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Extreme Environments - Materials and Spatial Configuration for Architectural Mediation

Leonor Marques Mano Domingos

Doutoramento em Arquitetura dos Territórios Metropolitanos Contemporâneos

Orientadores(as):
Doutor Vasco Rato, Professor Associado,
ISCTE-IUL

Mestre Carla Leitão, Professora Assistente,
Pratt Institute School of Architecture

Dezembro, 2021

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Júri:

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ISCTE-Instituto Universitário de Lisboa (Presidente)

Doutor Bruno Marques, Professor Auxiliar,
Universidade Lusíada do Porto

Doutor Manuel Correia Guedes, Professor
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Doutor David Viana, Investigador Integrado,
ISCTE-Instituto Universitário de Lisboa

Doutor Vasco Rato, Professor Associado
ISCTE-Instituto Universitário de Lisboa

“Few can foresee whither their road will lead them, til they come to its end.”

J. R.R. Tolkien

Agradecimento

Ao chegar à finalização desta Tese de Doutoramento, resta-nos registar os nossos sinceros agradecimentos a quem contribuir para fazer desta investigação uma realidade.

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Resumo

As alterações climáticas criarão novos riscos para os sistemas naturais e humanos. Ambientes hoje considerados temperados tornar-se-ão desafiantes para a sobrevivência humana. As cidades e os habitats humanos terão que se adaptar para assegurar a segurança e o conforto. O objetivo da investigação foi desenvolver um modelo de análise integrada de propostas de arquitetura para climas com temperaturas extremas, considerando critérios de adequabilidade arquitetónica, eficiência energética, impacte ambiental dos materiais e facilidade de construção. Estudando a morfologia arquitetónica, a distribuição funcional e os materiais de construção, são analisadas morfologias prismáticas e elipsoidais, tendo sido selecionada, após uma análise detalhada de propriedades selecionadas, a madeira como material de construção.

Recorrendo a modelos de análise multicritério, as diferentes morfologias foram avaliadas em dois climas extremos (temperatura exterior muito reduzida ou muito elevada) e no clima de Lisboa (como referência de clima moderado). Foram considerados quatro cenários: sem distinção entre critérios de análise; privilegiando a eficiência energética; privilegiando a leveza dos materiais; atribuindo maior importância relativa ao conjunto eficiência energética / leveza dos materiais. Em termos gerais, conclui-se que a morfologia elipsoidal é mais eficiente do que a prismática. Por outro lado, um edifício de piso térreo é mais eficiente nos climas frios enquanto que, nos climas quentes, deve ser adotada uma construção em altura, com menor área de cobertura.

O trabalho desenvolveu um modelo multicritério para a seleção de soluções arquitetónicas para climas extremos. Os dados de análise necessários estão facilmente disponíveis em fases iniciais do projeto, contribuindo assim para melhores decisões mais atempadas.

Palavras-chave: Temperaturas Extremas; Avaliação Multi-critério; Morfologia Arquitetónica; Configurações Arquitetónicas; Eficiência Energética

Abstract

Climate change will create new risks for natural and human systems. Environments today considered temperate will become challenging for human survival. Cities and human habitats will have to adapt to ensure safety and comfort. The aim of the research was to develop a model for an integrated analysis of architectural proposals for climates with extreme temperatures, considering criteria of architectural suitability, energy efficiency, environmental impact of materials and ease of construction. Studying architectural morphology, functional distribution and building materials, prismatic and ellipsoidal morphologies are analysed. After a detailed analysis of selected properties, wood was selected as the building material.

Using multicriteria decision analysis models, the different morphologies were evaluated in two extreme climates (very low or very high external temperature) and in the Lisbon climate (as a reference moderate climate). Four scenarios were considered: without distinction between analysis criteria; favouring energy efficiency; favouring lightness of materials; attributing greater relative importance to the combination energy efficiency / lightness of materials. In general terms, it is concluded that the ellipsoidal morphology is more efficient than the prismatic one. On the other hand, a ground floor building is more efficient in cold climates while, in hot climates, a high-rise building with a smaller roof area should be adopted.

The work developed a multi-criteria model for the selection of architectural solutions for extreme climates. The necessary data for analysis are easily available at early design stages, thus contributing to better and more timely decisions.

Keywords: Extreme Temperatures; Multi-criteria Evaluation; Building Morphology; Architectural Configurations; Energy Efficiency

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Introduction

Climate change and future weather conditions will cause an increase in extreme climatic phenomenons, such as extreme temperatures, heavy rainfalls, storms or desiccation. This will require an adaptation of the cities and buildings people inhabit, as it will be necessary to withstand these harsher environmental conditions. Will architects, designers and builders be able to respond adequately to these new needs? What should change in the process of designing architecture in order to ensure that new buildings provide the required comfort to their inhabitants? And how can pre-existent buildings be adapted to fulfil the same purpose? What are the best type of buildings and materials for environments humans cannot inhabit comfortably? Is there a way to properly evaluate architecture projects and buildings for these conditions? These are some of questions this research aims to answer.

This research first began while looking into concepts such as Space Architecture, and self-sufficient habitats. As outer space and other planets are the most extreme environments of all, the habitats are designed to self-sustain humans for a pre-defined period of time, safely and comfortably. Due to climate change, many temperate environments on Earth will become more extreme and, as such, looking into architecture for extreme environments seemed like a proper way to approach these new climatic challenges. Extreme environments have existed on Earth since the beginning of its existence, these are environments such as deserts, very high mountains, swamps, Artic and Antarctic locations, and many others, which have extreme climatic conditions, that humans cannot be physically comfortable or live in. Using the existent knowledge developed surrounding these themes, it should be possible to design and build architecture which can withstand extremely cold and extremely hot temperatures, and understand which type of building could be the best. To achieve this, three main questions are taken into account in this research: architectural morphology, interior spatial configuration, and construction materials.

The first, is related to the exterior shape of the built form. Depending on the building's shape, it can be more or less effective in terms of energy performance. In theory, the ideal would be a building which is as compact as possible, so that the energy demand for thermal comfort in the building is lesser. To access this question, values of Form Factor are considered. This a value which relates the external building envelop surface with an internal geometrical measure of the inhabited space and accesses the compactness of the building shape.

The second, relates to design principles to produce an adequate building for locations which are very challenging climatically. Minimal areas must be considered, to ensure the well-being of those who inhabit the building, as well as a minimum comfortable height. Other than this, a set of rules defined by literature are followed, and research shows that architects are well-equipped to deal with these issues, and since people depend a lot on the interior-built environment, it should be as safe and comfortable as possible. Questions such as flexibility of spaces, use of colour, natural light, private and social areas, contribute greatly to the mental and physical well-being of the inhabitants of these types of buildings.

The third question, relates to which/what type of construction materials would be better for such extreme environments, why, and would there be a difference between a very hot environment and a very cold environments, or could the same materials be used for both? They should be as thermally effective as possible, to aid in energy savings, but have enough resistance to withstand extreme temperatures.

The purpose of this research is to develop an evaluation process for architecture projects in the context of extreme environments, with very hot and very cold temperatures. In order to achieve this, the three questions explained above are investigated, and depending on the provided results, this evaluation process is devised. This is achieved through digital tools, first, the projects are tested for their energy efficiency in digital energy performance simulations, using digital softwares Rhinoceros 3D and plug-in Grasshopper. Then, using the acquired information, a multi-criteria model is created, and populated with the retrieved information to properly access various architecture projects.

To achieve this final goal, the research is divided into 5 tasks, and presented in 8 chapters. The first, requires extensive bibliographic research, regarding extreme climates, digital energy performance simulations, case studies of architecture for extreme environments, and multi-criteria decision analysis models. The second chapter of this research presents a "Methodological Note", where the investigation methodology is layed out. The third, is relative to Architecture Morphology, and what type of exterior building shape would be better for extreme environments. Here, four possible architecture projects are proposed, two prisms and two semi-ellipsoids. The fourth, focuses on Interior Spatial Configurations for these types of buildings, and what are the principles of design that must be taken into account, as designing for these types of environments is a very specific task. The fifth chapter, describes the Material Selection for the research, starting from creating data bases to defining a self-proposed material assembly, to be used in very challenging climates. The sixth chapter, presents the results for both the energy performance simulations, and the final multi-criteria decision models. Here, are presented the results of which would be the best buildings considering a very hot and a very cold environment. The seventh and eight chapter provide discussion and the conclusion of the research, as an evaluation method for architecture for extreme environments is created, experimented, analyses and validated.

CHAPTER 1

State of Art

1.1. Climate Change | Context

The United Nations Environment's sixth Global Environment Outlook (GEO) "Healthy Planet, Healthy People" was launched in March 2019, calling on decision makers to take action against climate change, and urging them to achieve the Sustainable Development Goals[1], as well as other environment goals, such as the Paris Agreement. The first Outlook was launched in 1997, and it gathers world-wide information about the state of the environment, future environmental trends, and analyses the effectiveness of the international policies in place.

In the 2019th edition, it is stated that the changes in Climate will create new risks for natural and human systems, the greater risks being for disadvantaged communities. The annual global mean surface temperature increased at a rate of 0.07 ºC per decade since 1880, and 0.17 ºC per decade since 1970 (United Sates National Oceanic and Atmospheric Administration, 2015). The rises in sea surface temperature, sea level, ocean heat content, marine air temperature, tropospheric temperature and specific humidity are similar. These changes have various consequences, including affecting the global water cycle, warming the oceans and melting the Arctic ice cover. This has caused the global sea level to rise for about 0.19 m (ranging between 0.17 and 0.21 m) between 1901 and 2010. These alterations on the cycle impact on a global scale the precipitation patterns over land, and changes in salinity, contributing for the intensity of daily temperature extremes since mid-20th century, and the frequency and intensity of wildfires throughout the land. The various consequences and evolutions of these indicators between 1850 and 2014 can be seen on Image 1. Climate change

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[1] The sustainable development goals (SDGs) were defined in 2015 by the United Nations, they are considered an international plan to protect the planed, reduce inequalities, and end extreme poverty. They consist in 17 goals total, which are "no poverty", "zero hunger", "good health and well-being", "quality education", "gender equality", "clean water and sanitation", "affordable and clean energy", "decent work and economic growth", "industry, innovation and infrastructure", "reduced inequalities", "sustainable cities and communities", "responsible consumption and production", "climate action", "life below water", "life on land", "peace, justice and strong institutions" and "partnership for the goals" (UNITED NATIONS FOUNDATION, 2021).

has large impacts in ecosystems, with regions in high latitudes already experiencing a greater rise in temperature than the global tendency, it’s mean temperature rise exceeding 1.5 ºC.

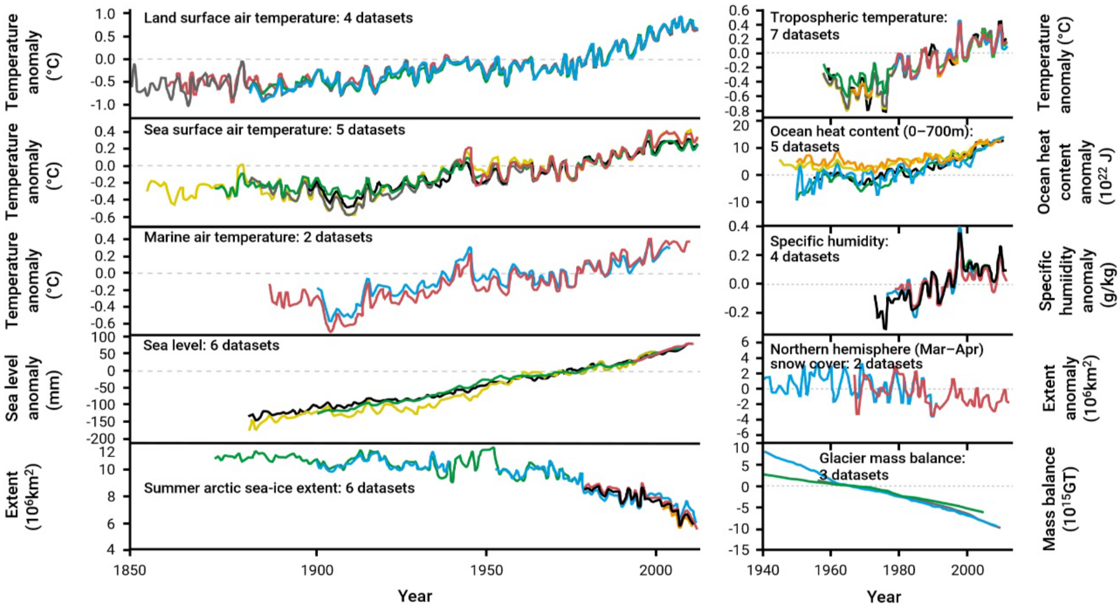


Image 1.1 - Multiple independent indicators of a changing global climate (Intergovernmental Panel on Climate Change , 2014).

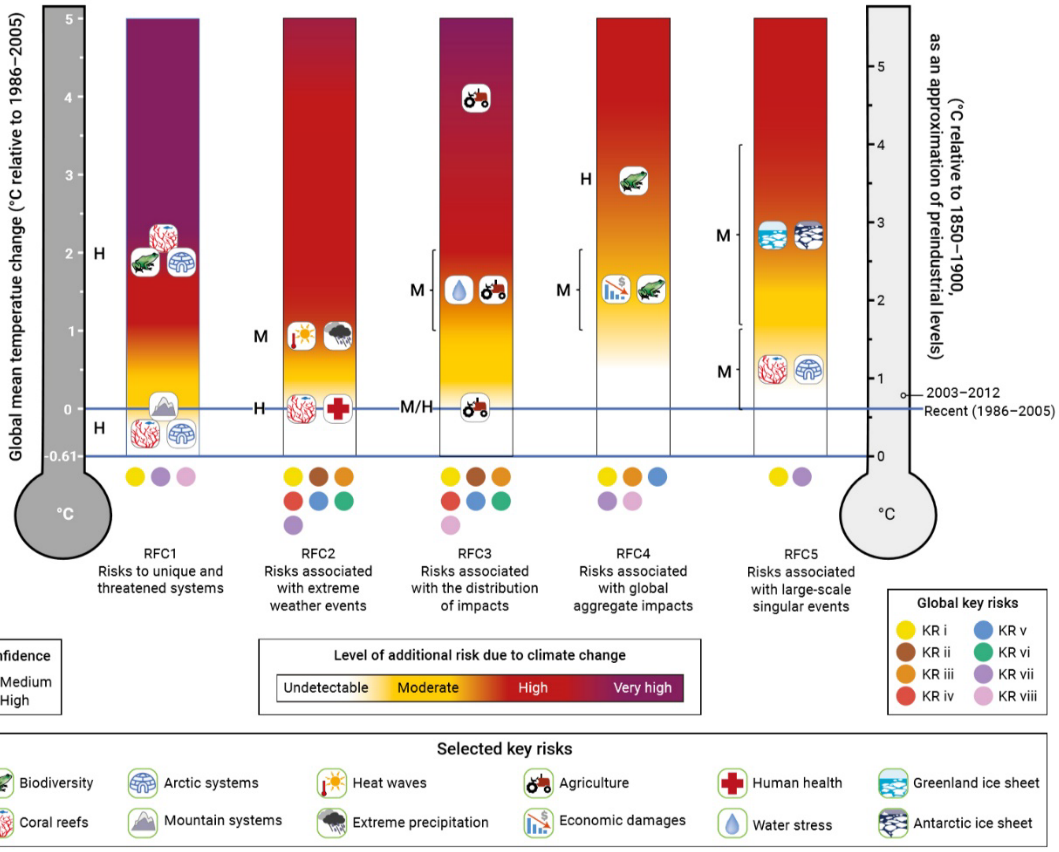


Image 1.2 – Burning embers diagram, provides a global perspective on climate-related risks *(O'Neill, et al., 2017)*.

To prevent the devastating consequences of climate change, greenhouse gas (GHG) emissions must be reduced drastically, in order to not exceed the temperature threshold of 2 ºC above pre-industrial levels, to prevent further environmental effects. Under the Paris Agreement, countries agreed to pursue efforts in order to limit the global average temperature increase to 1.5 ºC above pre-industrial levels (so that temperature increase could be hold below the 2 ºC) (UNITED NATIONS FOUNDATION, 2021).

1.2. The Köppen-Geiger Climate Classification

To better understand how climate works and is subdivided on Earth, and the changes it will suffer, the Köppen-Geiger Climate Classification can be utilized (Image 3), a vegetation-based, empirical classification system which is the most commonly used worldwide. It was created by German botanist-climatologist Wladimir Köppen, being presented for the first time in 1900. His goal was to define climatic boundaries to uncover the biomes that were being mapped for the first time. After his death, Rudolf Geiger continued his work, in order to offer updated versions of the climate map (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006).

Köppen's classification system divides Earth's climate into six major types (A, B, C, D, E and H); except for B, they are all defined by temperature criteria (type B defines dryness, instead of coldness). Climate A is considered Tropical/Equatorial, climate B is Arid, climate C is Warm Temperature (also considered temperate), climate D is cold Snow and climate E is cold Polar climate. H was not originally a considered climate but was added further down the line (although not always represented) to incorporate highland climate regions, accounting for elevations higher than 1 500 m (Chen & Chen, 2013). Then, these main climates are sub-divided by Precipitation: W (desert), S (steppe), f (fully humid), s (summer dry), w (winter dry) and m (monsoonal). Lastly, they can also have a third letter, which sub-divides the climates by temperature: h (hot arid), k (cold arid), a (hot summer), b (warm summer), c (cool summer) and d (extremely continental) (table 1). In Image 3 the changes that will come to happen in the climate distribution of Earth as we know it are clear, by analysing the differences between the actual map (a), and the future map (b). It is clear that climates D (Snow) and E (Polar) will decrease significantly and become increasingly hotter with time. On the other hand, a lot of C (Temperate) as well as A (Tropical) areas will change into B (Arid) areas, causing an expansion of desertification and desiccation, which increases naturally with hotter temperatures and less precipitation. There are even some areas in northern Alaska that will likely change from a Polar to a Temperate/Arid climate, confirming the consequences of climate change and an increased global temperature.

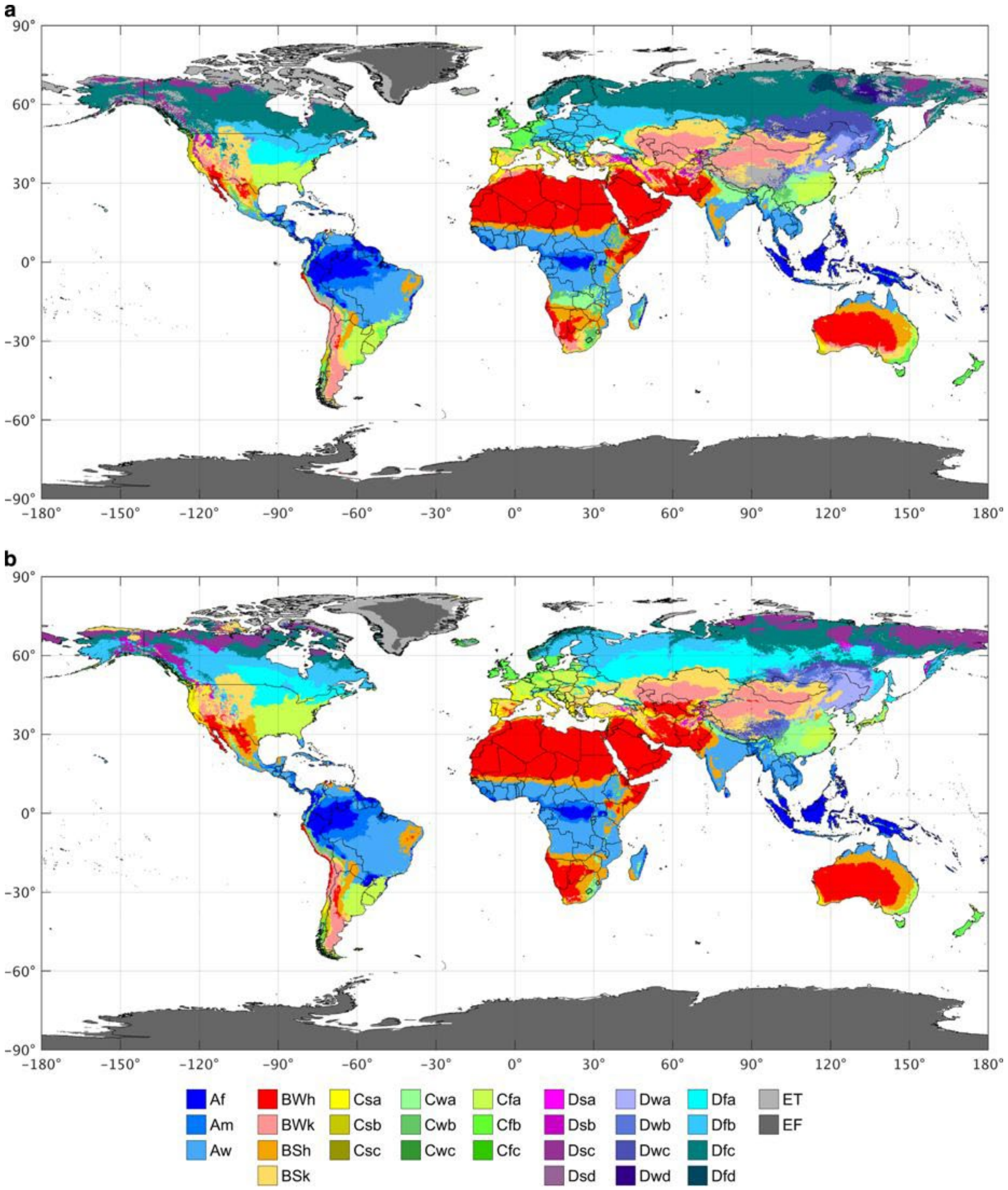


Image 1.3 - Part (a) shows the present-day Köppen-Geiger map (from 1980-2016), and part (b) shows the future climate distribution map (2071-2100), with sub-types *(Beck, et al., 2018)*.

