble of Noble Environmental Technologies, San Diego, CA, USA	[77]	T1 Cardboard Waste	Reconfiguration	High Biological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable with treatment	Non-Flammable with treatment	Durable	Irregular Texture, Dull, Opaque, Brown, Odourless

Preferable	Medium	Less Preferable

Table 7. Performance levels of the materials and construction solutions from wood wastes.

Sample	Ref.	Environmental Parameters					Functional Parameters						
		T	CTR	PRC	TC	ALP	MCR	TP	AP	WMR	FR	D	SP
1-14 PAVILLON CIRCULAIR, Encore Heureux, France	[78]	T1 Doors and furniture	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treatment	Non-Flammable with treatment	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
1-14 POLISH PAVILION AT MILAN EXPO 2015, 2PM Architekci	[79]	T1 Fruit Boxes	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treatment	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
1-14 Ami-Lot, Malka Architeture	[80, 81]	T1 Palettes	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treatment	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
1-14 Vegan House Fachade, Block Architects, Vietname	[82]	T1 Blind	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
1-14 Collage house Fachade, S+PS Architects, India	[83]	T1 Doors	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
1-14 SongWood Engineered Timber Resources, Boulder, CO, USA	[84]	T2 Carpentry waste	Reconfiguration	Low Biological Cycle	Low	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Brown, Odourless
1-14 Wood Foam, Fraynhifer Instituit for Wood Research	[55, 85]	T2 Carpentry waste	Reconfiguration	High Biological Cycle	Null	10 km	Low	High	High	Hydrophilic water-resistant	Non-Flammable with treatment	Durable	Irregular Texture, Dull, Opaque, Brown, Odourless

Preferable	Medium	Less Preferable

Table 8. Performance levels of the materials and construction solutions from steel/aluminium wastes.

Sample	Ref.	Environmental Parameters							Functional Parameters			
		T	CTR	PRC	TC	ALP	MCR	TP	AP	WMR	FR	D	SP
1-14 D3 Abwab Pavilion, Lot-el, South Africa	[86, 87]	T1 Industrial containers	Simple	High Biological Cycle	Null	10 km	High	Low	Low	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Odourless
1-14 Dubai Design Week 2015 Pavilion, Fahed Architects	[88]	T1 Springs for collisions	Simple	High Biological Cycle	Null	10 km	High	Low	Low	Impermeable with treatment	Non-Flammable	Durable	Irregular, Glossy, Translucent, Copper Odourless
1-14 Can Cube, Archi-Union Architects, Xangai	[89]	T1 Aluminium Cans	Simple	Low Biological Cycle	Null	10 km	High	Low	Low	Impermeable	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
1-14 ALKIMI, Renewed Materials, LLC, USA	[90]	T2 Aluminium and acrylic waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Colored, Odourless
1-14 Alusion–Stabilized Aluminium Foam Panels, Cymat Technologies Ltd., Mississauga, ON, Canada	[91]	T2 Scrap	Molecular	High Technological Cycle	Null	10 km	High	Low	Medium	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Gray, Odourless

Preferable	Medium	Less Preferable

Table 9. Performance levels of the materials and construction solutions from agriculture waste.

Sample	Ref.	Environmental Parameters						Functional Parameters					
		T	CTR	PRC	TC	ALP	MCR	TP	AP	WMR	FR	D	SP
1-14 TRAshell e Bio-flexi | Plant Cultur	[92]	T1 Cardboard waste	Reconfiguration	Low Biological Cycle	Low	10 km	Medium	Medium	Medium	Impermeable with treatment	Non-Flammable	N.Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
1-14 AGRICULTURAL WASTE PANELS	[59]	T1 Agriculture Waste	Reconfiguration	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treatment	Flammable	N.Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
1-14 HY-FI, Ecovative, Green Island, NY, USA	[93, 94]	T1 Agriculture Waste	Cultivation	High Biological Cycle	Null	10 km	Medium	High	High	Impermeable with treatment	Non-Flammable with treatment	N.Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
1-14 Mycoform, Terreform ONE, New York City, NY, USA	[93, 95]	T1 Agriculture Waste	Cultivation	Low Biological Cycle	Null	10 km	Medium	High	High	Impermeable with treatment	Non-Flammable with treatment	N.Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
1-14 THE GROWING PAVILION, The Living, New York City, NY, USA	[96, 97]	T1 Agriculture Waste	Cultivation	High Biological Cycle	Null	10 km	Low	High	High	Impermeable with treatment	Non-Flammable with treatment t	N.Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
1-14 DECAFE TILES, Raul Lauri Design Lab	[56]	T1 Coffee dregs	Reconfiguration	High Biological Cycle	Null	10 km	Low	Low	Medium	Impermeable with treatment	Non-Flammable with treatment	N.Durable	Irregular Texture, Dull, Opaque, Brown, Coffee
1-14 WINE CORK TILES, Yemm & Hart Green Materials, Marquand, MO, USA	[56]	T2 Wine corks	Reconfiguration	High Biological Cycle	Null	10 km	Low	High	High	Impermeable(wi treatment	Non-Flammable with treatment	N.Durable	Irregular Texture, Dull, Opaque, Brown, Odourless

Table 9. *Cont.*

Sample	Ref.	Environmental Parameters						Functional Parameters					
		T	CTR	PRC	TC	ALP	MCR	TP	AP	WMR	FR	D	SP
1-14 SUNFLOWER ENTREPRISE, Thomas Vailly, Holand	[98]	T2 Sunflower production waste	Reconfiguration	High Biological Cycle	Null	10 km	Low	High	High	Impermeable with treatment	Non-Flammable with treatment	N.Durable	Irregular Texture, Dull, Opaque, Green, Odourless
1-14 CHIP [S] BOARD, Rowan Minkley Robert Nicoll, The Netherlands	[99]	T1 Potato Waste	Reconfiguration	High Biological Cycle	Null	10 km	Low	Medium	Medium	Impermeable with treatment	Non-Flammable with treatment	N.Durable	Irregular Texture, Dull, Opaque, Brown, Odourless

Preferable	Medium	Less Preferable

Table 10. Stages of the production chain, authors, and places to obtain the plastic waste in Lisbon.

Type of Waste			Stages in the Production Chain	Actors	Places	Potential Places Where Waste Can be Obtained in Lisbon
Plastic	Urban Waste	PET Bottles	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul–Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul-Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha • Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar-Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo - Tratamento Resíduos Sólidos Eim-Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo • Recipolymers, Reciclagem de Polímeros, S.A.; Arranhó
		Various types of plastic waste	Consumption Collection Sorting Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies	
		Plastic bags	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies	
		Containers to preserve food	Consumption Collection Sorting Waste treatment	Municipal Collectors, Waste Treatment Companies	Public waste treatment companies	
	Industrial Waste	Sticker Printer Waste	Adhesive Paper Production Final Adhesive Printing and Cutting Waste Collection Waste Treatment	Graphics, Sticker Shops Silk Screen Printing. Municipal Collectors Waste Treatment	Printing Companies Printing and Reprographics Markets or Consumers Public waste treatment companies	• Cópia Igual-Centro de Informática, cópias e Papelaria, Lda, Benfica • LET'S COPY-Printshops; Saldanha • Azul e Amarelo, Centro de Cópias e Impressão, Chelas • Copy Campus; Alta de Lisboa • Mar de Cópias, Algés • Diolicopia-Centro De Copias, Lda; Benfica • Zoomcópia, Saldanha • Centro de Cópias Arco Íris de Pedro Proença, Lda, Campo P. • CopyCenter Centro de Cópias; Cid.Un. • Reprografia Comercial Planeta Colorido, Campo Grande

To assess *Availability and Local Proximity* (APL), it is necessary to define the stages of waste flow management, the actors involved, and the potential places to obtain this waste (in Lisbon). Table 10 summarises this process for plastic waste, and Appendix A, Tables A1–A5, includes all tables. It should be emphasised that urban post-consumption waste (bottles, cans, objects, and food) is placed in undifferentiated or recycling containers, collected and sorted by municipal collectors, and forwarded to the respective waste treatment and recovery centres. Therefore, these are the most probable places to obtain urban waste in large quantities. Objects that have a longer useful life (e.g., doors, tables, chairs, kitchen utensils) can be found in second-hand shops, online second-hand sales platforms, and specialised repositories such as the *Repositório de Materiais* in Portugal [100]. Regarding industrial waste, one of the best suppliers is the firm producing waste, thus contractors or building materials companies can establish a beneficial relationship with that industry.

4.4. Ranking

The M-Macbeth tool allows one to score each option according to the function of the partition wall component. Figures 8 and 9 show the overall thermometer, which ranks the solutions from the best classification (100) to the worst (0). To screen these results, all combinations characterised by a global weighted score lower than 75 are discarded in the 1st and 2nd scenarios. Given the function of the materials in the 3rd scenario, solutions with score lower than 90 are discarded. The structural support function demands a higher set of requirements, and the analyst considered that only those starting from 90 are adequate to perform it.