Table 1.1 – Köppen-Geiger Climate Classifications [Adapted from: *(Kottek, Grieser, Beck, Rudolf, & Rubel, 2006)*].

Code	Description	Group	Precipitation	Temperature
Af	Tropical rainforest climate	Tropical/ Equatorial (A)	(f) Fully humid	-
Am	Tropical monsoon climate		(m) Monsoonal	-
As	Tropical dry savanna climate		(s) Summer Dry	-
Aw	Tropical wet savanna climate		(w) Winter Wet	-
BSh	Hot steppe climate	Arid (B)	Steppe	Hot Arid
BSk	Cold steppe climate			Cold Arid
BWh	Hot Desert Climate		Desert	Hot Arid
BWk	Cold Desert Climate			Cold Arid
Cfa	Humid subtropical climate	Temperate (C)	Fully Humid	Hot Summer
Cfb	Temperate oceanic climate			Warm Summer
Cfc	Subpolar oceanic climate			Cool Summer
Csa	Hot-summer Mediterranean climate		Summer dry	Hot Summer
Csb	Warm-summer Mediterranean climate			Warm Summer
Csc	Cool-summer Mediterraenae climate			Cool Summer
Cwa	Monsoon-influenced humid subtropical climate		Winter Dry	Hot Summer
Cwb	Temperate oceanic climate			Warm Summer
Cwc	Subpolar oceanic climate			Cool Summer
Dfa	Hot-summer humid continental climate	Cold / Snow (Continental)	Fully Humid	Hot Summer
Dfb	Warm-summer humid continental climate			Warm Summer
Dfc	Subartic climate			Cool Summer
Dfd	Subartic continental climate			Extremely Continental
Dsa	War, dry-summer continental climate		Summer Dry	Hot Summer
Dsb	War, dry-summer continental climate			Warm Summer
Dsc	Dry-summer subarctic climate			Cool Summer
Dsd	Dry-summer subarctic continental climate			Extremely Continental
Dwa	Monsoon-influenced hot-summer humid continental climate			Hot Summer

Dwb	Monsoon-influenced warm-summer humid continental climate	Cold / Snow (Continental) (D)	Winter Dry	Warm Summer
Dwc	Monsoon-influenced subarctic climate			Cool Summer
Dwd	Monsoon-influenced extremely cold subarctic climate		Winter Dry	Extremely Continental
EF	Ice cap climate	Polar (E)	-	Polar Frost
ET	Tundra		-	Polar Tundra

Another indication of the potential impacts of climate change is the frequency of climate-related loss events, (see Image 4), which has doubled since 1980 (Hoeppe, 2016). These events are estimated to have resulted in 400 000 deaths and had a cost of 1.2 trillion US dollars on the global economy. Coastal, agricultural and forest communities, less-developed and less-resilient countries are the most fragile and will suffer the most from the potential damages of climate change, which is at the moment the biggest threat to our future well-being and the ecosystems on which humans depend on (United Nations Environment Programme, 2019).

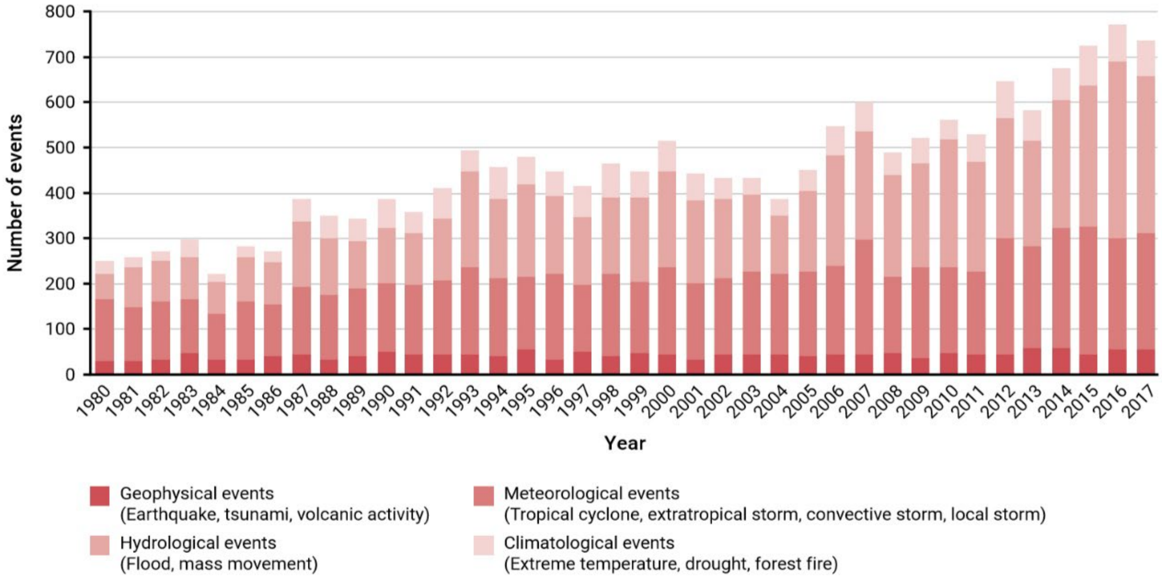
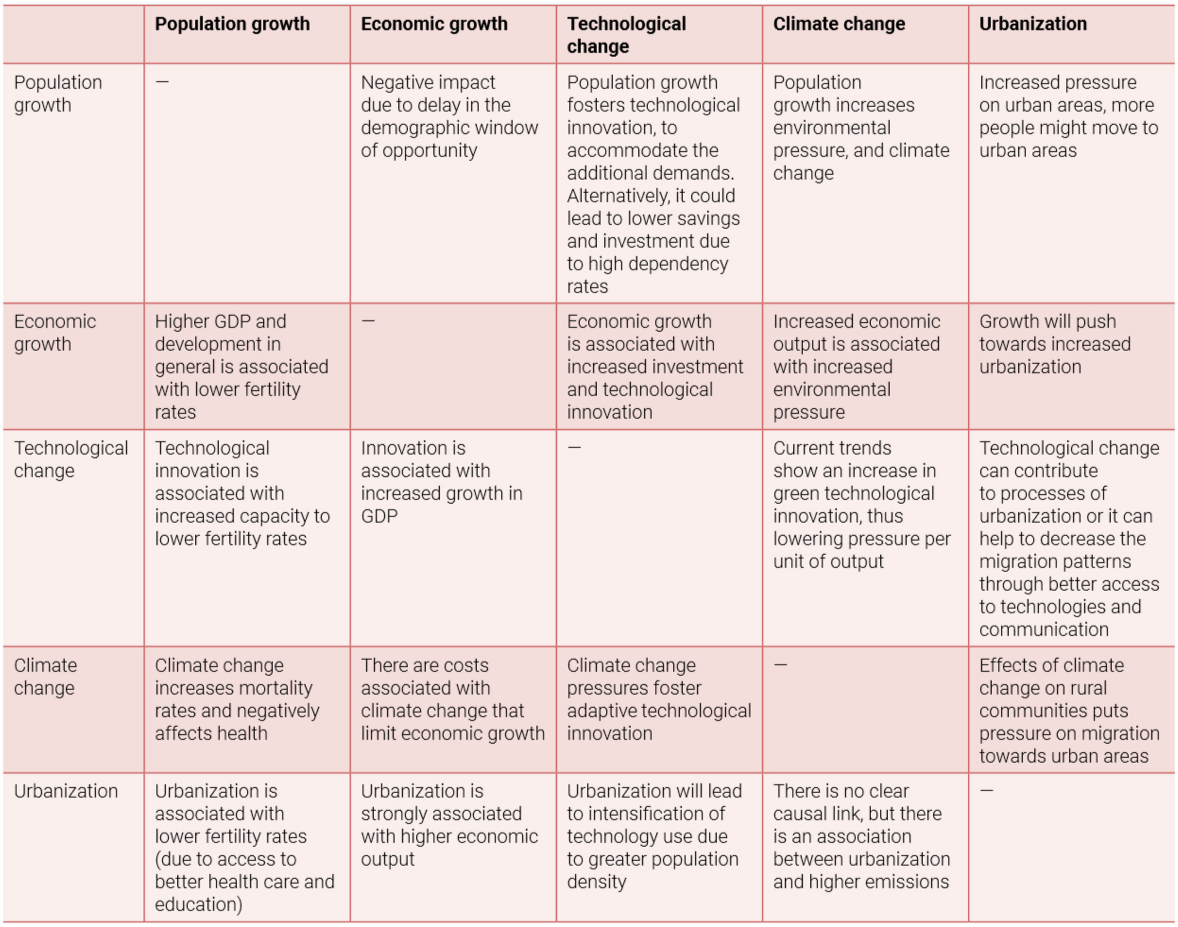


Image 1.4 – Trend in numbers of extreme events, from 1980 to 2017. (REF Munich Re 2017).

There are a lot of questions to take into account when considering climate and environmental change and challenges. There are various “drivers” or causes for it, which can have both positive and negative impacts. The GEO-6 considers five drivers of environmental change: Population Growth; Economic Growth; Technological Change; Climate Change; and Urbanization (which are interdependent and can be seen in the table 2). The relationships between these drivers have been heavily discussed in literature (Wu, Shen, Zhang, Skitmore, &

Lu, 2017). The accumulated consequences of the presented interactions between drivers are negative on climate change. The trajectory of GHG emissions has continued to increase in a rate that has accelerated in the last 15 years, compared to the 1980-2000 trajectory, which shows the consequences of what was discussed previously. One of these drivers is "Urbanization", and so that puts a special emphasis on architecture and designers to think, design and build for a world with new and changing demands, when it comes to urbanizing a space or thinking of different ways to do architecture and to build buildings, that can better contribute for both people and the environment

Table 1.2 - Interactions between the five drivers of environmental change *(United Nations Environment Programme, 2019)*.



	Population growth	**Economic growth**	**Technological change**	**Climate change**	**Urbanization**
Population growth	–	Negative impact due to delay in the demographic window of opportunity	Population growth fosters technological innovation, to accommodate the additional demands. Alternatively, it could lead to lower savings and investment due to high dependency rates	Population growth increases environmental pressure, and climate change	Increased pressure on urban areas, more people might move to urban areas
Economic growth	Higher GDP and development in general is associated with lower fertility rates	–	Economic growth is associated with increased investment and technological innovation	Increased economic output is associated with increased environmental pressure	Growth will push towards increased urbanization
Technological change	Technological innovation is associated with increased capacity to lower fertility rates	Innovation is associated with increased growth in GDP	–	Current trends show an increase in green technological innovation, thus lowering pressure per unit of output	Technological change can contribute to processes of urbanization or it can help to decrease the migration patterns through better access to technologies and communication
Climate change	Climate change increases mortality rates and negatively affects health	There are costs associated with climate change that limit economic growth	Climate change pressures foster adaptive technological innovation	–	Effects of climate change on rural communities puts pressure on migration towards urban areas
Urbanization	Urbanization is associated with lower fertility rates (due to access to better health care and education)	Urbanization is strongly associated with higher economic output	Urbanization will lead to intensification of technology use due to greater population density	There is no clear causal link, but there is an association between urbanization and higher emissions	–

1.3. Extreme Environments

1.3.1. What are extreme environments?

Usually, an environment considered to be extreme is understood as meteorologically challenging, and essentially defined by its geographic location, due to its climate and weather conditions. However, since “extreme” is a relative word, NAI (NASA Astrobiology Institute) states that an extreme environment can be defined by environmental conditions that are too harsh for humans to dwell or inhabit. These are inhospitable conditions for life and can be divided into various categories, such as temperature extremes (very hot or very cold), high salinity, high pressure, unrecommended amounts of radiation, levels of desiccation (dryness), pH (acidity or alkalinity), high levels of humidity (wetlands), and low oxygen level (Bannova, 2014).

With these characteristics in mind, it’s possible to indicate a couple of environments which we consider extreme and hazardous to humans, such as deserts (in very hot, or polar, areas), deep oceans, high mountains, the geographical poles of earth, swamps, the interior of volcanoes, and outer space or other planets. For reference, the maximum temperature into which vascular plants can grow in is about 48 ºC and, for fish, 40 ºC, which shows us why an environment like a desert is so inhospitable, and why the rising temperature of sea water is so dangerous for marine life. When it comes to extreme temperatures, literature states that the temperature limits for homo sapiens to feel comfortable starts from 15 ºC, and goes up to a survival temperature up to 60 ºC maximum (Rothschild & Mancinelli, 2001). However, this extremely high temperature is only tolerated for about 10 minutes, before the human body enters a state of hyperthermia, which requires immediate treatment to prevent disabilities or death. In a NASA report done in 1985, it is reported that the human body can survive in environments that are between 4 and 35 degrees Celsius. However, if the humidity is lower than 50%, it is possible to withstand higher temperatures. This happens because the human body sweats to maintain its core temperature, in order to lose heat and cool the body down, however, if there’s already too much humidity in the air, there’s already too much water vapor and, as such, sweat can’t evaporate as quickly, and won’t cool the body down as much as it needs (Crownhart, 2021).

1.3.2. Types of extreme environments?

The Köppen-Geiger climate classification can be used to identify where some of these environments exist presently on Earth. The climates with the classification BWh (Hot Desert Climates), marked in the map with the red colour, allow us to geographically identify the Sahara, Kalahari, Arabian, Gobi, Mojave, Atacama and the Australian Deserts, which are extreme environments for their extreme temperatures and desiccation (Atacama, for instance, is a salt desert, the driest of its kind on Earth, meaning it's an extreme environment both for its extreme high temperature, but also for its salinity (Tapia, et al., 2018)). On the opposite side of the spectrum, climates Dfc, Dfd, Dsc and Dsd (which are subarctic climates), EF (Ice cap climates) and ET (Polar climates), are extreme environments due to their extreme low temperatures. Marked in the map in dark blue/purple and grey colours, they allow us to identify areas such as the Arctic circle, the Antarctic continent, and a vast area of northern Russia and Alaska. It is also possible to see the modifications climate change will bring upon these climates, making all these colder areas warmer in time, and greatly diminishing the areas that these climates occupy.

Other than these, deep oceans (deep sea biome), are also considered an extreme environment. The oceans cover about 71% of the Earth's surface, and about 90% of that area contain deep waters (below about 180 meters). PH challenging environments are, for example, very active volcanic areas, in geysers or lakes, as are for example the Congress Pool or the Octopus Spring, in Yellowstone National Park, USA. For the first, the average pH is 3, with an average temperature of 80 ºC, and for the second, a hot spring with a pH of 8.8-8.3, with temperatures from 95 ºC to 65 ºC (Rothschild & Mancinelli, 2001). For high radiation environments, we must understand what is the maximum amount of radiation that the human body can handle, without risk for health. International standards allow up to 5 000 mrems (or 0.05 Sievert - Sv) per year, for those who work with (and around) radioactive materials. These are units that measure radiation dose in terms of biological effect (NASA, 2008). The lethal dose of radiation is about 4.66 Sv over 5 hours. In Chernobyl, for instance, the radiation levels in the reactor building after the 1986 incident were about 186.60 Sv per hour, resulting in the death of all those who worked on it in the span of a week (Medvedev, 1992). Everywhere a nuclear accident has taken place, or anywhere there are natural reserves of radioactive material that surpass the maximum permitted limit, is considered an extreme environment for humans.

When it comes to wetlands, where the problem is extreme humidity and water availability, these are characterized by nutrient-poor, acidic water, constant saturation, and peaty soils (U.S. Geological Survey, 1996), which makes life for human settlements extremely difficult. Finally, the last characteristic of extreme environments enunciated above, lack of oxygen or poor air quality, is a problem we face mainly in what concerns space exploration or in extremely populated and polluted areas here on Earth, as was stated in the *State of Global Air 2019* (Heath Effects Institute, 2019), which states that long-term exposure to unhealthy, polluted air, contributed to millions of premature deaths, mostly in Asian countries. This makes air pollution the 5th highest cause of death among health risks, worldwide.

1.3.3. Challenges for Architects and Designers

Physical factors are not the only ones to have in mind when planning and designing for extreme environments, because these areas often offer limitations in life support supplies, communications, transportations, and others. So, an extreme environment poses issues not only of physical climate but also resources, services/spaces unavailability, and lack of mobility. The lack of these factors, which we take for granted where we normally inhabit, lead to problems for every-day life, such as restrictions to do daily tasks, difficulty to operate social interactions, and an impossibility to achieve necessary living needs (Bannova, 2014).

Manuel Kretzer research platform "Materiability" works as a space to investigate new materials and architectural dynamics. In 2015 he conducted a workshop named "Dynamics in Extreme Environments" in which he explains that architecture will have to respond to extreme weather conditions, and that materials will also play a critical role in facing these challenges, on a global scale (Kretzer, Information Materials for Adaptive Architecture, 2017). These questions, however, were not only thought of by architects. Sally Augustin, psychologist, studies the attributes of well-designed spaces and how comfortable they are, which she states are often under-looked in the context of extreme environments. She explains this happens both because of budget limitations, and lack of designer involvement (Augustin, 2009). This is key, because when we built and design for extreme environments, the physical build object becomes one of the few resources available for inhabitants to cope and adapt to their extreme surrounding conditions. If a building is so isolated from other stimuli, the smallest detail can make a different in one's perception of it, and aid in the psychological well-being of those that inhabit it (Yan & England, 2001).

After extensive bibliographic research (Cahill, 2013), it becomes evident that even though there are many authors that believe architects are uniquely equipped to meet the challenges of extreme environments, there seems to be a lack of actual proposals to solve these questions. How can, or will, architects and designers be able to provide people with the tools to adapt to these new circumstances, a changing climate, and harsher weather conditions? How can architectural design and materials help people cope with these issues, while making buildings and urbanization more effective and environmentally friendly? The role of the architect is to design buildings that ensure the physical and mental protection of those that inhabit it, in order to give them the best living experience possible. These can only be done through creativity, that allows designers to solve the environmental stressors that humans face. To creators, these challenges are catalysts for creative thought, it's about time that architects join the conversations about extreme environments (Cahill, 2013). These are the environmental challenges for architects and for the architecture of today.

1.4. Interior Spatial Configurations of Extreme Environments

Planning and designing for extreme environments comes with its specific group of challenges and requirements, as it is necessary to respond to challenges that are not common in regular urban areas, in temperate climates. One of the ways to ensure the comfort of the building's inhabitants, is to provide them with a well-organized space, where the building's divisions and configuration contribute to the well-being of the people who utilize it, while also making the construction more effective in terms of energy management.

1.4.1. Principles

When it comes to designing for extreme environments, there have been great advances since spatial exploration became a reality, because researchers have been able to use a lot of findings from space exploration and apply them here on Earth. Such is the case of CAT Scans, LEDs, Nike Air trainers, foil blankets, wireless headsets, memory foam, camera phones, water purification systems, dust busters, baby formula, aerogels, amongst others (NASA, 2019).

Outer space and other planets are the most extreme environments of all because they can aggregate all the characteristics extreme environments can have - extreme temperature, salinity, pressure, pH, radiation, desiccation, and no oxygen. For NASA, Space Architecture has the duty of orienting and helping astronauts, ensuring they are as free as possible from mental stress to achieve the success of missions. Although there are many other concerns, such as structural and financial questions, and there isn't a lot of room for elaborate architecture, what allows a space to be inhabited in a pleasant way, and as close to what one would feel on Earth, with a sense of "home", cannot be disregarded (Seguin, 2005).

Researchers Yan and England conducted a study in Greenland in order to evaluate the physical attributes of Arctic Research Stations, and its inhabitant's satisfaction and well-being. Thanks to it, they were able to identify interior design essential successful principles, to ensure a healthy indoor living. Their research focused on six specific elements: possibility of personalization; perception of safety; noise; use of colour; separation between private and public areas; and illumination conditions (Yan & England, 2001).

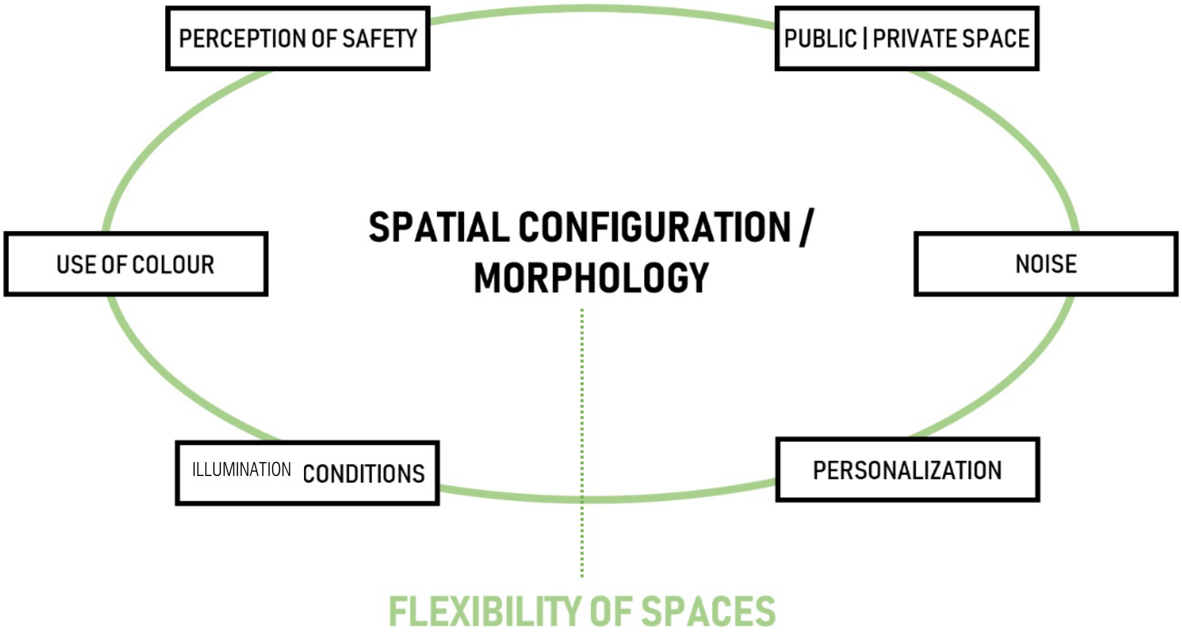


Image 1.5 - Design principles according to Yan and England for healthy indoor living for buildings in extreme environments.