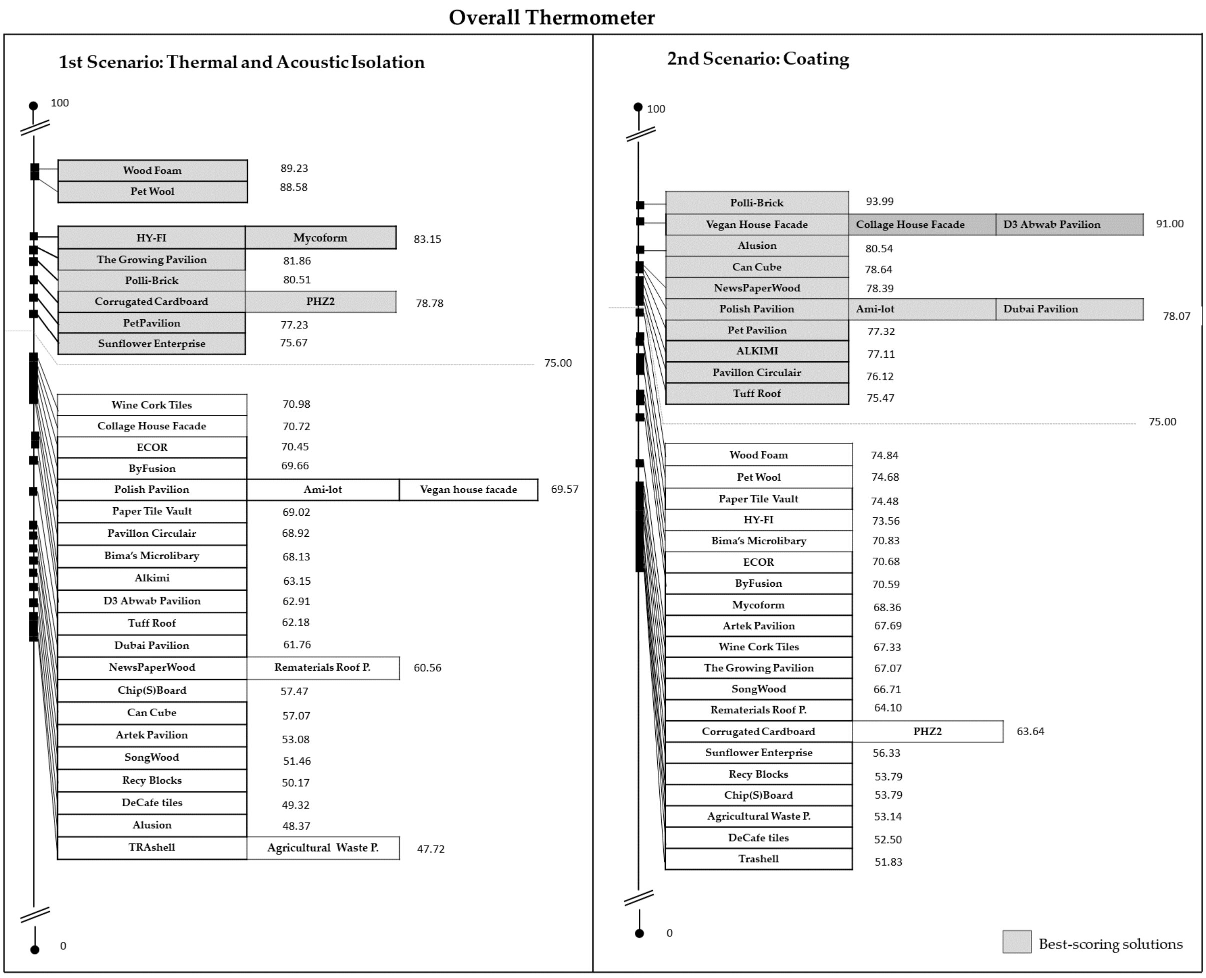


Figure 8. Visual scoring in 1st and 2nd scenario.

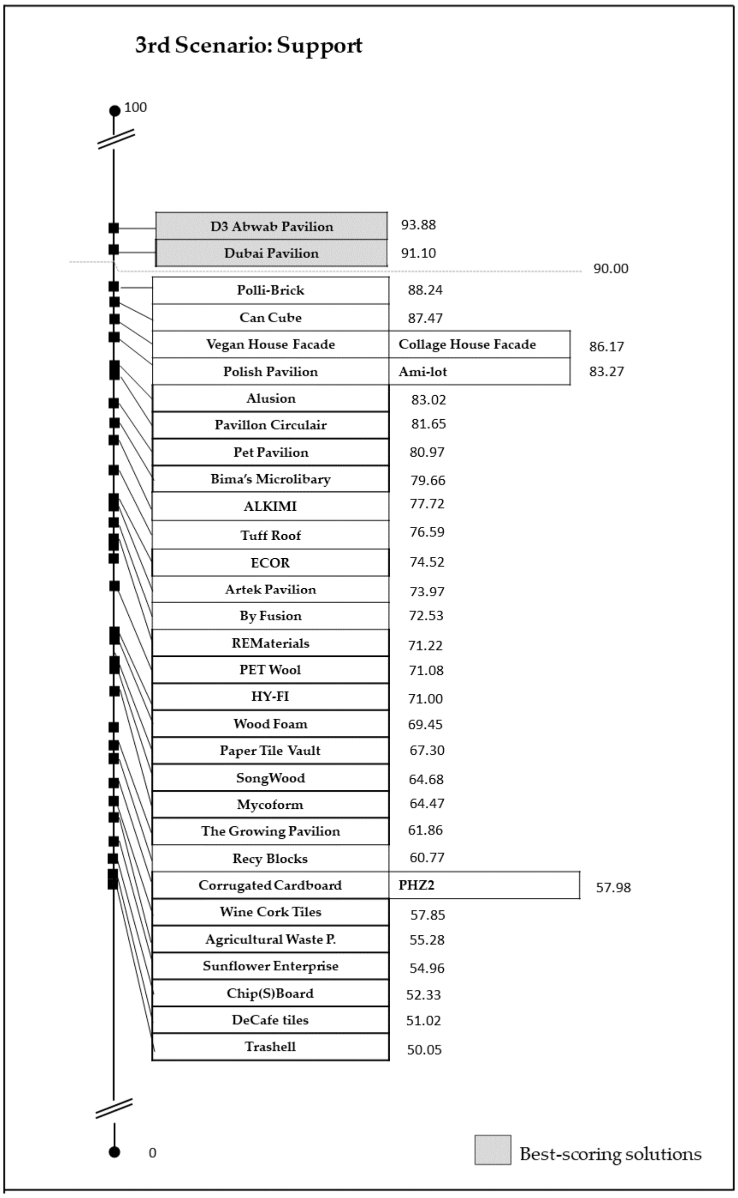


Figure 9. Visual scoring in 3rd scenario.

Ten solutions exhibit the best scoring in the 1st scenario. Among those, four best-scoring solutions stand out:

(a) Wood Foam (Score: 89.23/100) was developed by the Fraynhifer Institute for Wood Research in Germany. It is obtained through lignocellulose from the biomass of trees and other woody plants. The strength of this material does not depend on the quality of the wood. The wood can contain sawmill waste, forest trimmings and chips as raw material because the strength of the foam is related to the contact between the cross fibres and not their length or fibre quality. It can be produced with different densities from 40 to 200 kg/m^3 and has thermal conductivity levels comparable to expanded polystyrene, around 0.04 w/km. Being a porous and hygroscopic material, it behaves similar to a sponge in the presence of moisture, yet its volume remains intact. In general, wood foam bears high resistance, low thermal conductivity, and good behaviour with fire; in this sense, it can be applied as thermal insulation in product packaging, furniture, and non-structural panels. Besides being a waste-derived product, it is an effective alternative to foams made from petrochemical products [59,85].

(b) PET wool (Score: 88.58/100) or polyester wool is a thermo-acoustic material constructed from used PET bottle fibres. It is a 100% recyclable material, already marketed by some companies in different thicknesses (300–200 mm). It has a heat transfer coefficient of 0.04 W/mK, is waterproof, and has excellent sound absorption capacity, with no harmful chemicals or binders. It is entirely safe to handle as it is non-combustible [75].
(c) Hy-Fi and Mycoform (Score: 83.15/100) are similar materials, being composed of agricultural by-products and mushroom mycelium, which serve as natural digestive glue. This type of cultured material uses the natural growth of fungi as a bio-manufacturing method. The manufacturing process is straightforward; agricultural waste is mixed with water and the living organism (mushroom roots/mycelium). After five days, the mixture can be placed in a closed mould, where it rests for another five to ten days (25–27 °C). The roots and organisms grow and fuse into biomass, giving rise to a solid material subjected to heat (70–90 °C), hot pressed, oven-dried or dried in the open air to dehydrate the material, interrupting the growth process, and neutralising the fungus. Due to its thermal conductivity (0.04–0.18 W/mK), Mycelium composites are optimised using straw and hemp fibres (low density), and thus with a reduction of the values to 0.04–0.08 W/mK. Mycelium alone can absorb low-frequency sounds (<1500 Hz), outperforming cork [93,94].