When it comes to personalization, it is understood that fluid spaces, that can have alternated uses, make buildings more responsive, instead of remaining static and unchanging (Kretzer, Information Materials for Adaptive Architecture, 2017). This malleability allows inhabitants of a certain building to be able to make their spaces more personal and for them to relate more with the place they live in, which allows them to create a connection with the building and with that place. This also permits that both people and the building adapt to new situations, independent of culture or use (Kronenburg, 2007). The researchers found that the personalization of individual space was essential to the inhabitant's well-being, giving people the option to change the spaces they inhabit in through furniture change, different lighting or colours, increasing the workers productivity and leaving them feeling happier and more satisfied. Boring, non-flexible and static interiors can dull one's mind and take a toll on the morale of the crew (Berry, 1973). Perception of safety relates to how people feel regarding the habitat and their physical safety: if it is a habitat where it is dangerous to dwell or there is constant imminent danger, that will influence greatly both the physical and the psychological comfort of the inhabitants of the building. Therefore, when designing it, the architect must make sure that it is as safe as possible, more even than the regular designed building, for a normal environment. As for noise, this is something that requires some attention, regarding how spaces are organized within these sorts of habitats. The sleeping chambers cannot be close to the hygiene chambers, for rest hours are extremely important for people that are closed-off of the world, and must have a strict regimen of work and leisure, to ensure their mental health and productivity. For the use of colour, Yan and England quickly realized that the people they interviewed spoke fondly of the "green building" that was part of their research station. The reason for this is that in a very cold environment, a polar desert for example, people are surrounded simply by a white landscape, for months at a time. This scenery lacks the colour, the smells and the sounds that are familiar to people. The researchers concluded that the use of more colour was something to take more into account in future projects. This could even be created digitally, or have kinetic elements, because it would be more stimulant for the mind. Regarding the need for separation between private and public areas, the aim is to ensure that people have their required personal space and certain privacy, even if a small habitat is considered. Inhabitants should always have a quieter, more private place to be, instead of a noisy and very busy environment. On the other hand, it is advised that the central and biggest part of the habitat is occupied by the "social area", where everyone meets, so that it can be the centre of human interaction. This is seen on pretty much every built architecture example we can find in extreme environments, such as the Halley VI Antarctic Research Station, located on the Brunt Ice Shelf, and projected by Hugh Broughton Architects in 2013. Here, the social module is the big red one in the middle (Image 6) (Slavid, 2009). Finally, when it comes to lighting conditions, it is important that the inhabitant of the habitat is not completely isolated from the outside world. There should always be daylight, preferably through a big observation window, so that the crew feels they still have a connection to the environment outside, even if they cannot dwell in it. More than this, in areas where there is very little daylight, it is recommended that the lighting conditions maintain a certain daily schedule, in order to disturb the human body's natural functional conditions as little as possible, and to allow the crew to have a daily day-to-night routine, and that the light is always adequate for the utilization of the spaces.

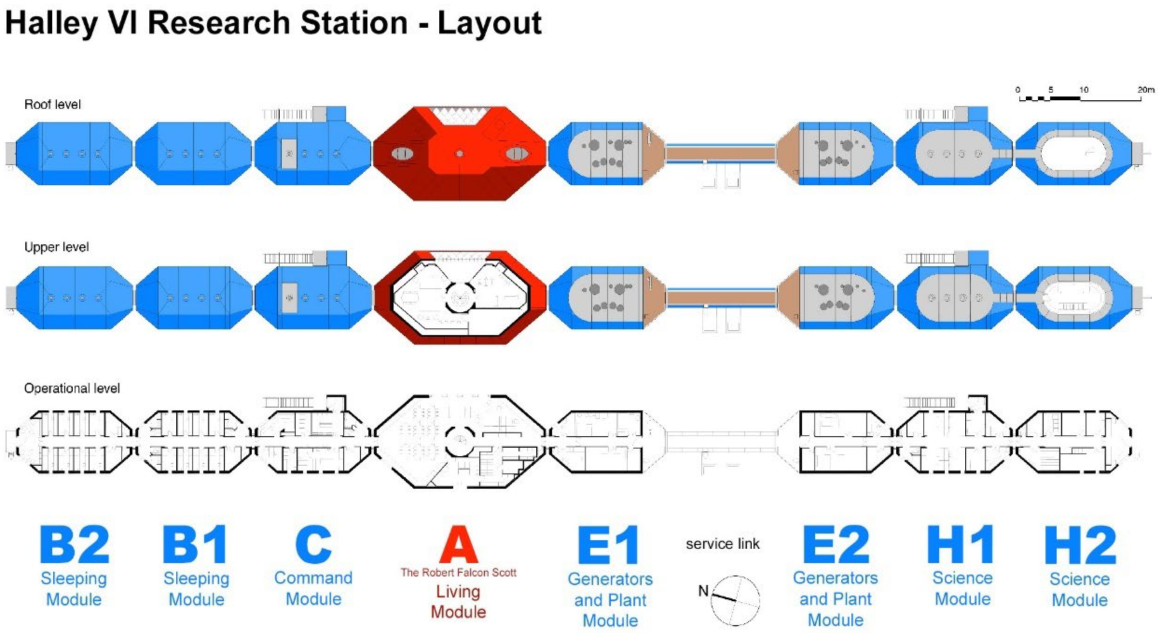
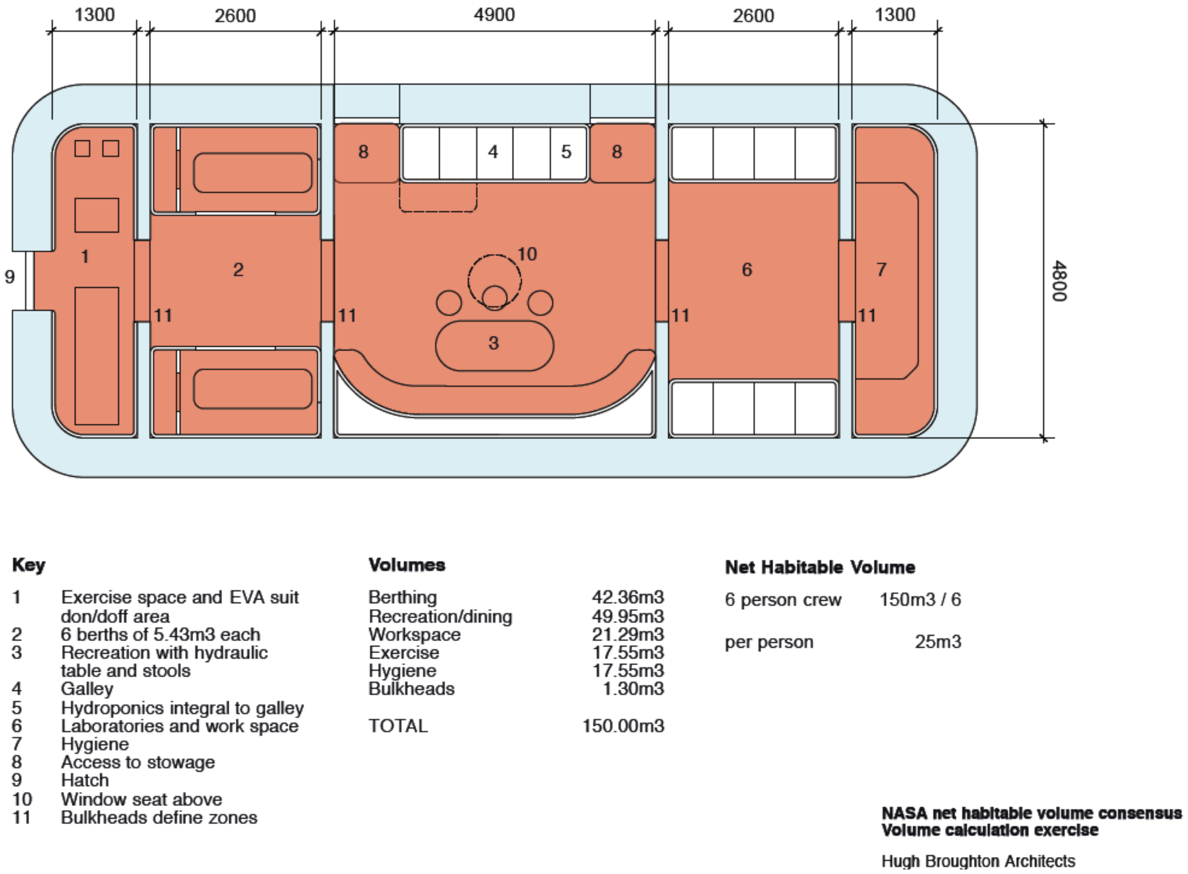


Image 1.6 - Layout of the Halley VI Research Station by modules *(N. E. Council, 2019)*.

1.4.2. Minimal Areas

Another question to have in mind when designing for extreme environments is that floor areas should be as small as possible, while still allowing to inhabit comfortably. This is because the smaller the building is, the more compact it is, the less energy will be spent trying to heat or cool it down. However, deciding minimal areas for extreme environments can be a challenge since each country has its own regulations regarding minimal living areas for architecture. Because of this, it was decided within the scope of this research that the best reference would be NASA's Human Research Program studies for explorations missions. These guidelines are independent of countries regulations and norms, and focus mainly on the best living areas/spaces for extreme environments, it being outer space or other planets, which can have equal characteristics to Earth's extreme environments.

NASA and Hugh Broughton Architects defined the Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions in 2015. Through it, they were able to determine the minimum acceptable volume for a crew of six people, not considering equipment, trash, stowage or structure, but solely the volume for the human body to occupy. This value was defined, for a 6 people crew, at 150 m^3, which would be 25 m^3 per person. It is stated that smaller volumes could be possible, but these values are considered the minimum for healthy and comfortable living. As these are very isolating and harsh environments, confining the spaces too much could greatly disturb the crew's mental health. They divide their proposed minimal habitat into seven sections: work space (which must allow for four people to work simultaneously); exercise space (two people must be able to exercise at the same time); hygiene quarters (must allow for two separate compartments); social space (the biggest one, for eating and joint activities); sleeping quarters (must allow for sleep, self-care and leisure); pass-throughs (must allow one person to pass through comfortably) and stowage (Image 7). Each sleeping module must have at least 5.4 m^3 in order to be comfortable. The rest of the minimum volumes for the spaces are also defined: 21.29 m^3 for workspace; 17.55 m^3 for both exercise



Key

1	Exercise space and EVA suit don/doff area
2	6 berths of 5.43m3 each
3	Recreation with hydraulic table and stools
4	Galley
5	Hydroponics integral to galley
6	Laboratories and work space
7	Hygiene
8	Access to stowage
9	Hatch
10	Window seat above
11	Bulkheads define zones

Volumes

Berthing	42.36m3
Recreation/dining	49.95m3
Workspace	21.29m3
Exercise	17.55m3
Hygiene	17.55m3
Bulkheads	1.30m3
TOTAL	150.00m3

Net Habitable Volume

6 person crew	150m3 / 6
per person	25m3

NASA net habitable volume consensus
Volume calculation exercise

Hugh Broughton Architects

Image 1.7 – NASA net habitable volume consensus – Volume calculation exercise (Areas and Volumes within habitat) *(NASA Human Research Program, 2015).*

and hygiene; 49.95 m^3 for the social area and 42.36 m^3 for sleeping quarters (NASA Human Research Program, 2015).

The minimal area can also be defined through the designs provided by the company: for a rectangle-shaped floor plan, they define that the interior dimensions for the whole habitat should be 12.7 m per 4.8 m, which gives us a floor area of 60.96 m^2. One can also calculate the same minimal interior area for the various compartments, them being: 12.48 m^2 (2.60 m x 4.80 m) for workspace; 6.24 m^2 (1.30 m x 4.80 m) for exercise space and hygiene quarters; 23.52 m^2 (4.90 m x 4.80 m) for social area and 12.48 m^2 (2.60 m x 4.80 m) for sleeping quarters. However, this internal area can be changed when we think about minimal dimensions for buildings on Earth because, for example, a space for EVA suits is not necessary, and one can exercise on another space, such as the social area for example, allowing space flexibility, as stated above. This happens because NASA's exercise equipment has specific dimensions, but on Earth it's possible to make some alterations to that. So, a minimum area of 54.72m^2 can be considered. Considering that 150m^3 is the minimum volume for a 6 people habitat, having 2.74 m in height is possible through the habitat if it is a prism, and if necessary, distribute part of the spaces vertically (Domingos & Rato, Optimization of living spaces morphology for extreme climates, 2019).

1.5. Construction materials for Extreme Environments

1.5.1. Materials used in traditional architecture

When trying to find solutions for Architecture for extreme environments it is important to study Bioclimatic Architecture because it is designed essentially with climate adaptation in mind. It consists of using native materials and design principles to ensure a healthy internal environment, while still respecting the natural environment that surrounds it, being very sustainable and energy efficient, in an active or passive way (Kibert, 2008) (Hegger, Fuchs, Stark, & Zeumer, 2008). Materials to be utilized in Extreme Environments should be as structural and energy-efficient and have a minimal environmental impact as possible, in order to not further destabilize the place they're being used in. Even though the climate of a certain location is defined by many factors, which are variable along the year, Bioclimatic Architecture usually addresses this challenge, and ensures that its solutions are valid for the climate that is felt during the whole year, even with its variations. Most of the case studies of Bioclimatic

Architecture are inspired by vernacular and ancient architecture, because it offered solutions to the needs of the people of ancient times, or ethnical groups nowadays, that are not normally associated with living within contemporary cities and big metropolitan areas (such as the Inuits, for example, that inhabit the freezing arctic regions of northern Canada, Alaska and Greenland) (Centre de santé Inuulitisivik, 2019). Although the architecture strategies might be similar, different and more advanced materials can be used.

Two essential sets of strategies of traditional Bioclimatic Architecture can be presented, one in a very hot climate and the other in a very cold climate. The first one can be the architecture of the city of Aït-Ben-Haddou. This is an ancient ksar[1] located in the Ouarzazate province in Morocco, on the old commercial route that connected the ancient Sudan to Marrakesh (UNESCO, 2019). Aït-Ben-Haddou is located in a BSh climate, according to the Köppen-Geiger climate classification, which marks it as a Hot Steppe Climate, a very arid and hot environment. The fact that the buildings are very tall and highly crumpled together, allows for narrow roads, which protect their users from the harsh climate conditions they face, managing temperature and offering protection for the desert winds (see Image 8). The materials that are used for these buildings are wood, stone and native clay. First, a frame is built in wood panels, which is then filled with stone, and then with rammed earth, which is posteriorly sealed with a mixture of sand, lime, plaster and native clay. This mixture ensures that the buildings walls are water resistant and can resist both very hot temperatures but also desert storms, if required (González, 2004). Although it is an extremely hot and arid climate, temperatures in the winter months can be as low as -2º C during the night, which may cause snowfall. The rainiest months are also the winter months, especially November, with an average precipitation of 14 mm. Climates above 150 mm precipitation are mostly wet, while climates below 30 mm precipitation are considered mostly dry. Snow days in Aït-Ben-Haddou can be accounted during December, January and February (meteoblue, 2021).

Regarding the use of these types of materials on the context of extreme environments, the use of a material that exists “in loco” is always advised, as it provides a more sustainable and cheaper alternative than to transport materials to the construction site, in order to build a habitat. One of ESA’s building proposals for habitats on the moon consists of using the moon ground material (regolith) in order to cover the habitats in a protective shell so that they are more thermally efficient (Foster + Partners, 2012). Also, the climate of Aït-Ben-Haddou being very

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[1] A Ksar is a collection of earthen buildings with high walls, typical from the south of Morocco. It is a defensive type of architecture, with houses crowded together with corner towers (UNESCO, 2019).

warm, the construction allows for sunlight protection by having very high walls, which is a valuable clue to use when considering very hot extreme environments. The use of wood as structural material also presents itself as a very effective and sustainable construction option.

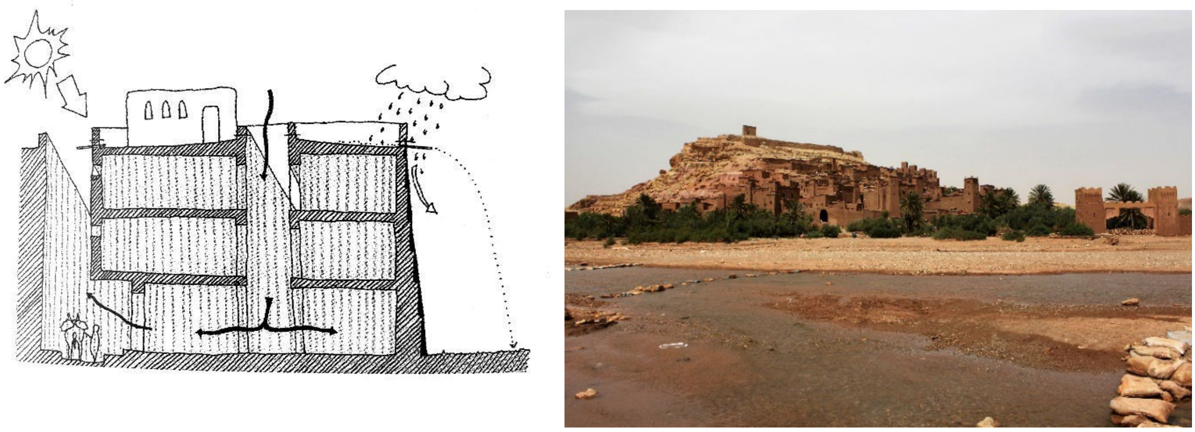

Image 1.8 – a) Drawn section of the traditional architecture of Aït-Ben-Haddou *(González, 2004)* and b) photograph of Aït-Ben-Haddou on the present day *(Domingos, Aït-Ben-Haddou Photograph, 2017)*.

For the cold climate, the case of the igloo from the tundras in the north of Canada can be analysed, where both EF and ET Climates exist, rated on the Köppen-Geiger scale as Ice Cap Climate and Tundra Climate, respectively, the two harsher cold, polar climates. Due to the climate conditions of these places, the igloo needs to be able to withstand cold strong winds and temperature to about -50 ºC.

These are used majorly by the Inuit people, who use them as temporary housing, because they must move frequently to pursue hunt. The igloo's main material is compacted snow, which they shape into 90 cm long blocks that are then piled on top of one another, alternately, and that will form the igloo's classical dome. Its construction always starts from within. The semi-spherical shape ensures that it is resistant to strong winds, and offers its inhabitants a large living area inside, which is then covered in animal fur.

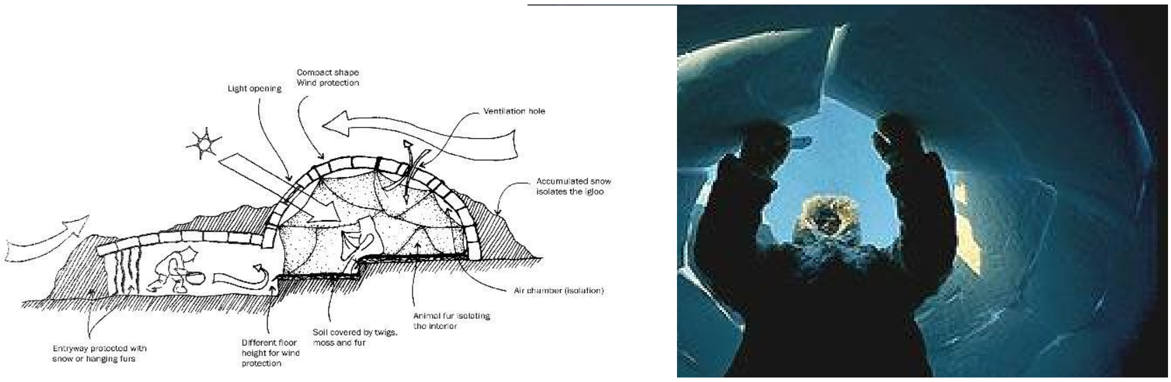

Image 1.9 – a) Drawn section of a typical Canadian Tundra Igloo [Adapted from: *(González, 2004)*] and b) Contemporary Inuit man building an Igloo *(Corel Professional Photos, 2006)*.

This process ensures that the indoor space is comfortable, while also guaranteeing the required thermal insulation, because of the air pocket that exists between the fur coats and the snow (see Image 1.9) (González, 2004). The longer an igloo stays in place, the more resistant it becomes and, having been created with the natural material of the environment that it is in, when its inhabitants leave, it does not disturb the landscape and its natural fauna and flora in anyway, making it as sustainable as possible.

If construction for extreme cold environments is considered, although an igloo does not offer the comforts of modern buildings and, as such, could not be considered by itself an effective response to habitats in extreme environments, it still offers important clues to build in these types of environments. Once again, native material of the land is used to build the igloo, similarly to the previous architecture example, which is a very sustainable construction option. In fact, for the igloo, when it is abandoned, it will fade into the landscape again, leaving no traces of human habitation behind. The shape of the igloo is also thermally very effective in cold environments, as it will be discussed in the next chapters of the research. Other than that, an air insulation layer is created between the ice of the igloo walls and the fur (which also works as an insulation layer) used to make the interior of the igloo more comfortable, while also ensuring natural ventilation, and light openings, as it's possible to see in Image 9. The igloo is also covered with snow around it, to ensure better insulation from the temperatures and the wind outside. With this construction system, the Inuit are able to create a habitat in a very cold environment, where they can inhabit, without the use of artificial heaters, proving it's possible with the materials of the land and smart construction design to create a building that can withstand extremely harsh climate conditions.