In the 2nd scenario, there are fourteen high scoring solutions. Among those, four best-scoring solutions stand out:

(a) Polli-Brick (93.99/100) from the Winimiz company are 100% recycled polyethylene terephthalate polymer bottles, designed to be re-used, as a translucent, lightweight after consumption and recyclable material. The design of the bottles is modified in 3D into a modular honeycomb-like shape, resulting in a very sturdy container that is suitable for the construction industry, and was used in the iconic EcoARK building at the 2010 International Flora Expo in Taipei (Taiwan) [71].
(b) Vegan house atelier Block Architects and Collage House Facade (91.00). The architects designed the facades of these houses using blinds and doors collected in the proximity of the construction site [82,83].
(c) 3D Abwab Pavilion (91.00/100) designed the Lot-el studio in the Maboneng district in South Africa. The building consists of 140 stacked containers connected with a twist lock and welded together. Each residence consists of two (or three) containers [86,87].

In the 3rd scenario, the best-ranking solutions are:

(a) 3D Abwab Pavilion 8 (93.88/100).
(b) Dubai Design Week 2015 Pavilion (91.10/100). A temporary pavilion for Dubai Design District was designed with materials from a local waste management company (Bea'ah). The pavilion was composed of 1100 springs from used mattresses, and the architects chose this residue for its strength, lightness, and silhouette. The springs exhibited the function of an organic (cloud-like) structural mesh that controlled natural light and recreated patterned shadows on the floor. At the end of the exhibition, the pavilion was dismantled, and materials were re-used by the company [88].

5. Discussion

The overall thermometers allow one to compare the performance of each construction solution under multiple criteria within each design scenario. Solutions derived from paper waste display great limitations, due to poor durability, low mechanical resistance and low water and weather resistance. However, some designers have explored its potential in construction, e.g., The Architect Shigeru Ban, well-known for his innovative approach using unorthodox materials. Ban designs emergency shelters, and other structures that are made from paper tubes. A composite material for the structure and cladding is employed at Arteck Milan in 2007, which contains raw material waste from printing adhesives and stickers produced by the Finnish company UPM. On the other hand, wastepaper sludge, a by-product of recycled paper products, can be incorporated into construction materials [101,102].

The construction solutions with plastic waste can be re-used and recycled. However, several reused options did not fulfil minimal functional requirements. On the other hand, recycling plastic waste to produce new materials such as mortar or concrete has been proven to be effective [101,102]. Wood, steel, and aluminium bear huge potential in re-using or recycling processes due to their intrinsic physical and chemical properties, as shown in their scores.

Virgin materials such as potentially harmful glues or resins need to be added during the transformation process to achieve an adequate functional performance, which compromises the circularity and health of the material.

Bio-based materials like Hy-fi, and Mycoform also tend to be less durable than technical materials as they are generally hydrophilic materials and are prone to the action of fungi. They should be kept in dry places or be coated with suitable and healthy materials as a solution. The material is coated with a sunflower varnish in the Sunflower Enterprise. The same phenomenon occurs with fire resistance requirements. Building materials and systems can be optimised through passive fire protection solutions such as healthy paints and coatings, e.g., black acacia tannin resin and modified lignin resin (epoxy–lignin) [68].

Although the use of local secondary materials can substantially reduce the life cycle impact, impact from primary materials (e.g., painting, resin) that need to be added during production can outweigh the benefits from using secondary materials [102].

The harvest map revealed that all waste flows analysed in this work were generated near the intervention area. Society produces waste streams regardless of regional and cultural influences, aside from sunflower and cereal cultivation.

The lack of accurate technical and environmental information regarding waste-derived products and experimental materials precludes a *Lifecycle Assessment* (LCA) of the selected solutions. This analysis addresses a comprehensive assessment to overcome this limitation. In this study, the environmental and functional performances are taken into account in three design scenarios, distinguished for the criteria weights and the thresholds.

However, the use of a multi-criteria analysis tool presents a limitation. First, the performance of the options is evaluated without considering the interactions between components. Second, a cost-benefit analysis should be addressed in further analyses to validate the effectiveness of each selected solution considering contextual constraints.

The principal drivers for enabling material circularity are cost-effectiveness, technical feasibility, and institutional public support [103]. According to [12], some obstacles encountered by companies for producing and re-using secondary materials include a difficult sales process, limited quantities and access, and lack of adequate infrastructure for sorting and collection [104]. European and national building codes can promote the use of secondary materials. Additionally, the use of environmental product declarations (EPDs), and inclusion in building certification schemes (e.g., BREEAM, Levels, LEED) can lead to making informed decisions [104].

Re-used and upcycled materials may require substantial transformation processes or require the input of primary materials during the transformation into a condition suitable for being used in the construction sector. To this end, meeting the legislative requirements such as energy efficiency and construction reliability is demanding.

The European Commission has recently updated Building Codes (Eurocodes) to incorporate climate impact requirements (e.g., mandate M/515). Specifications and guidelines for material selection should be improved to reduce uncertainties of the construction contractors, designers, financial investors, and to promote the use of secondary materials rather than primary materials. Taxes on primary materials (e.g., aggregates) applied in most EU Member States and reduced Value Added Tax (VAT) for recycled materials in the Czech Republic [103] are effective measures towards a more sustainable building economy.

6. Conclusions

A sustainable and circular urban metabolism can continuously produce the materials it needs to evolve, without exploiting natural resources. Manufacturers and designers are challenged to create efficient systems where materials exist in various states without ever becoming waste. Design strategies that enable decelerated and narrowed material flows will become a common practice in this industry, as new production processes, new techniques, construction processes, and new architectural languages incorporate upcycling remanufacture and re-use.

Designers play a lead role in innovation and must adopt a systematic approach, understanding building composition, assembly, and disassembly routines and their behaviour over time within different social and environmental contexts. Furthermore, designers and construction companies should perceive how the industry manages building material flows, selects new upcycled and re-used materials, and analyses their transformation processes. Despite rarely being put into practice, cascade recovery and upcycling represent competitive strategies for an effective waste management, since they contribute to the resilience in local value chains, and decreases in import dependence, and close material flows.

In this broad context, thirty-five re-used and upcycled materials (post-consumer waste and by-products from various industrial sectors) were evaluated in this study using a Multi-Criteria Analysis considering indicators related to environmental performance, i.e., (i) complexity of transformation processes; (ii) potential of reintroduction in the biological or technological cycle, (iii) toxic content, and (iv) local availability- and indicators related to functional performance, i.e., (v) mechanical resistance capacity, (vi) thermal performance, (vii) acoustic performance, (viii) water and moisture resistance, fire resistance, and durability. A total of ten study solutions were recognised as suitable for thermal and acoustic isolation, fourteen for coating, and two for structural functions. The analysed materials exhibit good environmental performance. Wood, steel, and aluminium waste materials bear great potential, regardless of their functional limitations, the proposed solutions based on waste materials have great potential within the construction industry.

The territory and cities in particular are digitized, not only in their "static" infrastructure–new and existing buildings through BIM models that contain material and component information—but also the material flows of industries, agriculture and domestic waste. This will open multiple opportunities for the exploration of overlooked resources, allowing more matches between demand and supply.

This study provides a methodology that fits within this scheme, by qualitatively evaluating building materials derived from domestic and industrial wastes through technical and sustainability criteria. Its scope can be extended in future research and adapted to other building components and to infrastructure projects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14063430/s1, Map1: Harvest map.

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Appendix A

Table A1. Relevant stages of the production chain, authors involved, and places to obtain plastic waste in Lisbon.

Typology of Waste and Symbology			Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
Plastic	Urban Waste	PET Bottles	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsu–Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul-Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha • Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar-Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo-Tratamento Resíduos Sólidos Eim-Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo • Recipolymers, Reciclagem de Polímeros, S.A.; Arranhó
		Various types of plastic waste	Consumption Collection Sorting Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies.	
		Plastic bags	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	
		Containers to preserve food	Consumption Collection Sorting Waste treatment	Municipal Collectors, Waste Treatment Companies	Public waste treatment companies.	
	Industrial Waste	Sticker Printer Waste	Adhesive Paper Production Final Adhesive Printing and Cutting Waste Collection Waste Treatment	Graphics, Sticker Shops Silk Screen Printing; Municipal Collectors Waste Treatment	Public waste treatment companies.	• Cópia Igual- Centro de Informática, cópias e Papelaria, Lda, Benfica • LET'S COPY - Printshops; Saldanha • Azul e Amarelo, Centro de Cópias e Impressão, Chelas • Copy Campus; Alta de Lisboa • Mar de Cópias, Algés • Diolicopia-Centro De Copias, Lda; Benfica • Zoomcópia, Saldanha • Centro de Cópias Arco Íris de Pedro Proença, Lda, Campo P. • CopyCenter Centro de Cópias; Cid.Un. • Reprografia Comercial Planeta Colorido, Campo Grande

Table A2. Relevant stages of the production chain, authors involved, and places to obtain paper waste in Lisbon.