1.5.2. Innovative Materials

Other than the traditional materials that are usually used in construction, as technology evolves so do the material possibilities for architecture. Such is the case of MycoTree (Heisel, et al., 2017/18), created using organic components from wood and agricultural waste, which are then given a structure using the root network of the grown mushroom mycelium (Ganoderma Lucidum of Basidiomycetes, commonly known as Lingzi mushroom), which acts as a natural binder. It is possible to turn it into a construction material through the use of a 3D matrix, compressing the material in order to make it structurally sound. This shows that cultivated building materials are a possibility, making buildings much more sustainable and environmentally friendly, without the need to use more regular, wasteful materials. A building constructed with a mycelium-bound structure could be simply composted after it reaches the end of its life cycle. In order to produce the said material, a substrate is first made using agricultural waste products; the mushroom is then planted in this subtract until it's fully grown. The mushroom is then put into an oven so that its moisture levels are reduced, which prevents future growth. Mycellium by itself is not resistant enough to use it for construction purposes, and thus proper geometry must be created. MycoTree's 3D geometry was developed by the Block Research Group at ETH Zürich, which assembled moulds to be filled with the mycelium mixture, that was compacted until it was densified enough to create construction blocks. In order to ensure clean connections between these blocks, they were capped with plates of bamboo composite material. A photograph of the MycoTree and the development of the mould geometry can be seen in Image 1.10.

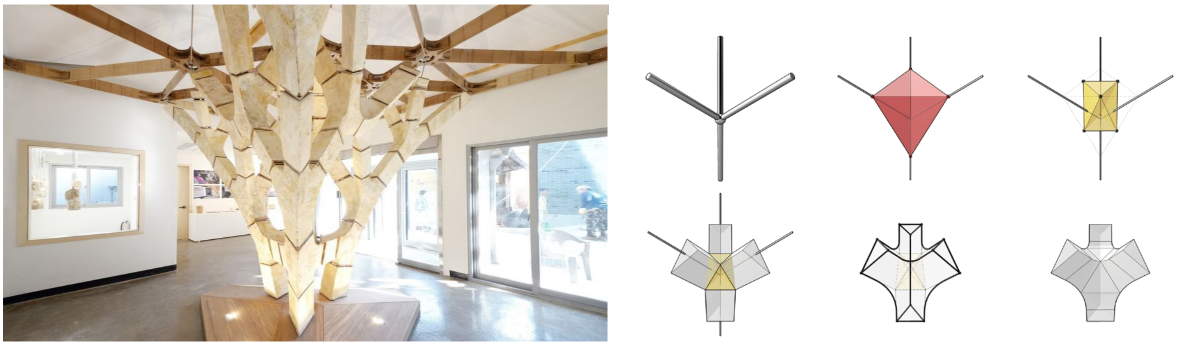

Image 1.10 – a) MycoTree presented at the 2017 Seoul Biennale of Architecture and Urbanism in Korea and b) Representation of the development of the mould geometry for the MycoTree *(Heisel, et al., 2017/18)*.

Other than new materials, innovative ways to turn specific materials into others for construction purposes is also a reality nowadays. This is the example of the material from BetR-Block, a start-up company that specializes in building blocks (similar to bricks) made out of

Image 1.11 – a) Various paper bricks to be used for construction are displayed and b) a smaller prototype example of the paper brick from the BetR-Block company *(Jones, 2016)*.

recycled paper and cellulose. The idea behind it is that paper is a resource that is not optimally used, as a lot of it is not recycled. Through this process however, 95% of the material that comprises the brick is recycled, and the final brick can also be recycled, so the material can be used indefinitely. The bricks last as long as any conventional construction materials and provide good levels insulation. The company states the blocks are also water, fire, termite and mould resistant (Millman, 2016). Literature confirms that Paper Pulp Bricks are an alternative raw material, and as such leads to relief on waste disposal concerns, as it does not consume energy nor emits pollutants, proving that there is an economical and environmental advantage over traditional bricks. Laboratory tests have also proven that they can withstand the required mechanical strength, and so they provide sufficient strength to walls. Since they're created from waste materials, it reduces the impacts on landfills, making them much less expensive than conventional bricks. Using paper bricks can reduce the total cost of a brick construction by 20 to 35%. The only downside to this material is that the paper bricks should not absorb more than 20% of water, and researchers found that the water absorption on these bricks was higher than 20%, making them not adequate for water logging, and external walls. However, as long as they are given a waterproof coating (such as Geo-bond or a silicon based waterproofing), they can also be used for external walls (Shakir, Naganathan, & Mustapha, 2013). A more durable option than paper bricks can also be bricks made with waste rubber and plastic, which also contribute to both the prevention of environmental pollution and more economically sustainable constructions. These materials also improve the insulating properties of these bricks, compared to the traditional ones. As such, thermal and acoustic properties are enhanced, contributing to energy savings. According to literature, the thermal performance of these types of bricks is highly effective, as with the used waste materials the compressive strength of the bricks increase, and the thermal conductivity decreases. Although the use of these materials is still very limited, efforts are being made for construction standards and properties to be clearly defined, so that the production can be increased and used worldwide (Karslioglu, Balaban, & Onur, 2021).

Materials such as Mycellium and paper bricks can be an effective answer to building in extreme environments. In the case of Mycellium, this root-like fibre from fungi allows for the creation of a sustainable material as it binds wood and agricultural waste into a possible architectural structure. This allows for less waste, less pollution, and an environmentally friendly solution to construction, which can be combusted at the end of its life, not contributing to more waste. Mycellium can thrive in a wide array of environmental conditions, which make it a low-cost and fast energy material production. When mycelium is dried, it can be used as a super strong, water, mould and fire-resistant building material (Bonnefin, 2017). Regarding insulation properties, the mycelium tissue can trap more heat than fiberglass insulation, and its mechanical strength by unit mass is stronger than for the case of concrete (Fisher, 2010). These properties make it an innovative material which is appropriate to environments with extreme climate conditions, with both hot and cold temperatures, while still being a cheaper and more sustainable alternative to the materials which are commonly used in construction today.

Regarding paper bricks, as they are much lighter than regular bricks, and offer better insulation properties, they are a cheaper alternative, both in terms of production costs, as they are created from essentially waste material, and transport, as they are lighter. Paper has also proved to be an effective material do use in extreme environments, as will be discussed later in the research (chapter 5, related to "Materials"). The only problem with paper materials is regarding humidity, in very cold environments, but as long as they are correctly waterproofed, then they are a valid construction option. Derivates of paper, such as cellulose fibre, are also extremely effective in terms of thermal insulation (Hurtado, Rouilly, Maréchal, & Raynaud, 2016).

There are also materials and assemblies which require further experimentation and research before they can be effectively used in construction, but that have great potential. This is the case of Thermobimetals (Kretzer, 2015). Bimetals are layered metallic composites, normally composed by strips of two metals with different thermal expansion rates (Howard, 1942). This causes one of the metals to bend more than the other when exposed to heat, as they have different expansion rates. When no external forces are applied the bimetal usually takes the shape of an arc. Electric energy can also be used to force the metals into expansion. Historically, bimetals have been used to ensure temperature indication and control, time limiting and control, as well as for ensuring safety. For architecture, they are starting to be used to autonomously move in response to temperature changes. This is especially interesting for building skins, which can change according to the outside temperature and thus provide ventilation and better thermal control for the building. It also offers the building a facade that moves and alters according to the climate it is exposed to or the sun path of a given region, changing its shape and form. Such a building skin would also be able to operate with no electrical power, making it more energy efficient. The problem posed with bimetals is that they are still very limited regarding the temperatures they can handle and the structural loads they can withstand, but they still have extreme potential and will likely become more commonly used as research continues and technology evolves.

For the case of extreme environments, these materials could be used ideally for temperature regulation inside of the building, especially in very hot environments, where high amounts of energy are necessary to keep building's cool. A material like this would allow for energy savings, as it's sun shading would help regulate temperature and ventilation. In terms of very cold temperature climates, it probably wouldn't be as useful as the outside is very cold, and ideally no heat should be lost from the inside of the building to the outside. However, if other properties of thermobiometals are considered, they could also be of use to both hot and cold environments. Such is the case of self-assembly, without the need to use hands or tools, and helping to increase the strength of lightweight structural surfaces

Thermobiometals can be used without requiring external energy to operate but can still dynamically react with the environment that surrounds them. The material responds to the climate and environment, although it does not require any energy (Mortice, 2015). These properties might prove to be extremely useful when the technology is more advanced, and these materials can be widely used, including in the context of extreme environments.

Image 1.12 - Responsive installation "Bloom" by Professor Doris Kim Sung, presented in 2012 at the Materials & Applications gallery in Los Angeles. The façade consists of 14 thousand smart thermobimetal tiles, which curl up when the temperature rises outside or they are hit by sunlight *(Sung, 2011)*.

1.6. Exterior building morphology for Extreme Temperatures

The Passivhaus (or “Passive House”) is a building standard that ensures the building is energy efficient, thermally comfortable and economically affordable. It is not a brand name but a design and construction concept with defined criteria that can be applied anywhere in the world, although some adaptations may be needed in regard to the original standard depending on the type of climate. It was first developed and applied in Central Europe, but its principles and concept remain the same and are still valid for different climates. Since it must be adapted. It must not be considered a universal solution or concept, as it doesn’t work on very hot climates, for instance. Regardless, building details do have to be adapted to its environment, meaning that to achieve the Passivhaus standards, a building will look different depending where in the world it’s located, to respond to the specific requirements of different climates (Passive House Institute, 2019).

The concept of Passivhaus was launched in May 1988, by Wolfgang Feist and Bo Adamson, at the University of Lund, in Sweden. Since the mid-1980s that low-energy buildings were already a legally energy standard for new buildings in Sweden and Denmark, and a lot of research was being performed in buildings with excellent insultation, preventing thermal bridges, and assuring airtightness, controlled ventilation and insulated glazing. Passivhaus was then defined as buildings that required an extremely small quantity of heating energy or active heating (where mechanical means are used to store, collect, and distribute solar energy, so that interior spaces can be heated up or, for example, provide hot water (U.S. DEPARTMENT OF ENERGY, 2021)), even in Central Europe Climate (Feist, Cost Efficient Passive Houses in Central Europe Climate, 1998). These houses could be warmed “passively”, only through internal heat sources and the solar energy that came within through the windows. This was proved to be theoretically possible in 1993 (Feist, Passivhäuser in Mitteleuropa, 1993).

In order to design energy-efficient architecture, one must consider the compactness of the volume to build, while also taking into account the heat losses from key points such as the windows, doors, floors, walls and roofs. The shape of the building envelope[1] will greatly affect the energy demands of the building. The Passivhaus standards state that building envelopes

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[1] A building envelope are the physical separators of the environment of a building. They consist of an air barrier, a thermal barrier and a weather barrier. These include resistance to air, light, heat, noise and water. In short, it gathers the various elements of the building, such as walls, floors, roofs, windows, doors, all that creates the barrier between the inside and the outside of the architectural object (Cleveland & Morris, 2009).

should be as continuous as possible, with an airtight barrier on the interior side of the insulation, and a windtight barrier on the outside of it. This will ensure a high-performance thermal envelope, which will result in less energy loss (Vallentin & Gonzalo, 2014). There are several requirements for a building to be considered a Passivhaus (see Image 13): the heating energy demand must not exceed 15 kWh/m^2 of treated floor area per year (in cases where cooling energy is required, the standard is the same but for cooling); the total energy to be used for domestic applications must not exceed 60 kWh/m^2 of treated floor area per year; there must be a maximum of 0.6 air changes per hour at 50 Pascals pressure to ensure airtightness and thermal comfort must be guaranteed for all living areas in winter and summer, and there must not be more than 10% of the hours in a year with and indoor temperature of over 25 ºC. Passivhaus defends that these criteria are achieved with design choices that stand on Passivhaus's five principles: ventilation with heat recovery, thermal bridge free design, superior windows, quality insulation and airtight construction (Passive House Institute, 2019).

For thermal insulation, for most cool-temperate climates, a maximum heat transfer coefficient of 0.15 W/m^{2}K (U-Value) is required. Regarding the house windows, they must be well insulated and fitted with low-e glazings filled with argon or krypton, to allow for a U-value of 0.80 W/m^{2}K, with around 50% of solar transmittance. For ventilation heat recovery, which is considered essential for a good indoor air quality, at least 75% of the heat from exhaust air should be transferred by a heat exchanger. Regarding air tightness, uncontrolled leakage through gaps should be smaller than 0.6 of the volume of the house, per hour, considering a pressure test of 50 Pascal. Finally, for thermal bridges, these must be avoided. If a thermal bridge cannot be avoided, it should be as minimized as possible (Passive House Institute, 2019).

Another essential concept to have into account when finding the best exterior morphology for extreme climates is the Heat Loss Form Factor (FF). It relates the external surface of the building envelope with an internal measure of the space people inhabit. There are two ways of calculating the form factor. The first one is the ratio between the external surface area of the building envelope and the heated (or cooled) interior air volume (A_e/V). The recommended A_e/V for a single-family house compliant with Passivhaus is between 0.5 and 0.8 m^2/m^3. The second way to calculate the FF value is through the ratio between the internal surface of the building envelope and the treated floor area (A_e/A_{hf}). It has also been used successfully in research in Sweden as a faithful indicator of the compactness of buildings. It can be concluded that the first form of calculating FF shows better the efficiency of a given geometrical volume, while the second better represents the efficiency of the architectural shape, since the treated floor area (instead of volume) seems to offer more conclusive quantitative results (Lylykangas, 2009).

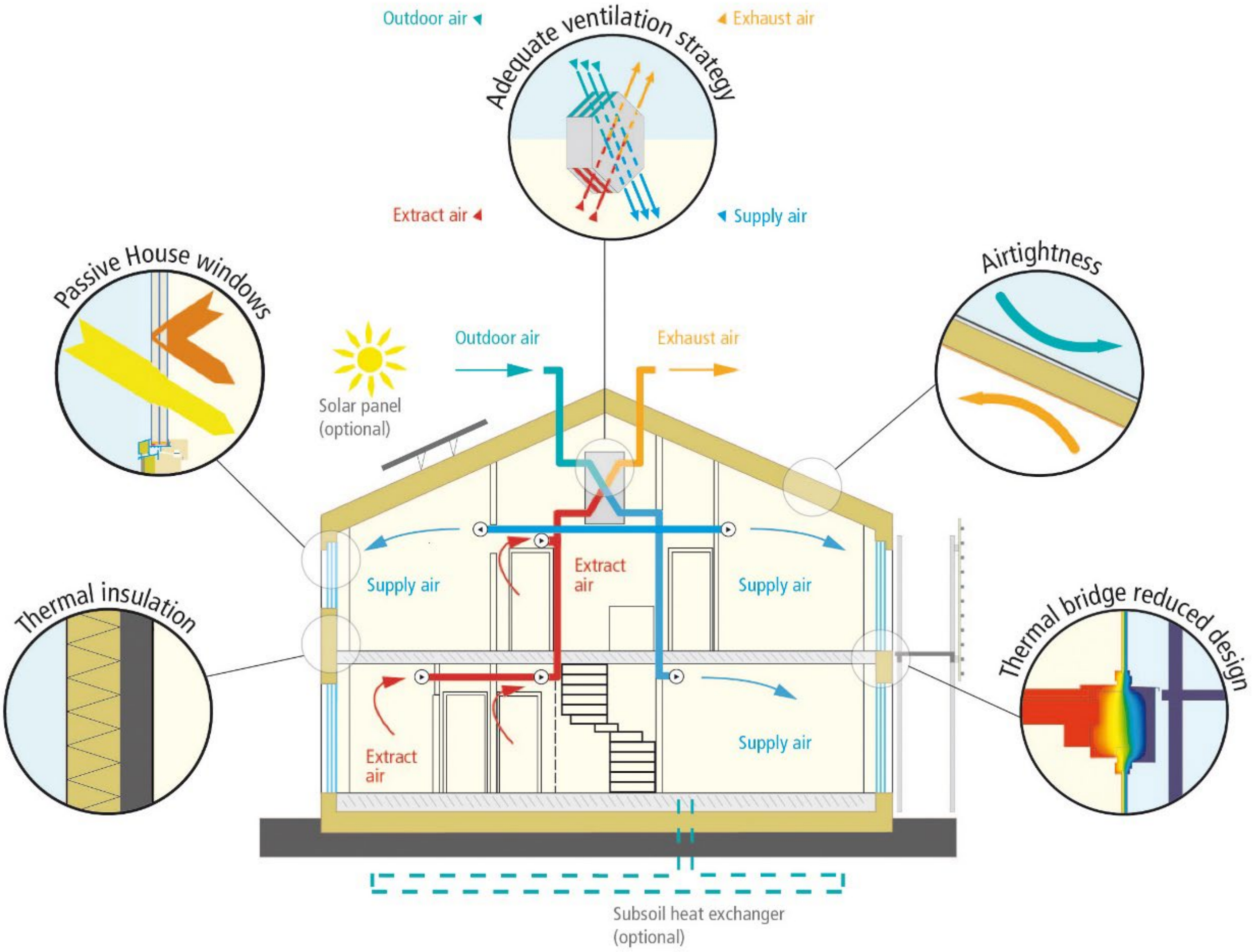


Image 1.13 - The five basic principles for the construction of a Passivhaus *(Passive House Institute, 2019)*.

This happens because the efficiency of a building, in all its architectural complexity and as a habitat for people to live in, depends more on floor area than on volume: it is the net floor area that conditions the available space for people to dwell (assuming that the space height fulfils comfort and legal requirements). This FF also seems to be the most logical choice for architecture because we consider heated floor area (instead of air volume), which is measured in square meters, the same as energy demand (Lylykangas, 2009). The differences on the calculations of both FFs can be seen on Images 1.14 and 1.15, it is worth noting that regardless of which is the chosen procedure to calculate it, the smaller the Form Factor of the building, the better; the smaller the FF, the more compact a building is.

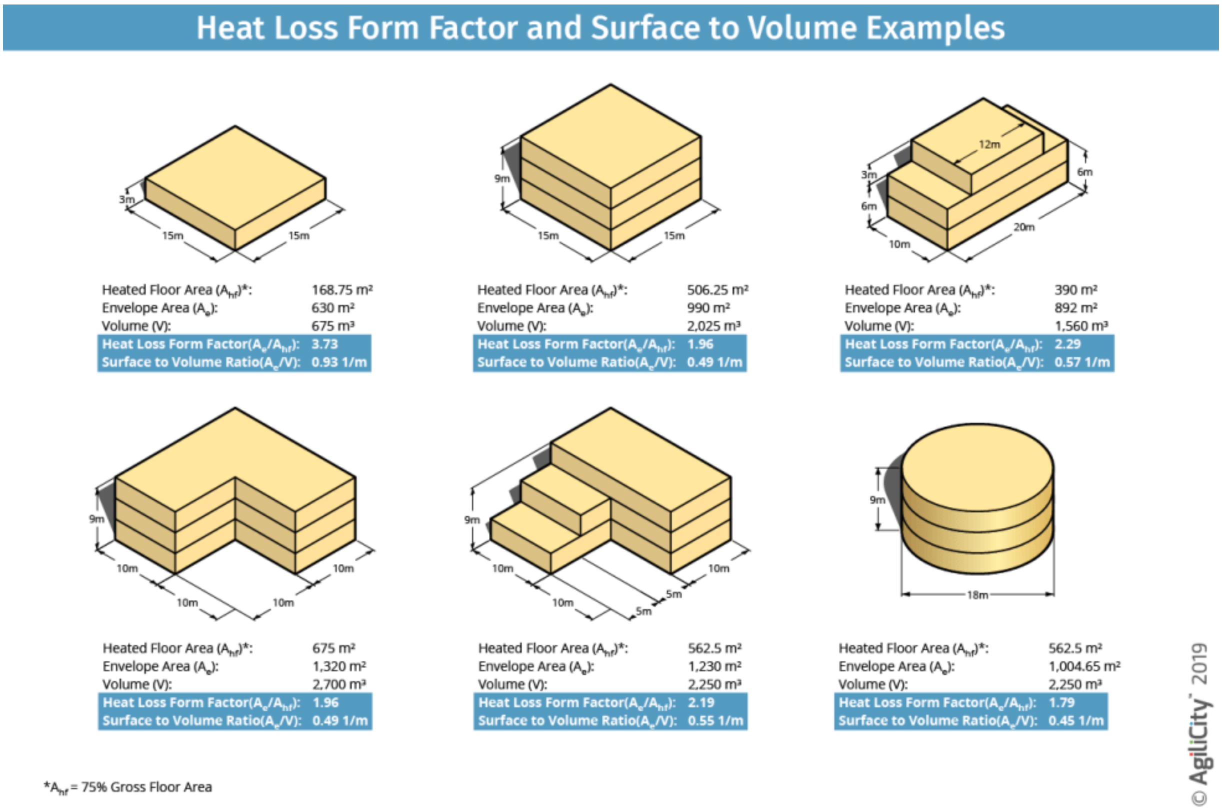


Image 1.14 – "Simulation cases with the net floor are of 150 m^2. In the upper row the A/V ration grows from 0.70 to 1.00. In the lower row the A/S ratio grows from 2.25 to 3.75. A/V is calculated using the outside dimensions of the insulation layer. A/S is calculated using the interior dimensions of the building envelope." *(Lylykangas, 2009)*.

Regarding the best option of morphology for extreme environments, taking into account examples of buildings in very challenging environments, which will be analysed in the next chapter, it seems to be a semi-spherical volume, or an ellipsoid-like volume. This is very common in very cold environments, or for habitats in other planets, while for very hot environments a low-rise, more orthogonal shape, seems to be preferred. The reason for these choices will be analysed further on the research, while an optimal building shape for these climates is devised.

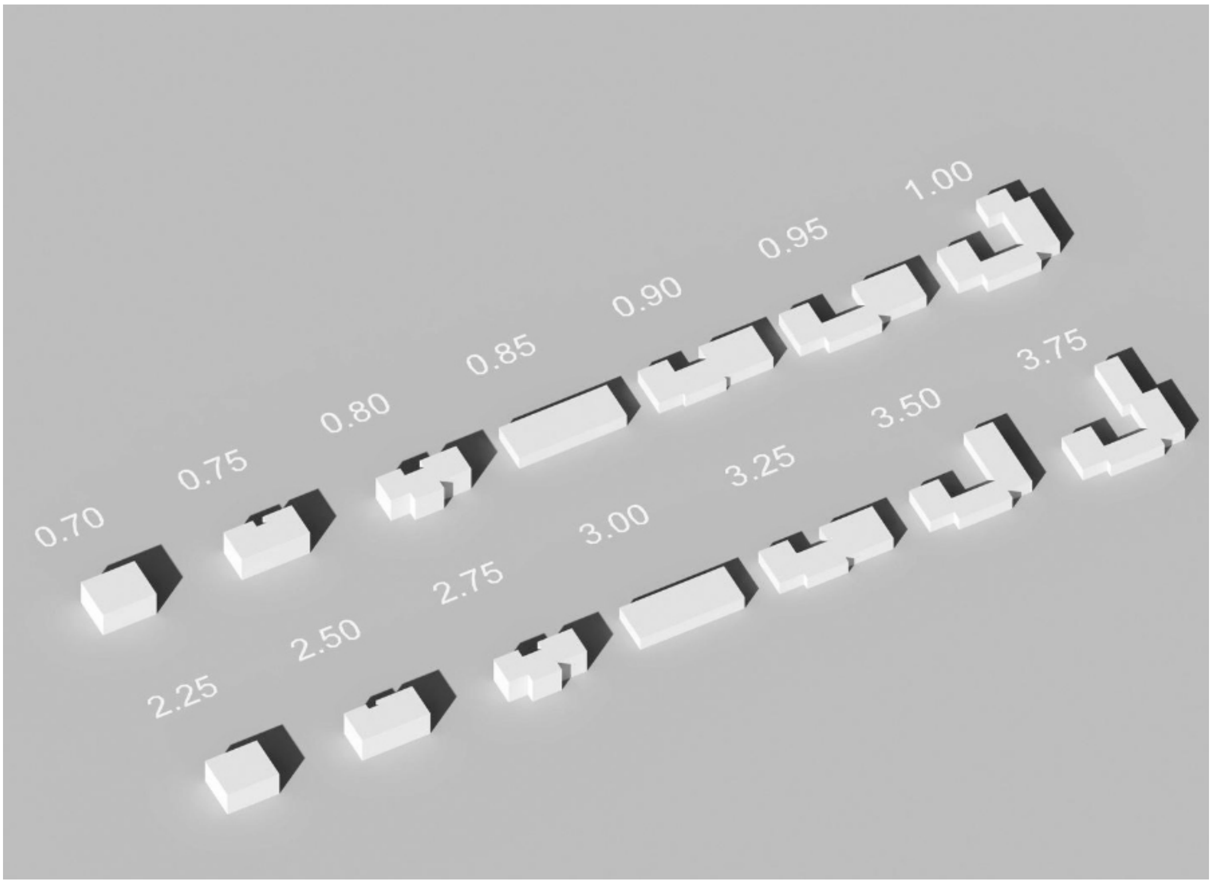


Image 1.15 – Representation of the two types of Form Factor and how it changes according to the different shapes *(Passive House Institute, 2019).*

1.7. Extreme Temperature Architecture Case Studies

When it comes to design and build for extreme environments on Earth, the biggest number of references come from Arctic or Antarctic research stations, the largest one being Halley VI Research Station, on Antarctica, which is composed by various aggregated modules, that are suspended above the ground. It was planned to last about 20 years, and must be slightly risen every year, due to the snow piling up on top of the Ice Shelf. This was the solution (rising the Station in height) devised to address the major issue with the previous Halley Stations. If the building cannot rise above the rising shelf, the snow will pile on top and the building will be buried and collapse due to the weight of it, as it was the case of all the Halley Research Stations up until Halley V (see Image 16). All of the previous Halley stations ended up having to be abandoned due to the amount of snow that got piled around them, making it very hard for the inhabitants to access the exterior, or to keep the windows free of snow. On Image 16, it's possible to see a section of the station Halley III, after the ice broke, and to see all the snow that was piled above it, from 1984 (when the station was closed) to 1993, when it emerged from the Brunt Ice Shelf again. Every year, approximately 1.2 meters of snow accumulate on the Ice

Image 1.16 – Halley III Station, buried and soon to calve off the Brunt Ice Shelf *(N. E. Council, 2013)*.

Shelf, making it very challenging to keep buildings above snow (NATURAL ENVIRONMENT RESEARCH COUNCIL, 2021). The consequences of the snow rising in the Shelf can be seen on Images 1.17 and 1.18, of Halley Stations I and II, respectively. At the moment, Station Halley VI operates throughout the year. Temperatures at Halley rarely rise above 0º Degrees Celsius, typically temperatures are at about 20º Degrees Celsius, with extreme lows of -55º C, and 52 people can live on it at the same time (this number is normally only reached during the summer).

Image 1.17 and 1.18 – Photographs of Halley Station I and II, respectively. Halley Station I was buried under 14 meters of snow, when it was abandoned in 1968, and Halley Station II was only operable for 6 years (1967-1973), as the new steel-reinforced roof was not enough to hold the ice *(Nielsen, 2017)*.

The Station consists of several modules, connected between them. Although the modules create a great long hall, all of them have been personalized with different colours, and the spaces are strategically divided: the sleeping chambers and hygiene spaces are on one side of the station, while the work areas are on the opposite side of the station, with the large social module in the middle, with a large window to observe the surrounding environment (Slavid, 2009). As it's possible to observe in Image 16, the design of the layout of the Halley VI Station answers perfectly to those principles of indoor spatial configuration enunciated above. There is a planned interior organization, there is the use of daylight and colour, attention to noise and a clear separation between private/public spaces. On top of that, it is possible for the inhabitants to personalize their sleeping quarters as much as possible (see image 19). Relatively to the Research Station's outer appearance (see image 20), it is separated into two for safety reasons, and if necessary, they can both self-sustain autonomously. The bridge between them allows the sharing of energy and water. The walls are built with robust S355NL steel structure and clad, being highly insulated with composite relatively lightweight glass reinforced plastic (GRP) panels (Tuplin, Ayres, & Hugh Broughton Architects, 2005). The indoor spaces are separated by plywood panels. The chosen exterior shape is concordant with the review above of what the best building exterior shape is for extreme environments: the modules are not perfect semi-ellipsoids, but they are very close to it. The modules have been prefabricated in South Africa and then shipped by cargo ship to Antarctica, and took 12 weeks to assemble at Halley V (which was still in operations at the time and was posteriorly closed in 2012), and were then transported 15 kilometres inland to the new Research Station site, where Halley VI was built, and operations on it began in 2013 (Hugh Broughton Architects, 2019). Although it is possible to dissemble the whole station, the steel legs that hold it high above the snow will end up being permanently buried in the snow because the ice shelf rises 1.2 m every year, which is environmentally undesirable. However, Halley VI remains the most sustainable station of its kind, since nothing will remain of the buildings once they're relocated or removed, and the only other waste product (apart of the steel legs) left behind will be treated wastewater.

Image 1.19 – Photos of the interior of Halley VI Research station, the photo to the left shows a sleeping chamber (for two people) and the social area to the right *(Hugh Broughton Architects, 2019)*.

Image 1.20 – Exterior photo of the Halley VI Research Station, with the big red social module in the middle *(Hugh Broughton Architects, 2019)*.

Another example of architecture for extreme environments, that takes advantage of its particular location, it's the Svalbard Global Seed Vault (see image 1.21), which is located on an island of the Svalbard archipelago, between mainland Norway and the North Pole.

Image 1.21 – View of the entrance of the Svalbard Global Seed Vault outside Longyearbyen on Spitsbergen, Norway on February 2016 *(CBS NEWS, 2017)*.

It was designed by architect Peter Soderman in 2007 as a long-term storage facility built to stand natural and man-made disasters. It holds the biggest collection of crop diversity in the world. Only the entrance is visible, the vault itself being 130 meters buried into the mountain, under 40 to 60 meters thick rock. Because of this, it is possible to maintain temperature much better than at surface level, because it fluctuates minimally, with little to no energy losses. Its location is geologically stable with low humidity levels and way above sea level so that it doesn't flood, even considering the sea level rise due to climate change. Radiation within the mountain is practically non-existent and methane levels are very low.

The surrounding permafrost soil offers the perfect temperature conditions through natural freezing, maintaining a constant temperature of -5 ºC: in order to perfectly conserve the seeds, the vault needs to be cooled at a constant -18 ºC, it's easier to keep this temperature if the ground that surrounds the building is already at a very cold temperature, making the cooling system more effective and more energetically effective. The permafrost is also essential because if something goes wrong with the cooling system, the permafrost will keep the seeds frozen until repairs can be made (Fowler, 2017). The vault consists of three halls, built where the natural temperature was the coldest and measuring 9.5 m x 27 m. They accommodate up to 2.25 billion individual seeds, in a total of 4.5 million seed samples (see Image 1.22). The vault doesn't have an "exterior shape" per se but being buried within the rock gives it the required thermal properties to be able to maintain the mandatory interior temperature. The vault was envisaged as a structure and a system that would require minimal human intervention, that would almost operate by itself (Fowler, 2017).

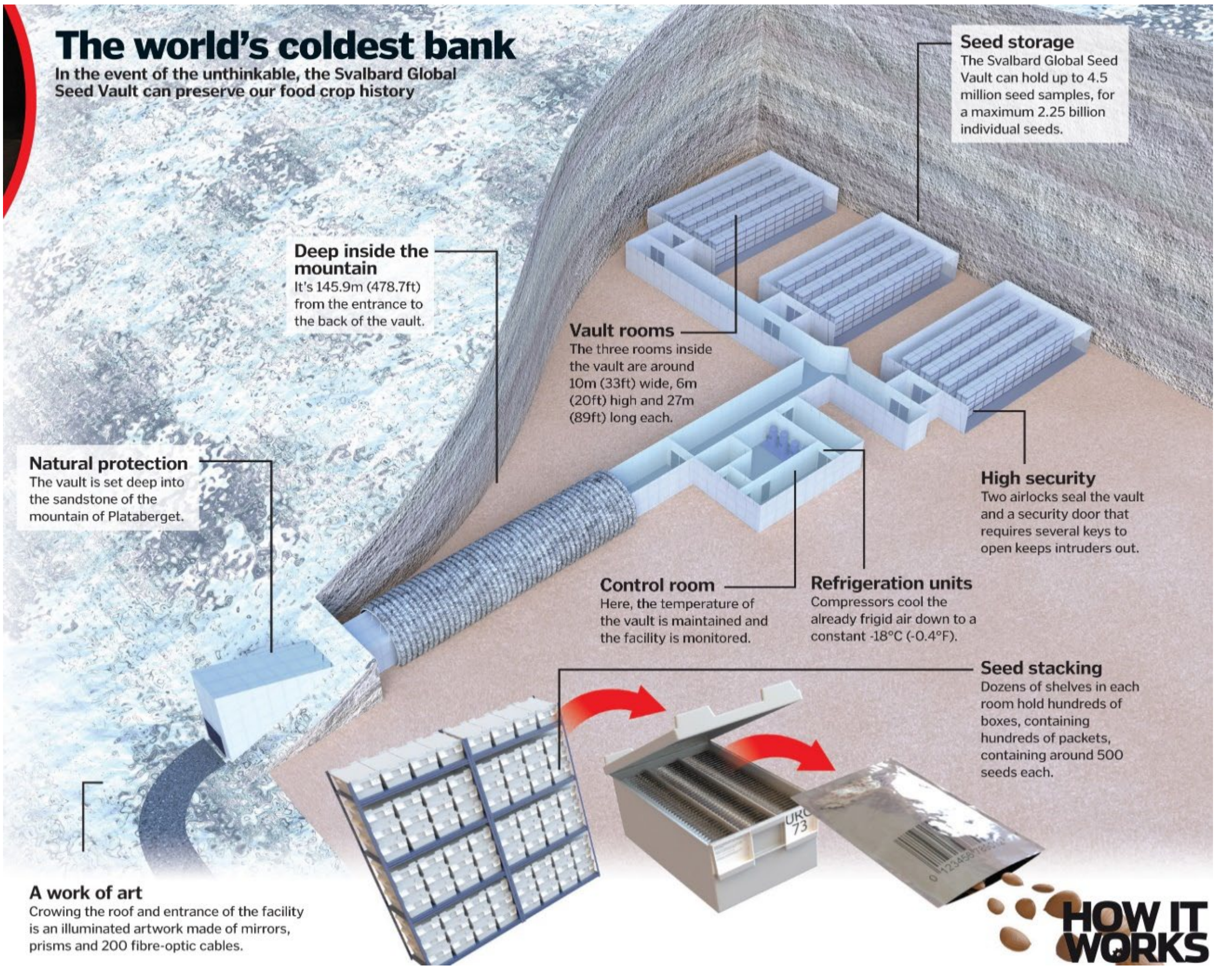


Image 1.22 – Scheme of the interior of the Svalbard Global Seed Vault *(How it Works Team, 2016)*.

Taking a look at the other side of the climate spectrum, where there are arid desert and steppe climates, relevant architectural examples are also found. The first would be a guest house in the Egyptian desert, the Ecolodge I, designed by Felix-Delubac Architectes and built in 2007 (FELIX+DELUBAC Architectes, 2015). The main living room is facing north and is protected from the direct harsh desert sun, opening onto a pergola that overlooks the salt lake. The southern facade has as minimal openings as possible and was built to handle the sandy winds. The house was built using a natural building material called “kershef”, which is made of native mud, sand, and sun-dried salt. Other materials include palm wood, reeds, red stone, and salt stone, all from the surrounding landscape. These materials have a high thermal inertia, keeping the house fresh in the summer and warm in the winter, and allows the building to blend with its surroundings. A nearby spring provides the water for the palm grove, kitchen, and bathrooms, as well as the pool and the basin that cools the courtyard and the surrounding rooms. The water is treated with the use of reed grove. There is also no electricity in the house, the kershef walls have excavated niches on them for candles.

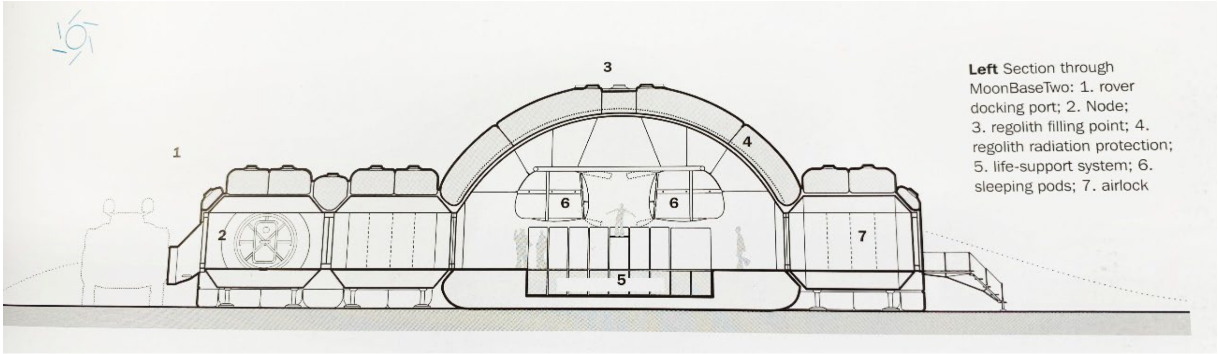
Image 1.23 – a) Photograph of the Ecolodge I and b) Floor plan of the Ecolodge I *(FELIX+DELUBAC Architectes, 2015)*.

Another example is the Tucson Mountain Retreat, design by DUST Architects, a single-storey residence completed in the Summer of 2012. It is located at Saguaro National Park, at the heart of the Sonoran Desert, in the United States. It was built away from animal migration paths so that it disturbed the natural fauna as little as possible, and its walls were built with local natural rammed red earth, which we can see in the finishing of the walls. The architects tried to make sure that the construction would have as minimal physical impact as possible, because they were dealing with such a fragile environment.

The house is separate into three zones: a sleeping and bathroom area, a music studio, and a central living room. In order to access different zones, residents have to leave the building, this is to ensure good acoustic separation. The walls on the side of the living room slide open to allow natural cross ventilation. The music room has a deck facing north and the bedrooms have a terrace with a canopy to protect them from direct sunlight. The house is self-sustaining in terms of water supply since it uses a large rainwater harvest system that filters it until it is safe for human consumption (DUST Architects, 2012).

Image 1.24 – a) Photograph of the Tucson Mountain Retreat and b) Floorplan of the first floor and the terrace of the Tucson Mountain Retreat *(DUST Architects, 2012)*

Finally, in order to study architecture for extreme environments, it is mandatory to have a look into projects that were, and are, created for the most extreme environment of all, which is outer space and other planets, as they aggregate various characteristics of these environments. For example: extreme temperature (both very high and very low), lack of oxygen and radiation. Of the various existent projects, we will consider “MoonBaseTwo”, one of the projects created for a human habitat on the Moon, by ARCHITECTURE AND VISION. This project was created to sustain up to 107 ºC and -153 ºC. Its shape can be compared to that of an igloo (see Image 25), and it is to be transported and then inflated on location, changing from a cylinder 6 m long with 7.5 m in diameter to a semi-sphere with a height of 10 m and a diameter of 20 m. It will hold up to 6 people for up to 6 months at a time, with an entryway with a docking port, and a big hybrid module in the middle. Its configuration is slightly different as the sleeping pods are located in the central block, but at a higher level, so they are suspended above the large social module. The building has quite a height due to the fact that on the moon there is less gravity, and so astronauts will bounce more, and move in different directions. If this were a project for Earth’s standards and requirements, a much lower ceiling would be adequate. When it comes to insulation, this is ensured using Regolith, which is the moon soil, which will be used to cover the structure after it is fully inflated and assembled. This layer of bedrock will not only ensure insulation against exterior temperature but against radiation as well (Slavid, 2009).



Left Section through MoonBaseTwo: 1. rover docking port; 2. Node; 3. regolith filling point; 4. regolith radiation protection; 5. life-support system; 6. sleeping pods; 7. airlock

Image 1.25 – Section through MoonBaseTwo *(Slavid, 2009).*

3D printing has also been indicated as the better alternative when it comes to building human settlements in other planets, so instead of shipping out entire prefabricated and semi-assembles modules, NASA would ship 3D printers and the settlements would be created using a mix of ice and native natural soil of said planet. This would also make the buildings more sustainable as they would be easily disintegrated after mission dispatch. Architect and Professor Michael Morris and Yoshiko Sato founded the SEArch+ (Space Exploration Architecture) and the Morris Sato Studio, contributing with architectural projects and insight for NASA, exploring the possibilities of building for extreme environments (CCB, 2019). Their project "Ice House" was the winning designed 3D printed Martian habitat from NASA's 2015 Centennial Challenge, a collaboration between SEArch+ and Clouds AO (see Image 23) (SEArch+ / Clouds AO, 2015). As its name indicates, the habitat is built of ice, using the water deposits it is now known that exist on Mars, instead of martian regolith. This way, the habitat can be naturally illuminated, due to the semi-transparency of the ice, also providing shielding against radiation. A clear silica additive would also be added to the mixture, to increase the strength of the ice, and the walls would be constituted with two layers, an inner and an outer layer. The inner layer would be insulated with a hydrophobic aerogel, which is essential for the inhabitants and the indoor vertical garden to survive in the extreme harsh climate conditions of MarsThe habitat is constructed vertically, with four different levels (see Image 24) (SEArch+, 2019). The first one consists of the entry way and the docking stations, which gives access to an elevator, as well as the courtyard, that functions as a transition zone between the indoor habitat and the exterior environment. The hygiene area, library, laboratory, and exercise/medical room are all located at level two. It is also at this level that starts the vertical green garden, that rises all the way up to the top level. At level three, we have the crew quarters with another central hygiene area. Finally, the wardroom/gallery and the food prep area are located at level four, where there will also be large windows filled with radiation protected gas, that will give the view of the surrounding Martian landscape. The vertical garden is essential to the project, because it will provide the crew with oxygen, as well as enable the growth of consumable produce, while offering natural plant life and colours that contrast with the arid environment of the red planet. This highly contributes to the inhabitant's mental state and well-being.