Typology of Waste and Symbology			Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
Paper	Urban Waste	Miscellaneous Paper Waste	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul–Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul-Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha • Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar-Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo-Tratamento Resíduos Sólidos Eim-Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo • Gráficas (ver Adesivos Resíduos de Impressoras de Autocolantes)
		TetraPack Packaging	Consumption Collection Sorting Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies.	
	Industrial Waste	Cardboard Cutting Waste	Cardboard production Cardboard derivatives industry	Graphics, Sticker Shops Silk Screen Printing. Municipal Collectors Waste Treatment	Public waste treatment companies.	• Sacopor-Sociedade de Embalagens e Sacos de Papel S.A, Pior Velho • Cartembal-Cartonagens e Artigos de Papelaria Lda, Benfica • Antunes & Piorla Lda, Charneca • Lamina-Indústria Transformadora de Materiais de Embalagem Lda., Bobadela • Multicaixa-Equipamentos e Consumíveis de • Embalagem, Lda, São Domingos de Rana • Embacar-Embalagens De Cartão Para A Agricultura, Lda., Unhos • Globespan-Indústria De Cartão, S.A., Linda a Pastora • Carbion Portuguesa-Cartão Bi-Ondulado, Lda., Campo P. • Cart-Cartonagens E Transformados De Papel E Cartão, Lda, Odivelas
		Badly printed newspapers	Newspaper Printing	Graphic Printing Companies	Graphic Printing Companies	• Jornal I, Beato • O Jornal Económico • O Emigrante-MUNDO PORTUGUÊS Observador, Campo Grande • Olagarroa Publishing, Lda, Campolide • Diário de Notícias, Benfica • Sábado, Jornal Record e Jornal de Negócios, Benfica Empresa Gráfica Funchalense, Sintra

Table A3. Relevant stages of the production chain, authors involved, and places to obtain wood waste in Lisbon.

Typology of Waste and Symbology			Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
Wood	**Urban Waste**	Doors, furniture, and partitions	Consumption Collection Sorting Second-hand Shops Waste treatment	Resellers, Demolition Companies	Second-hand shops Construction and Demolition Companies Online Platforms	Second-hand shops Móveis Usados E Restaurados, Arrentela • Antiguidades E Velharias, Almada • Top Usados, Comercio De Artigos • Usados, Olival Basto • Tchiule-Antiguidades e Móveis • Usados, Campolide • Móveis Usados ASO, Vila Cândida • Móveis Da Casa Zuzarte Lda, Santa Cruz Demolition Companies • Montagil Demolições, Unipessoal, Lda, Olival Basto • DOMIPLANA-Terraplanagens E Materiais de Construção, LDAAMGC, UNIPESSOAL, LDA, Beato • LiftUp DEMOLIÇÕES, S.A., Alverca do Ribatejo • AMBIGROUP DEMOLIÇÕES, S.A., Arranhó • MAQUIGAVINHA-Aterros e Desaterros, • LDAABIMAPE-Sociedade de Construções, E Terraplanagens, LDA, Alvalade • Miguel Duarte Pimentel, Demolições, Lda. • Demotri, Demolições, Reciclagem e Construção S.A, Odivelas • Luzipereira-Demolições E Terraplanagens, Lda., Bararena • Manobras De Génio-Demolições E Terraplanagens, Lda, Camarate
		Fruit boxes	Industry use (fruit transport) Disposal of Boxes, Waste treatment	Fruit producers, fruit distribution companies, super, hyper and mini markets, Collectors, Waste Treatment Companies	Fruit Distribution Companies, Supermarkets and Mini markets	• Antalves-Paletes E Embalagens De Madeira, Lda, Pêro Pinheiro • Recopal-Recuperação e Comercialização de Paletas, Lda.