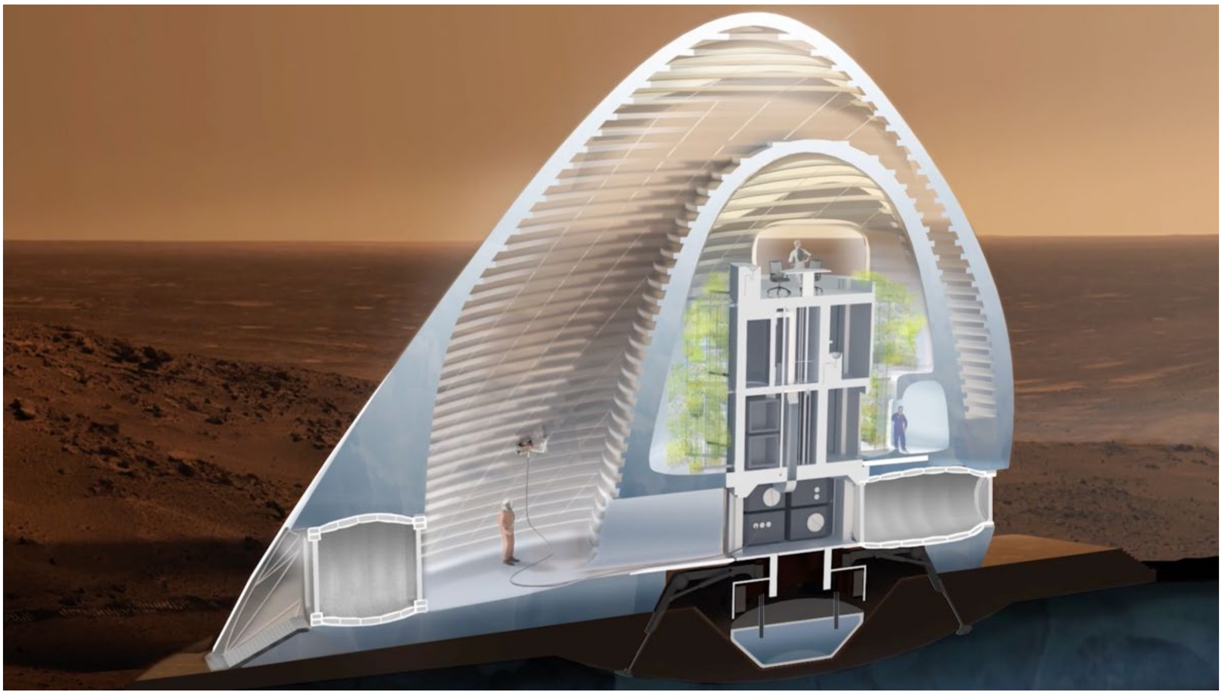


Image 1.26 – Section of the "Ice House" for Mars *(SEArch+, 2019)*.

Among the analysed examples of architecture for extreme environments, it's possible to identity three different types of buildings, based on what climate they're planned for: very cold climates, such as the case of the Halley Stations and the Seed Vault; very hot environments, such as the Eco-House and the Mountain Retreat; and outer space, with MoonBaseTwo for the Moon and the Ice House for Mars. For the very cold climates, it seems the greatest challenge was the accumulation of snow, in the case of the Halley Stations, which has so far been solved with steel legs which keep the Station elevated from the ground level, and can be risen each year, to keep up with the rising level of snow. This, however, poses an environmental problem, as the legs have to remain in the landscape once the Station is removed from site. Other than this, its design allows for a big module in the centre, which comprises the social areas, and the rooms and private areas are in separated modules.

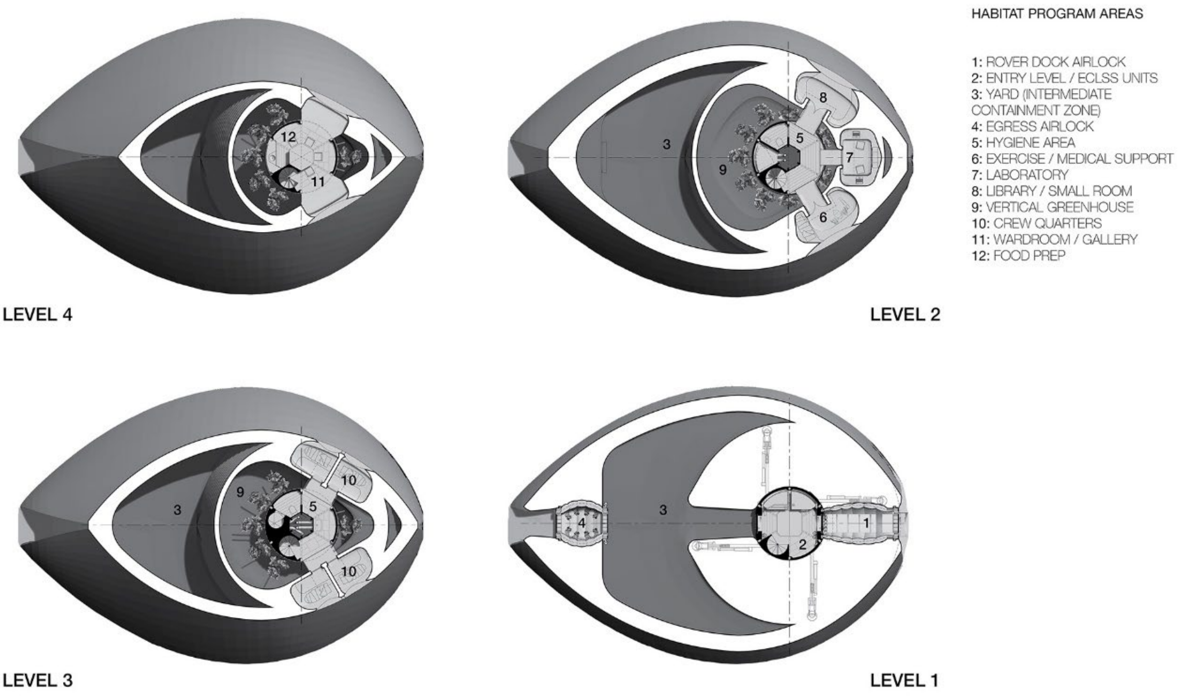


Image 1.27 – Floor plans of the various levels of the “Ice House” *(SEArch+, 2019)*.

There are various windows from which the inhabitants can see the landscape and the rooms are as customizable as possible for each inhabitant. There also a large use of colour in the modules, to contrast with the essentially white landscape. All of these questions are important when considering the mental well-being of the people which will live on these buildings, and that cannot have regular access to the exterior environment. On the case of the Seed Vault, although its purpose is to store seeds and not to serve as a habitable space for humans, it also provides a couple of leads for designing and building for challenging climates. The fact that it is buried helps greatly with keeping the interior temperature of the building, as it allows for much less heat loss through the walls. In the specific case of the vault, the interest is that if the cooling system fails, the temperature within the building would keep steady, taking it long to warm up, and thus allowing for the system to be repaired without danger to the seeds. However, if it was to keep the building warm, being buried would still be an advantage, as there would be less heat loss, meaning that less energy would be required to keep the volume warm, compared to a building that’s exposed to the cold exterior air. Another example of this type of (vernacular) construction is the igloo, mentioned in a previous chapter, which is also partially covered in snow, because it allows for better insultation and less heat loss.

Regarding the very hot climates, both case examples are of buildings which are built with materials which are native to the area, comprised of essentially native clay/earth, which have high thermal inertia. This helps keep the buildings fresh in the summer, and warm in the winter, if it's required. On the first example, the Eco-House, the openings of the windows are very small, to avoid over-heating of the building through sunlight; this also happens in the architecture of Aït-Ben-Haddou, analysed earlier in the State of Art, where the openings of the houses are very small, and the walls are very high, to ensure streets are shaded. On the second example, the Mountain Retreat, greater importance to natural ventilation was given, as the walls can slide open to allow more air to come through, in order to cool the building. The outside resting is also turned North, so that it's more protected from the harsh sunlight of the South. On both examples, the buildings are essentially built only at ground level, the structures remaining close to the ground.

Lastly, a couple of the previous guidelines can be seen in the examples used for architecture in outer space. This is the case of MoonBaseTwo, which is very similar in appearance to an igloo, and is covered in native ground material after being inflated, to ensure better insulation. It comprises essentially of a hybrid module in the middle, where the sleeping pods are hanging close to the ceiling, and the rest of the social activities happen below. Regarding the Martian Ice House, it is to be 3D printed in the surface of Mars; however, it's not planned to be built in native ground material, but in ice instead, using the natural water reservoirs of the planet. It would be built of two layers of ice, one of each would be properly insulated, granting the inhabitants the necessary insulation and protection from external climate conditions, while still allowing for natural light to come through the walls, without the need of windows. In this case, the levels are well divided, there's a transition/entrance area, the next floor contains the working/social areas, the third level is where the sleeping area is located, and finally the food preparation area is on the fourth level. In this project, the architects included a vertical garden, as literature states that green areas are extremely important for the inhabitant's well-being, in such extreme and desolate climates.

In all these six architecture projects, planned and designed for extreme environments, proper insulation and natural ventilation (for very hot climates) are major concerns, and must be ensured when dealing with such challenging conditions. In such extreme environments, keeping the buildings comfortable is essential, and it's very costly in terms of energy. The more effective the building is in keeping its internal temperature through the use of adequate materials and clever design, the better and the more energetically sustainable it will be. The use of native materials is also a constant option for these types of environments, as they offer an easier and cheaper alternative to construction, by not being necessary to transport other materials to the construction sites, which are usually very isolated. The interior design of these buildings is also similar in the sense that interior spaces are cleverly divided into more social spaces, with larger areas, and more private spaces, such as the sleeping quarters, further from the noisy areas, allowing the inhabitants to have a sense of normalcy.

Of course, these questions depend on the use the building will have, as research stations and outer space habitats do not serve the same purpose as a desert retreat or an eco-house, but there are many similarities on the way buildings are planned for environments which are inhospitable to humans, since the exterior is not adequate to live, the interior of the buildings must ensure the basic needs for humans to survive.

1.8. Generative Parametric Design

In 2008, Patrik Schumacher utilized the term “Parametricism” (Schumacher, 2008) to cite new design movements in architecture that used parametric design methods. Before him, it was simply seen as a form to deal with architectural construction, instead of a conceptual tool to create forms and experiment with different design possibilities. Although Schumacher regards “Parametricism” as the new style for architecture, (the style that comes after Modernism), when it comes to the mainstream use of parametric design by architects, it can hardly be considered a new style. In fact, many working architects are apprehensive about the challenges of this kind of design methods, and even if they benefit greatly from them, they cannot be aware of how different this is from the traditional CAD (computer aided design) methods. This happens due to the fact that many architects believe parametric design works solely as a “representation tool”, such as CAD, where an architect simply uses the software to draw the finished product. As such, it could not be used as a “design tool”, to develop an architecture project, only as a “representation tool”, and could not be used to design or create architectural space, as an architect does through hand-drawing, for instance (Zarei, 2012).

For the purpose of this research, “Parametric Design” is about using parameters in order to create an architecture form in the design process, or even the set of parameters within the design that can be manipulated in order to automatically modify others. The main difference between Parametric Design and traditional CAD is that CAD objects do not have relations between them: when one designs lines in a CAD program, there is no relation between these lines, in a way that one will influence the other, they work as separate identities. On the other hand, on Parametric Design, defining relations between elements is possible, if one changes the size of a certain element, or its positions, that will influence the elements attached to it, and so on. Also, the purpose of CAD is to aid the designer/user with representation as a drawing tool. BIM (Building Information Modeling), on the other hand, was created to help the collaboration of the design team and the construction teams. BIM programs, which are based in parametric principles by nature, are object-oriented, meaning that one does not create lines, but construction elements, such as walls, windows, floors, roofs and doors, and they work as intelligent objects, creating relations between them (Garber, 2014). However, it's not always used in terms of Parametric Design, as a BIM model is one which consists in an assembly of objects, instead of composing an object which is generated by logic and an input construction script, which consists of pre-programmed rules or algorithms (Kensek & Noble, 2014).

On the other hand, Generative Design is another concept whatsoever: instead of a software it is an exploratory design process. A designer inputs what design goals he/she wishes into the generative design tool, together with parameters of spatial requirements, material specifications, performance, cost limitations and manufacturing characteristics. The chosen software researches all the possible combinations, and it generates various alternative design solutions. More than this, the software can also test and learn from each repetition and solution and saves information about what functions and what does not. It has various benefits, from exploring different and ampler possibilities of design solutions, (because the computer can generate thousands of solutions with the data the designer inputs), making the process much faster than just through the use of CAD or parametric tools. Suddenly, designs that were impossible before are now possible to create because the software can devise optimized complex shapes and internal lattices. These designs are normally impossible to replicate using traditional building methods, but can be built through new additive manufacturing methods, such as 3D printers, for instance. Lastly, it is possible to optimize materials and manufacturing processes through the use of Generative Design. This is possible by setting objectives and parameters, so that the software can create high-performance design solutions, based on them. The program also solves conflicting design constraints, so that the designer can focus on innovation and creating better and better options (AUTODESK, 2019). It is important to notice that Generative Design happens through the use of parameters and parametric design, and it is the core of this new way of designing, so dominating parametric BIM is necessary in order to be able to use it as Generative Design tool (Zarzycki, 2012).

Generative Design tools offer new paths to architects and designers by breaking traditional predictable form and representation for generated complexities. This allows for the development of new topologies and morphologies, it changes the focus from "form making" to "form finding" (Kolaveric, 2003). However, these tools come not without criticism: many believe that computational approaches disconnect architectural outputs from its purpose and its creators, which then leads to loss of spatial quality. It is also argued that totally computerized approaches lead to a disconnection from the physical modelling and drafting techniques that are to teach and create architecture, that are essential to educate architects, and that in doing so causes the loss of material qualities and properties. However, it is important to notice that form-finding architectural techniques already existed before the digital revolution, just not on the format we are now used to seeing and experiencing. Frederick Kiesler (1890-1965) and Frei Otto (1925-2015) applied design methods that are similar to nowadays computational design approaches. Although there are new tools in this era, the form-finding design approach seems to be very much the same (Otto & Rasch, 1996). In fact, pioneers like Otto, Gaudi (1852-1926), Isler (1926-2009) and Musmeci (1926-1981), rejected topology and searched for self-formation processes in nature in order to compose and organize buildings. Since they could not obtain form through proven solutions, traditional representation methods like drawing could not be used to predict what the result design would be. Because of this, these architects relied on different physical models, and this way, drawing as a method to search for form was replaced with the physical experiences performed on analogue apparatus, which showed how forces would mould new self-optimized forms on architecture (Tedeschi, 2014).

Many architects, designers and educators are sceptical of such unconventional design methods, because of the belief that design control, craftsmanship, functionality, materiality and relationship to context will be lost. Although true that designing solely with digital tools make materiality and gravity disappear, physical digital fabrication can help designers and students to reconnect with these factors, which are essential in architectural production. Testing digital findings with physical prototypes, architects can understand if a certain computational complex solution offers programmatical, aesthetical or spatial qualities to a determined project. Another question to pay attention to when it comes to Generative Design is that complex geometrical shapes often offer challenges in order to represent their outputs on a traditional architectural design kind-of-way. A lot of times, representing these outputs requires non-standardized and unconventional methods as well. Because advanced design technology offers these challenges and requires a different mind-set from the traditional architectural representative ways, it becomes a design path that is often excluded, and unexperimented due to dogmatism or unfamiliarity with these design tools. The mix of advanced design tools, changing from traditional physical modelling to advanced 3D modelling and printing has been shown to have great educational value and professional use as well (Agkathidis, 2015).

1.8.1. ADD: Algorithms-Aided Design

"Architects do not make buildings, they make drawings of buildings." (Evans, 1989). Drawing is a natural gesture that is the medium through which architects organize ideas and represent space, in order to predict design outcomes. However, representation methods have evolved, such as the use of perspective during the Renaissance period, as well as projective geometry in Modernism, and this has pushed design and architecture forward. The tools used for these methods have been the same for a very long time: pen and paper, compass, and ruler. This creative act established a link between the idea and the design. This process can be considered an additive process, because we add information to the drawing as we overlap traces on paper. Because of this, the traditional way of representation has limits: it is different than the cognitive process that gives shape to the drawing, since it works by establishing interrelations and not by adding information; and the drawing also rules out physical aspects and forces that generate forms in the real world, such as gravity, for example. Because of this, architects had to reiterate tectonic systems and topology, because the act of drawing cannot evolve in itself. CAD software does not allow a solution for this, because it simply allows the designer to perform drawing tasks more efficiently, it ends up being a representation method that is just faster and automated. CAD layering can actually be compared to the additive process of the traditional drawing, as the designer is consequently adding layers, just as if he/she was drawing. In CAD, the computer mouse works as an extension of the brain, it is the hand that holds the pencil, except it is in the digital environment (Tedeschi, 2014).

Since the 1980s, academic research and avant-garde professionals started to search for new ways to explore new forms of using software, instead of settling for the simple editing CAD process and its subsequent limitations (Tedeschi, 2014). They realised that through programming, programs could produce and manage complex shapes beyond human capacity, the computer could take an algorithm and through it create a language that would result in a different type of modelling, where algorithms lead to geometries. The Cambridge Dictionary defines an algorithm has a "set of mathematical instructions or rules that, especially if given to a computer, will help to calculate an answer to a problem.” Through algorithms, the designer can create a set of rules, which the programme will then transform into complex objects. This process allows creatives to plan and input a design process into a computer, instead of only representing the idea of it. In other words, the designer shows the computer how to think in order to form shapes, mimicking the process of architectural thought (Meredith & Sasaki, 2008). This process is actually more important than the final result, because if the final result is the finishing line, then one will achieve nothing more than it. However, if the process is the main objective, one will have many possibilities for that end result, it might not be as controlled as if the one final result was the only motivation, but one will have many more possibilities, and will have created a mental process, translated in computer terms, to achieve a certain result (Tedeschi, 2014). In 1998, design legend Bruce Mau wrote the *Incomplete Manifesto for Growth,* in which states: “(…) process is more important than outcome. When the outcome drives the process, we will only ever go to where we’ve already been. If process drives outcome we may not know where we are going, but we will know we want to be there.” (Mau, 1998). This approach encompasses the essential idea behind algorithmic design: the pre-defined set of rules can produce complex, unpredictable forms and results that are, however, consistent with the input parameters. This process allows designers to go beyond CAD and regular 3D modelling processes (Terzidis, 2006).

1.8.2. Rhinoceros 3D & Grasshopper

Grasshopper consists of a node-based algorithmic editor plug-in for software Rhinoceros 3D, it is an advanced popular algorithmic modelling tool. It was originally created by David Rutten at Robert McNeel & Associates, in 2007 for version 4.0 of Rhinoceros. It is a free tool within the software and runs on Rhino 5.0 or higher. It is the major chosen platform for architectural formal exploration due to a variety of factors: it’s ecosystem, that allows for other plug-ins created for Grasshopper to be utilized within the software itself, extending its potential, it is possible within Grasshopper to run structural, dynamic and environmental simulations, in order to ensure the validity of your proposal; it is being constantly upgraded; has a wide on-line community where one can share questions and challenges; it has the potential to interact with other softwares and allows for real-time connections with programmes like Photoshop, Excel, Revit, Ecotec, amongst others; more than software interaction, it also allows for hardware interaction with its various possible plug-ins (Tedeschi, 2014). Due to this, both Rhinoceros 3D and Grasshopper were chosen as the softwares to tackle this research and to test the expected architectural results.

1.8.3. Grasshopper Plug-Ins – Analysis

Grasshopper's ecosystem allows for the use of various plug-ins for environmental, thermal, and energy analysis. For this research, two main ones were used, plug-in LadyBug and plug-in HoneyBee. Both run within the Grasshopper system and must be downloaded and installed, as they are free softwares that do not come originally with Rhinoceros 3D. They were chosen as there are proved results in energy simulations in the early stages of Architecture projects, offering reliable and valuable information in computational simulations (Tedeschi, 2014). The first plug-in allows the user to import data from weather files, visualize them and further analyse weather data, processing simulation results through the creation of visual graphic outputs. These weather files are retrieved from the Department of Energy of the United States of America, which uses a software named EnergyPlus. Both LadyBug and HoneyBee use the simulation engine of EnergyPlus to conduct the digital simulations, so having EnergyPlus installed on your computer is an obligatory requirement to use these two plug-ins. The weather files provided by USA's Department of Energy are from different places around the world and extremely complete when it comes to climate data, spawning for several years, which allow technicians to conduct accurate simulations, and obtain reliable results (Department of Energy, 2020). On the other hand, HoneyBee populates the imported Rhinoceros 3D model with materials, (either from the EnergyPlus database or user-created), schedules of building occupation, and loads (energy requirements). This plug-in can run energy, daylight, temperature, and humidity simulations, all according to the inputs the user gives the model and the type of results he/she expects to retrieve from it. Image 1.28 shows the connections various plug-ins make within the system of Grasshopper, the analysis they can perform and their connection to outside engines such as EnergyPlus.

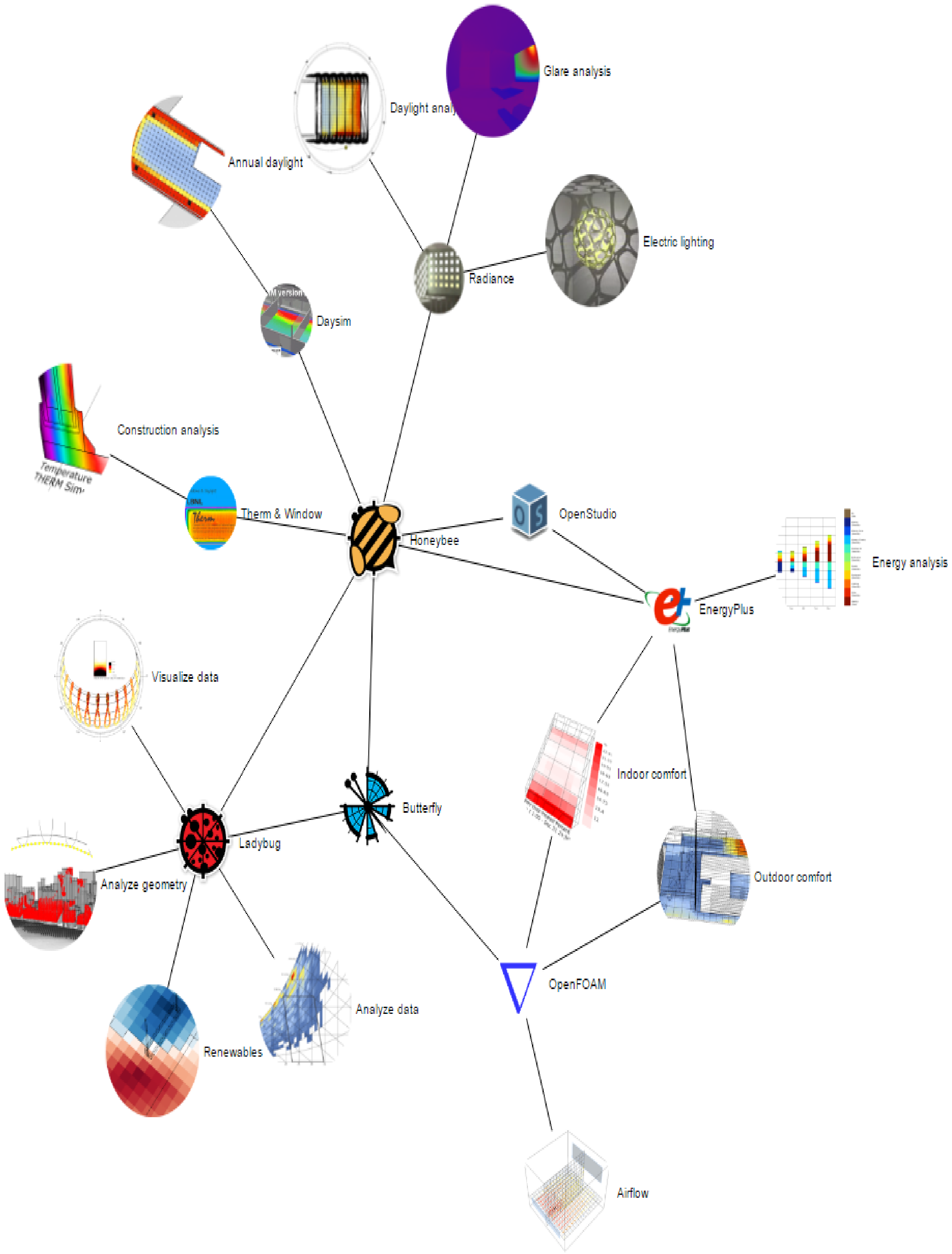


Image 1.28 - Relations between the various environmental/energy analysis plug-ins that run within Grasshopper, their functions and connections with outside engines such as EnergyPlus *(Ladybug Tools LLC, 2021)*.