Table A3. *Cont.*

	Typology of Waste and Symbology	Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
	Pallets	Consumption Collection Sorting Waste treatment	Goods distribution companies (retail); Collectors; Waste treatment companies	Public waste treatment companies.	• Renasxer, Frielas • Manjos Rec. Recuperação e Fabrico de Estruturas de Madeira, Lda, Alverca do Ribatejo e Loures • Antalves-Paletes E Embalagens De Madeira, Lda, Pêro Pinheiro • Recopal-Recuperação e Comercialização de Paletas, Lda. • Marquesapal-comércio De Paletes E Produtos Reciclados Lda
Industrial Waste	Waste and shavings from the wood products industry	Production of wood-based products, Waste treatment	Wood-based materials industry; Waste Treatment Companies Waste Treatment	Carpentries Wood waste treatment companies	• MDB Gestão de Resíduos Lda Av. Infante Dom Henrique • AMBIGROUP DEMOLIÇÕES, S.A., Arranhó Carpintarias: • Carpintel-carpintaria E Construções Lda • Vítor Luís Santos-Carpintarias e Marcenarias • Carpintaria E Marcenaria Grilo Lisbonense, Lda, Beato • Carpintaria Lino & Filhos, Lda., Campo Grande • Carpintaria Vasco Oliveira, Amoreiras Renasxer, Frielas

Table A4. Relevant stages of the production chain, authors involved, and places to obtain wood waste in Lisbon.

Typology of Waste and Symbology			Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
Steel and aluminium	Urban Waste	Mattress Springs	Consumption Collection Sorting Waste treatment	Waste Treatment Companies (Scrap)	Waste Treatment Companies (Scrap)	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul–Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul-Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha • Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar-Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo-Tratamento Resíduos Sólidos Eim-Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo
		Soft Drink Cans	Consumption Collection Sorting Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies.	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul–Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul-Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha • Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar-Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo-Tratamento Resíduos Sólidos Eim-Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo

Table A4. *Cont.*

Typology of Waste and Symbology		Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
Industrial Waste	Cutting and sawing waste	Cardboard production Cardboard derivatives industry	Graphics, Sticker Shops Silk Screen Printing; Municipal Collectors Waste Treatment	Public waste treatment companies.	A Agricultura, Lda., Unhos • Globespan-Indústria De Cartão, S.A., Linda a Pastora • Carbion Portuguesa-Cartão Bi-Ondulado, Lda., Campo P. • Cart-Cartonagens E Transformados De Papel E Cartão, Lda, Odivelas
	Industrial containers	Industry (transportation), Collectors, Waste Treatment (Scrap)	Waste Treatment Companies (Scrap)	Waste Treatment Companies (Scrap)	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul–Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul-Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha • Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar-Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo-Tratamento Resíduos Sólidos Eim-Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo

Table A5. Relevant stages of the production chain, authors involved, and places to obtain agricultural waste in Lisbon.

Typology of Waste and Symbology			Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
Agricultural waste	Urban Waste	Wine Corks	Consumption Collection Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies	Significant quantities of this waste are generated (not mapped)-Availability ≤ 10 km • Restaurants • Coffee Shops • Potato Derived Products Production: • F. B. F. Fábrica de Batatas Fritas Lda
		Coffee Boring	Consumption Collection Waste treatment	Households, Restaurants; Municipal Collectors; Waste Treatment Companies	Families, Restaurants, Coffee Shops	
		Potato Peel	Consumption Collection Waste treatment	Households, Restaurants; Municipal Collectors; Waste Treatment Companies	Families, Restaurants, Coffee Shops	
	Industrial Waste	Miscellaneous agricultural residues	Producers (agriculture), Disposal in fields or incineration, Derivatives industry y	Producers (agriculture), Derivatives industry)	Derived products companies and cultivation fields	Urban Gardens (some urban gardens were mapped, but there are 40 urban gardens in the Lisbon metropolitan area and most of them are located less than 10 km from the intervention area): • Parque Hortícola Telheiras • Parque Hortícola Quinta da Granja • Parque Hortícola Bensaúde • Parque Hortícola de Campolide: • Parque Hortícola do Casal Vistoso Cerealicultura: • Farinhas Firmos, Moagem de Cereais, Lda, Colares • Belsuino-Agro-Pecuária da Serra de Cambra, Lda • GRANEL-MOAGEM DE CEREAIS, S.A. VILA FRANCA XIRA

Table A5. *Cont.*

Typology of Waste and Symbology	Relevant Stages in the Production Chain	Actors Involved	Places	Potential Places Where Waste Can Be Obtained in Lisbon
Residues from sunflower cultivation	Producers (agriculture), Disposal in fields or incineration, Derivatives industry y	Producers (agriculture), Derivatives industry)	Derived products companies and cultivation fields	Cultivation: • Parque Hortícola Telheiras • Horticultural Park Quinta da Granja • Horticultural Park Bensaúde • Parque Hortícola de Campolide • Parque Hortícola do Casal Vistoso • Derived products companies: • Sovena Group, Industrial Facilities, Barreiro

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