1.8.4. Digitally Generated Architectural Case Studies

The studio Mamou-Mani works a lot with generative design and Grasshopper, a good example being their project Eco-Resort, in the desert of Dona Ana, in New-Mexico. It was designed for Virgin Galactic and is inspired by the cave dwellings of Tunisia and the geometry of spiral galaxies. It is a resort for contemporary Bedouins that are searching for an oasis in the desert. This eco-friendly retreat has 10 suites that are organized around a central lounge that offers a cool and humid climate, which is generated by the zinc roof that is surrounded by waterfalls (MAMOU-MANI, 2019). It was majorly important to have a roof that would answer to solar movements, what was achieved through Grasshopper, where the designer can link various tools and simulations directly to the parametric architecture model, and GECO, through importing solar coordinates. This allowed the building to be able to continue to grow up, while ensuring the roof panels allowed light in during winter, but it would remain out during summer (AAdip, 2014) (see Image 1.29 to 1.34).

The Chester Zoo's Heart of Africa Biodome is a biodome for animals and plants from central Africa designed by Proctor and Matthews Architects, located in Chester Zoo, in the United Kingdom. Grasshopper was used to offer solutions to the roof's geometry, because a specific shape was necessary to increase the greenhouse effect through very large openings and a thin structure. It ended up being possible to design a thin but very strong structure larger at the peaks and denser in the valleys, which engineers proved to be possible. This is a project that would not have been possible without Grasshopper plugins, since the alternative was going for an orthogonal and conventional construction form (see image 32) (AAdip, 2014). Zaha Hadid Architects designed the Morpheus Hotel, in Macau. The construction being finished in 2018, it is a hotel and casino 160 m high with 39 floors, a large free form opening in the middle, which is crossed by two footbridges (see Image 33). The façade is held by 2 500 steel members and, in the middle, it's single-curved, with 24 577 doubly curved panels, made of aluminium. To design this building, the studio used Grasshopper to build a parametric model (see Image 34 and 35). It created the lines of the exoskeleton for the building's façade. To this, 3D architectural parametric elements such as columns and floors were added, but only as simple standard structural elements. Another plug-in was used for this project, named Front Inc., which is capable of turning Grasshopper generated geometry into BIM elements. This allowed the studio to automatically have and offer the required documentation to allow the digital fabrication of the elements, as well as ensuring the correct assembly of the constructive elements and their connections.

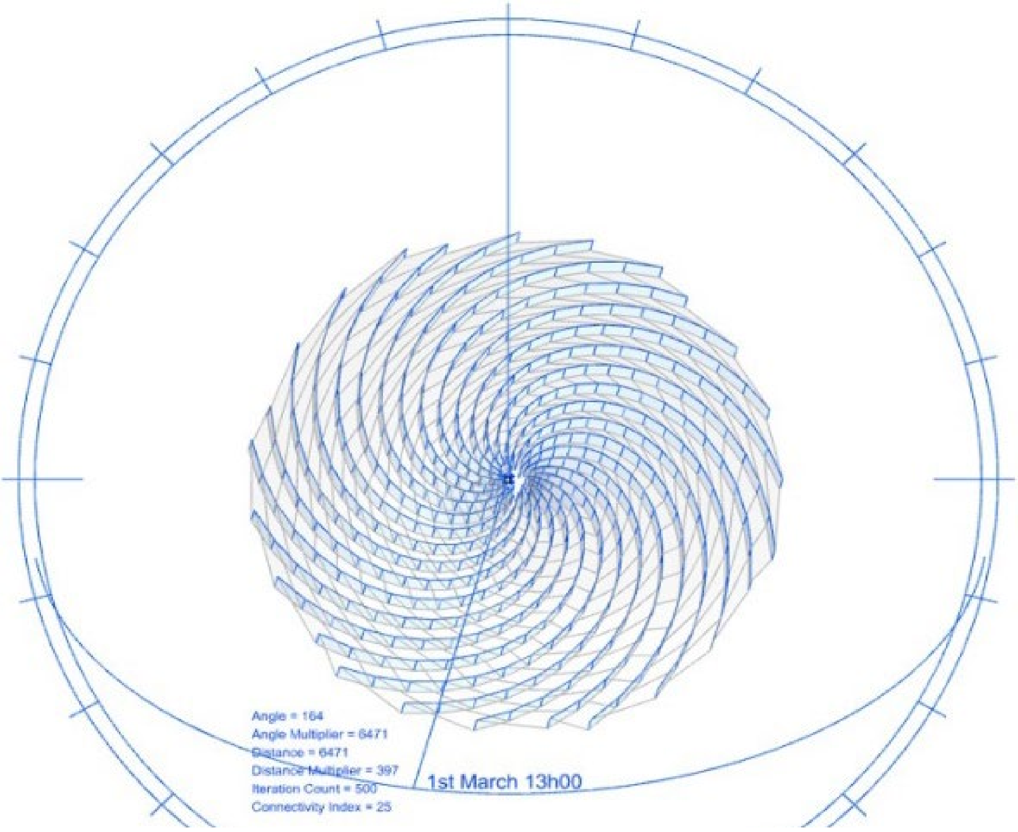


Image 1.29 - Eco-Resort Solar Strategy for roof (3D view) – Only allowing sunrays at particular times *(MAMOU-MANI, 2019)*

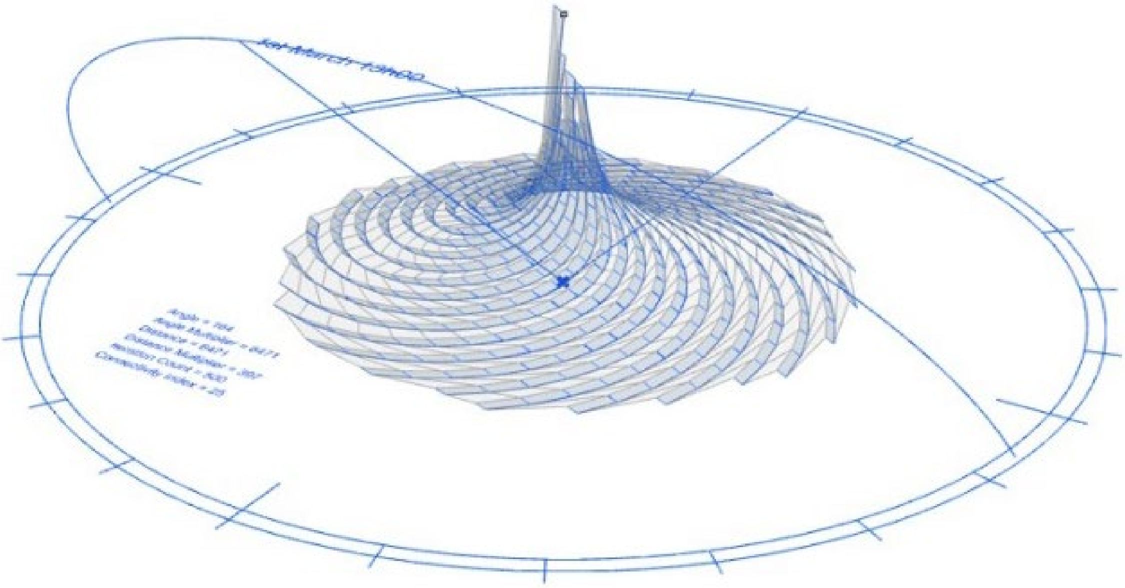


Image 1.30 – Eco-Resort Solar Strategy for roof (roof plan) – Only allowing sunrays at particular times *(MAMOU-MANI, 2019).*

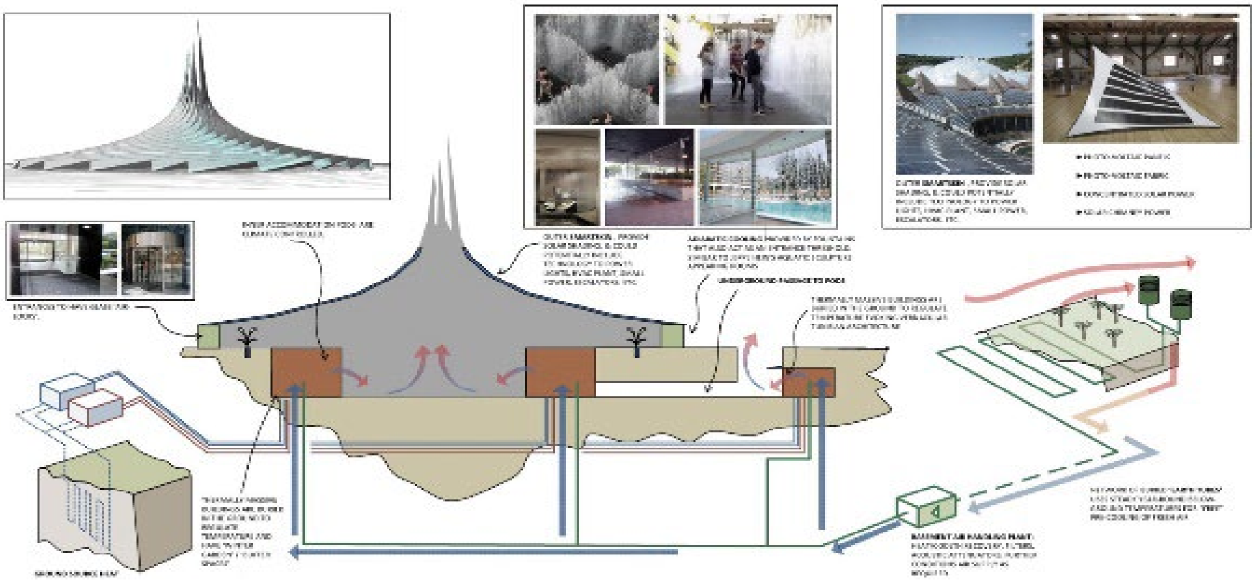


Image 1.31 – Eco-resort environmental strategies *(MAMOU-MANI, 2019)*

Image 1.32 – Aerial view of the Chester Zoo’s Heart of Africa Biodome *(Proctor & Matthews Architects, 2019)*

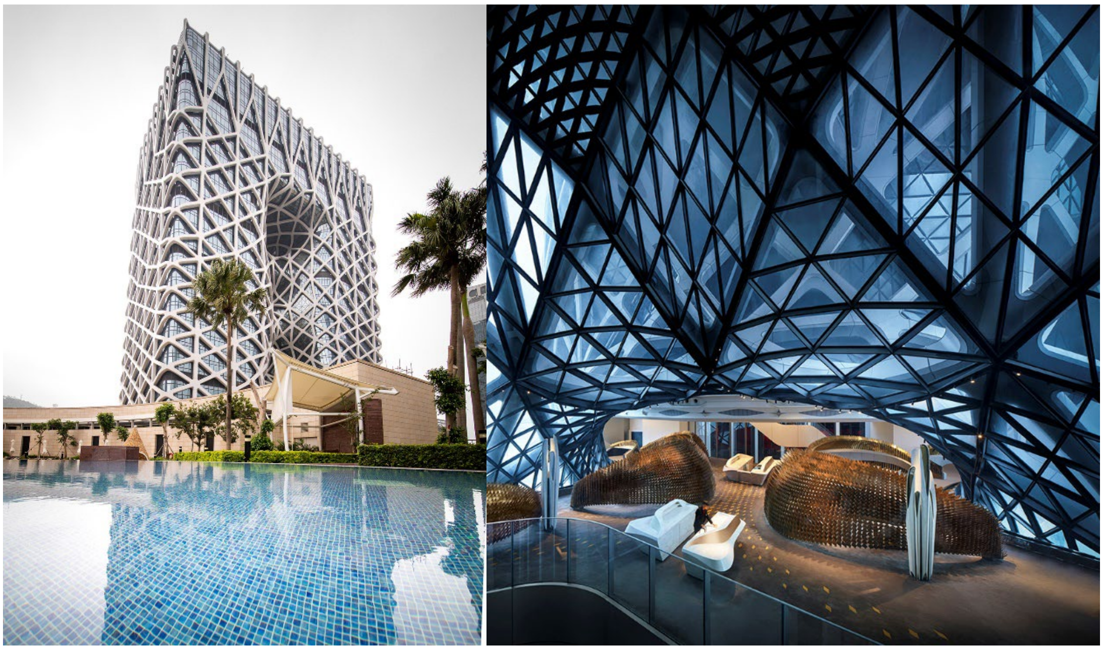


Image 1.33 – City of Dreams Morpheus Hotel by Zaha Hadid Architects in Macau *(Zaha Hadid Architects, 2019).*

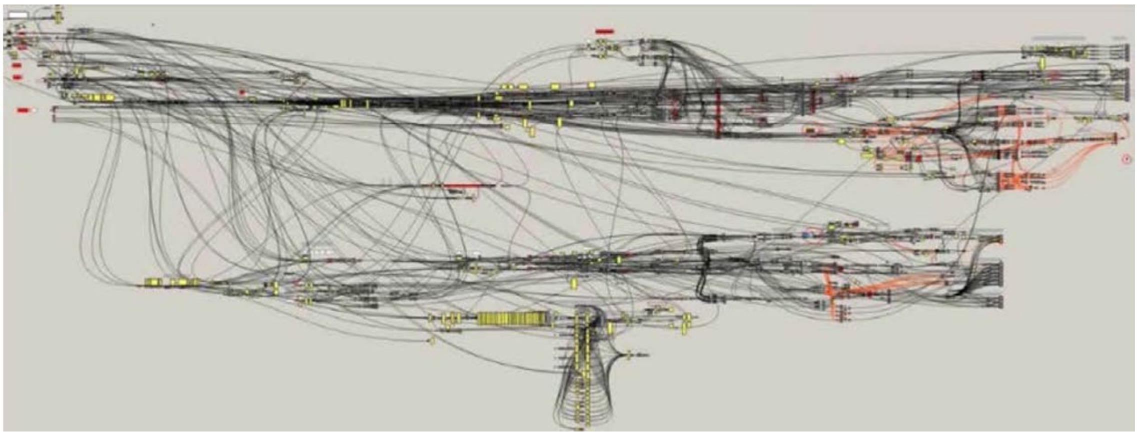


Image 1.34 – Grasshopper model developed by Zaha Hadid Architects for the exoskeleton of the Morpheus Hotel *(Wortmann & Tuncer, 2017)*.

In all referred projects, Rhino 3D and plugin Grasshopper have been used to generate, simulate, create, fabricate and/or analyse 3D virtual geometry. Through it, designers were capable of creating singular projects with an accelerated workflow, which would not have been possible without the use of these computational tools. Generative Design allows for the exploration and testing of new architectural ideas through form shaping and form finding, that can offer new solutions for modern and actual problems.

The above-mentioned case studies were intended at illustrating the contribution of generative parametric tools and methods to the architectural design process. These examples are not necessarily considered as responding to the requirements of extreme environments.

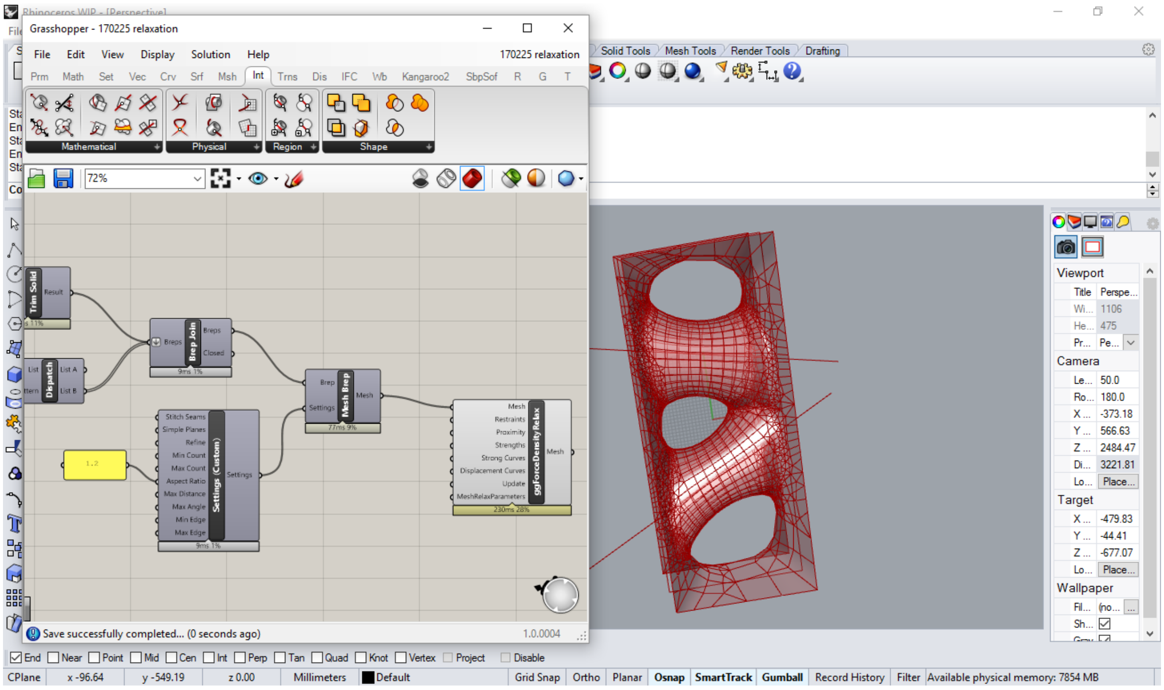


Image 1.35 - Example of a Grasshopper script for the shape of the Morpheus Hotel by Zaha Hadid, shared on the Grasshopper on-line platform *(Mirtschin, 2017)*.

CHAPTER 2

Methodological Note

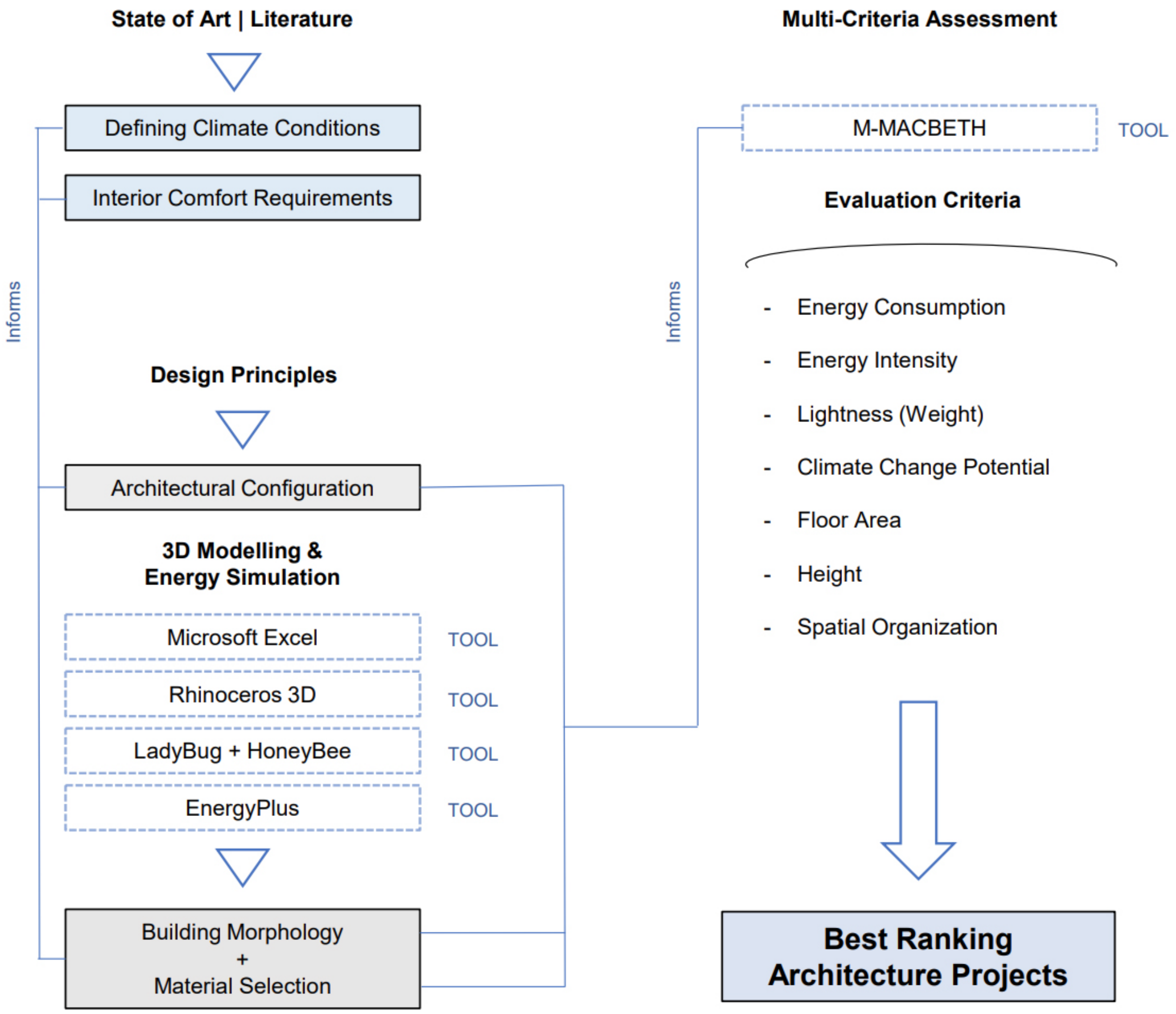


Image 2.1 – Graphical abstract describing the Methodology process of the research and digital used tools.

Designing for extreme environments is a very specific task, and it requires answering to distinct issues that are not commonly addressed in architecture. In order to conduct the following research, it is necessary to create an assessment methodology, as the purpose of the research is to define, test and validate a set of criteria to better inform architects and buildings, regarding designing and building for extreme environments. To achieve this, the research is divided into 5 tasks, which are presented bellow and discussed in the next chapters.

Firstly, before defining the most individual aspects of the methodological process, it is necessary to acquire the correct climate information, so that solutions can be tested in the scope of real, extreme environmental conditions. As it is defined in Chapter 1, extreme climates are defined by having extremely aggressive conditions, that make human life exceedingly difficult, or even impossible. These are conditions such as extreme temperatures, high salinity, extremely high humidity, lack of water, lack of oxygen, acidity, high pressure, radioactivity and very strong wind. However, for the purpose of this research, the focus is on extreme temperatures, whether they are extremely cold or extremely hot temperatures.

Being extreme temperatures the essential environmental characteristic focus of this research, it is mandatory to understand how buildings can deal with these conditions, and how architectural characteristics can influence or define internal comfort temperatures. To address this challenge, two extreme environments are selected, opposites temperature wise. The first is the city of Yakutsk in Russia, with the lowest ever recorded temperature of -64 ºC (Gamble, 2015). Secondly, the city of Needles, in California, United Sates of America, where the highest ever temperature of +52 ºC (WRCC, 2011) was recorded, being also the city with the highest lower recorded temperature ever, +38 ºC (NWS, 2020). It is important to notice that these are not the highest and lowest ever temperatures recorded on Earth, they are, however, the highest and lowest temperatures recorded on permanently inhabited places with climate files that could be accessed through the EnergyPlus webside and, as such, used for energy simulations. For reference, the lowest ever recorded temperature on Earth was in the Vostok Research Station, in Antarctica, with -89.2º degrees Celsius, in 1983 (ARIZONA STATE UNIVERSITY, 2021). The highest ever recorded temperature was in the Death Valley National Park, in the United States, with +56.7 degrees Celsius, in 1913 (Masters, 2021).

Having two very different and extreme climates allows experimentation in order to understand the relationship between the architectural shape/volume, the internal spatial configuration, the materials used, the internal temperature, and the energy needed to keep these buildings comfortable for human life in these environments.

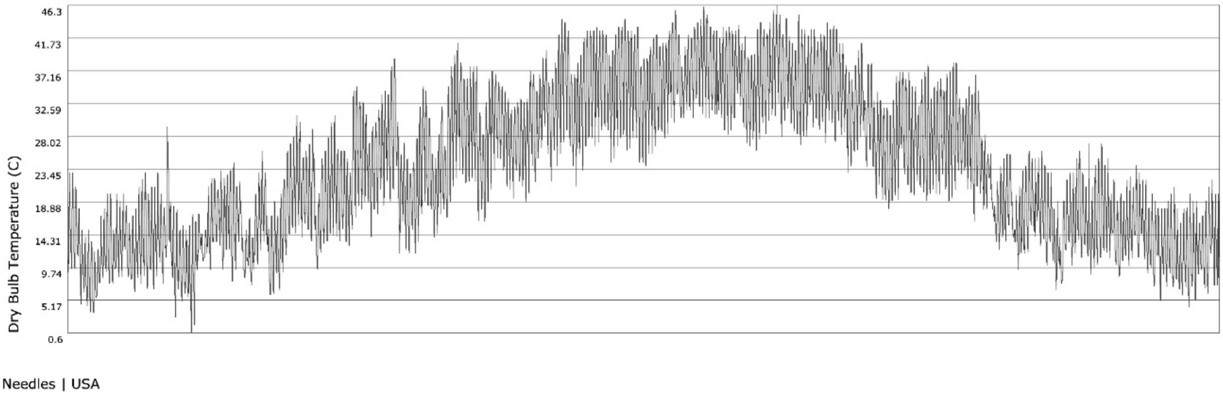


Image 2.2 - Graphic for the average yearly Dry Bulb Temperature, which goes from +0.6 to +46.3 ºC, for the climate of Needles, in the USA, retrieved from the climate file from the EnergyPlus on-line database.

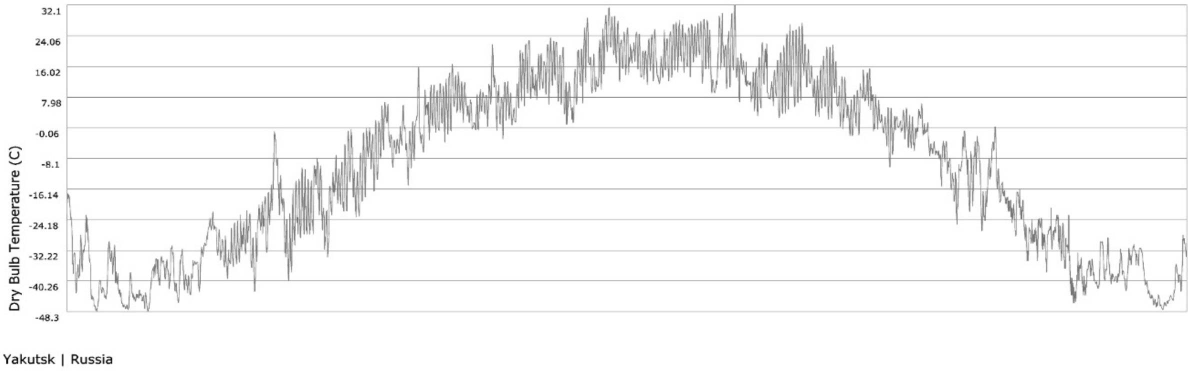


Image 2.3 – Graphic for the average yearly Dry Bulb Temperature, which goes from -48.3 to +32.1 ºC, for the climate of Yakutsk, in Russia, retrieved from the climate file from the EnergyPlus on-line database.

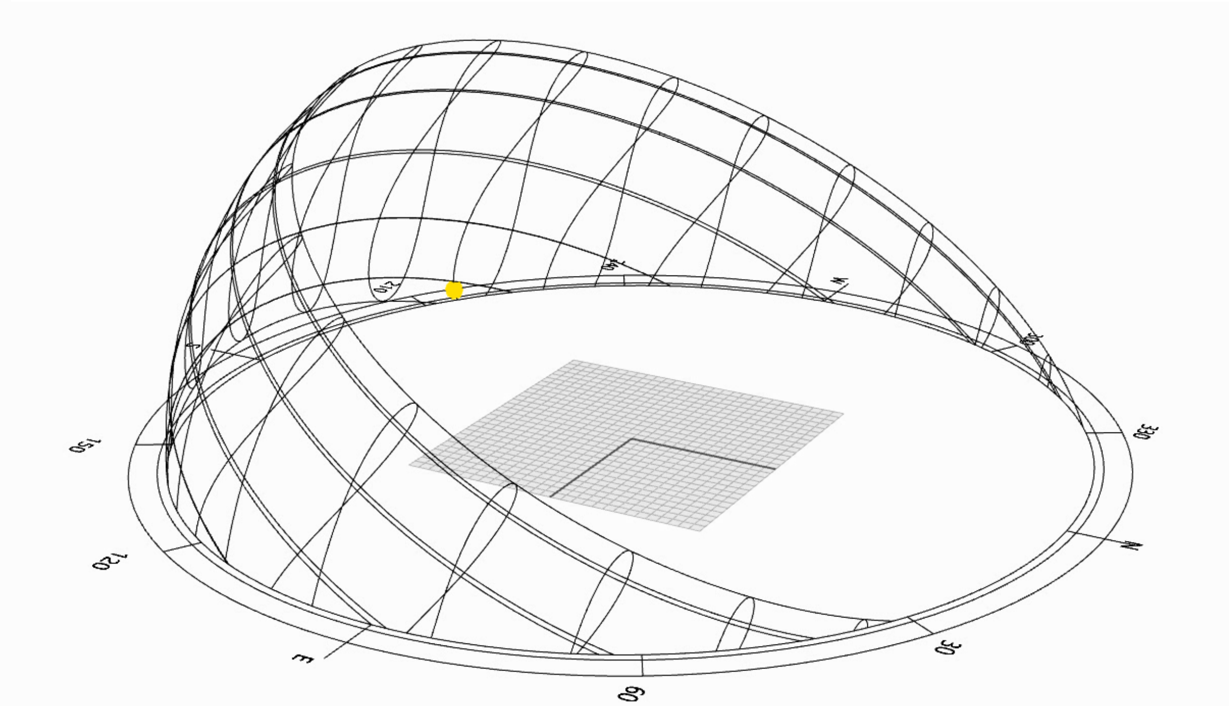


Image 2.4 - Yakutsk’s sun path during the three winter months (December, January and February), the represented sun is the position on January 15th at 3 p.m. Representation by Ladybug in Grasshopper.

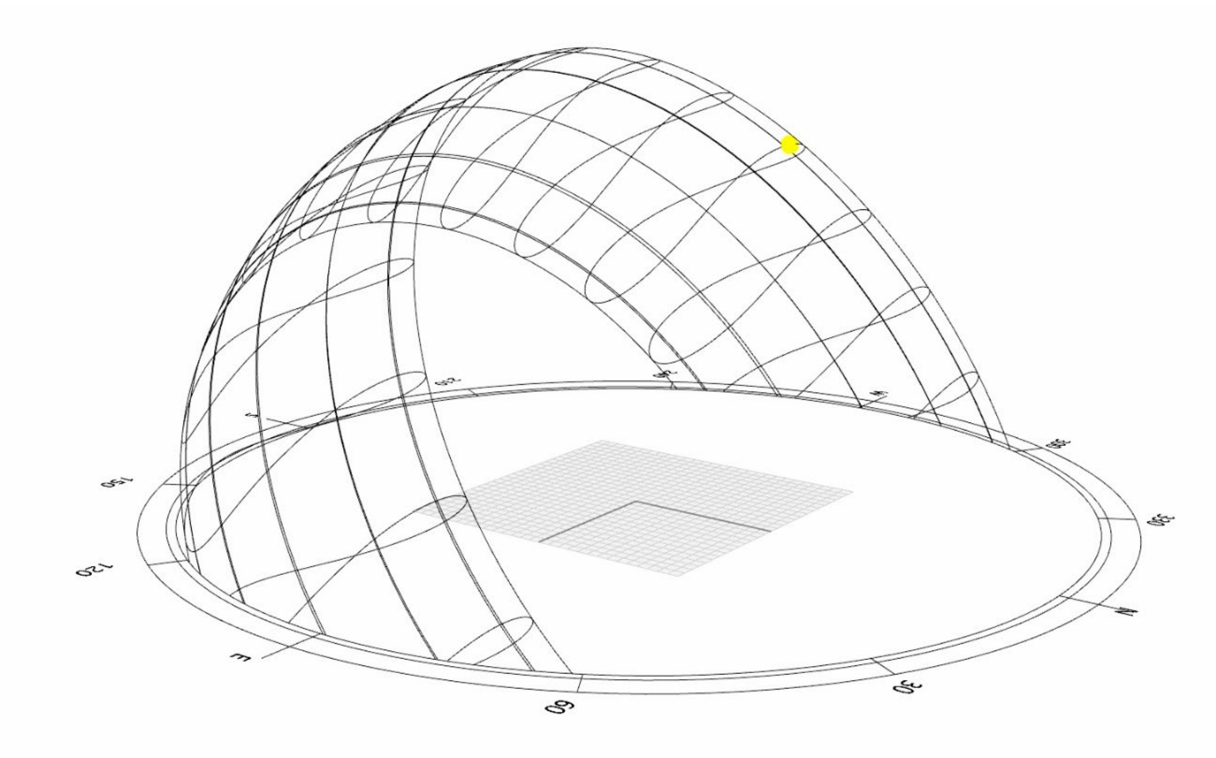


Image 2.5 - Needle's sun path during the three summer months (June, July and August), the represented sun is the position on July 15th at 3 p.m. Representation by Ladybug in Grasshopper.

The first task of the research after defining the specific climates to work with is to understand what the best architectural morphology of buildings in extreme environments would be. In order to comprehend and being able to measure the effectiveness of a determined building shape, in a way that can be analysed later as a valid criterion, form factor calculations are performed. Form factor values represent how compact a building is, and the ideal is that a building is as compact as possible, as it will be more energy efficient leading to less energy use for adequate levels of comfort. Afterwards, considering information gathered for the State of Art, which states that minimal surface areas reduce heath transfer, various types of morphologies (shapes and volumes) are tested, to try to understand which shape would be better in terms of having less heath transfer. This ensures that a building is more effective in places with extreme temperatures, as it would be necessary to keep the building as comfortable as possible, for people inhabiting it, taking into consideration the extreme exterior temperatures. For this stage of the research, the first calculations are made using MS Excel spreadsheets, comparing cubes, prisms, semi-spheres and semi-ellipsoids. Next, digital simulations are performed using 3D modelling software Rhinoceros, together with plug-in Grasshopper, Honeybee and LadyBug, which allow to run energy simulations, making use of the energy simulation engine of EnergyPlus. This allows to understand which type of exterior architectural shape would indeed be preferable, and more effective in terms of energy, for a very cold environment (Yakustsk) or a very hot one (Needles), as simulations are run for both environments. The buildings are 3D modelled in Rhino and then simulated accordingly within the software plug-ins.

The second task of the research is focused on Spatial Configuration, as it is necessary to understand what would be the best spatial distribution for buildings in extreme environments. This is essential as humans can't perform regular activities or depend on the external environment that surrounds them. Based on the previous information presented on Chapter 1, minimal areas are defined through the study of NASA's habitat proposal (NASA Human Research Program, 2015), for six people to inhabit, as well as all the other recommendations regarding space usage, presented in the literature. However, as these are environments located on Earth, it is possible to make certain adjustments to the guidelines from NASA, making it possible to adapt the habitat to different building morphologies. For a question of practicability, a couple of interior configurations are changed, to better accommodate living on earth and the living experience of the people that would use the building. Having the information of which can be best architectural morphology for buildings in extreme environments, it is possible to adapt this base project into floor plans with more layouts (NASA's research considered a rectangle shaped floor plan, solely). It is always necessary that the quality of the habitat's design and interior configuration can be evaluated, based on how it fulfils all the requirements for minimal areas and interior configuration, and turned into valid criteria.

The third task of the research deals with which would be the best possible materials and construction assemblies for buildings in these types of environments. As the main goal of buildings in extreme temperatures climates is to keep a comfortable temperature for its inhabitants, materials are an essential contribution, as they can ensure a lower energy consumption, at the same time that they need to withstand harsh conditions affecting their durabiilty. In Chapter 1, materials used in bio-climatic architecture are referred. Architecture that is adapted to its surrounding climate should use proper, and preferably native, materials, with ecological criteria. The first step in this stage is to create a material library, with various types of materials, in order to access each individual material properties, and understand how a material would fare in such extreme conditions. All the info regarding the materials is retrieved from two main references from the same renowned researcher in order to achieve coherent results and data (Ashby M. , 2013) (Ashby & Johnson, 2014). A first MCDA (Multi-Criteria Decision Analysis) model is created during this task, to validate the use of these materials for these environments, while also being able to input some of the other criteria, which had been already explored.

On the other hand, it is critical to understand how construction assemblies perform in in these extreme climates and what is their contribution for energy efficiency. Therefore, 3D digital simulations are performed using pre-defined default construction assemblies from the EnergyPlus database. These simulations, together with the above-mentioned MCDA models, offer important clues about what is the preferred construction material for extreme environments.

Another material library is created, specifically dedicated to glazing materials, consisting of low-e glass materials for windows, to assess which would be the best window material to use in these types of environments.

Lastly, the last step of this third task is to define an individual, specifically defined construction assembly for these environments, based on all the research experimental simulations done previously. This results in a self-proposed construction assembly. This construction assembly is tested digitally for these climates, as well as the low-e glass materials mentioned earlier, to define the best possible construction material solution for these extreme environments (Yakutsk and Needles). Characteristics of these materials are used as valid criteria input in the next tasks of the research.

The fourth task is focused on conducting the final digital simulations taking into account all the information that was retrieved on the previous tasks. The architecture plans are designed in AutoCAD, then modelled in Rhinoceros 3D. These projects comprise of different types of architectural morphologies, have adequate interior spatial configurations, and are digitally built with the self-proposed construction assembly of materials for extreme environments, that were defined previously. This task is performed in order to test out the final energy simulation criteria, and to be able to achieve consolidated accurate results.

On the fifth and final task, an MCDA (Multi-Criteria Decision Analysis) model, using the software M-MACBETH, is created in order to achieve the major goal of the research, which is to create an assessment methodology to evaluate buildings and architecture projects for extreme environments, based on morphology, spatial configuration and construction materials. To build this model, the conclusions, data and defined criteria of all previous stages are input into the model, as well as all the options relating to all the projects explored on the research. A final set of criteria, based of previous research, is established, and 3D energy simulations are performed accordingly, to achieve the most accurate possible final results. These included the 3D models of the architecture projects, as well as the construction assemblies' materials and simulation inputs regarding usage of space, interior temperature and energy needs. Regarding the inputs for the final MCDA model, the criteria set is divided into three essential themes: "Energy Consumption", "Material Performance" and "Architectural Performance", based on previous research conclusions, resulting in a total of seven final criteria. After the creation of the base model, three variations were implemented, so that different problems can be assessed. For the first model, all criteria has the same relative weight, and no judgments among the levels in each criteria are considered, making it the first basic general model. The second model is focused on the criterion of energy consumption, weighting 50% of the MCDA importance scale, while the other criteria share the same importance (8.33%). This is done to understand which architecture project would be more energy efficient. The third model has as its most important criterion the material weight, which was given a 50% relative weight, while the other criteria were also given the same importance each (8.33%). This allows to comprehend which of the projects fares better if its weight was the essential question, i.e., if ease of transport was a critical limitation factor. Finally, the fourth and last model, is focused on analysing both energy consumption and weight in the same way and, as such, both criteria are given each a 35.3% relative weight, while the rest of criteria are computed with a significance of 5.88%. This is done so that the projects can be analysed in a way that energy needs and construction weight are equally important in the final selection decision. The objective is to evaluate the proposed architecture projects, according to various goals, and understand which projects are more adequate to each climate, for either a very cold or a very hot environment. This allows to create an analysis and find conclusions, on which of the projects is the best solution for a specific environment, or a specific goal within the analysis.

The described methodology allows to achieve the final goal of the research, which is to find an evaluation model to assess what would be the best type of architecture project for extreme environments, and the final results validate both the MCDA models approach, as well as the methodology and investigation process that precedes them. These models can also be adapted and the simulation scripts can be changed in order to accommodate other types of architecture projects, construction assemblies materials, and different evaluation goals.

CHAPTER 3

Morphology

As it was stated previously, designing for extreme environments is a very specific task. This chapter is focused on exterior architecture morphology, as finding out the best relationship between the shape of the buildings envelope and its overall volume and internal functional distribution is an essential part of this research. The objective is to ensure the maximization of energy efficiency while keeping track of other critical requirements, such as strong wind. This chapter presents the various steps that are taken in order to conclude what the best building shape would be, starting from Form Factor calculations, to temperature digital simulations, to proposed project shapes which are then evaluated through the use of a Multi-Criteria Decision Model.

3.1. Form Factor Calculations

In is necessary to comprehend and to be able to measure the effectiveness of a determined building shape, in a way that can be analysed later as a valid criterion, and input into evaluations models. Due to this, in the first part of the research, Form Factor (FF) is used. The shape's form factor represents how compact a building is, and the ideal is that the building is as compact as possible. The literature is clear in that the more compact a building is, the less heat will be transferred to/from the external environment and therefore it will be more energy efficient (Lylykangas, 2009)**Invalid source specified.**. FF can be calculated in two different ways. The first one, is achieved by dividing the shape's surface by the total volume of the building (S/V), while the second one, by diving the shape's surface by the treated floor area of the building (S/A). The second is the main one used in this research, as the treated floor area is relative to the floor area that people use, and that is required to be kept comfortable. In the span of this research two specific studies are conducted dedicated solely to form factor and morphology selection. Their main objective is to determine the building shape with the lowest form factor, and to understand how the morphology affects the internal temperature of a determined building, as well as the energy it is required to keep the volume comfortable, in two different environments with very extreme temperatures, the results of these studies are addressed below, as they are adamant in selecting and analysing the best building morphology, and how this connects later with selecting the final set of criteria, for the final simulations.

3.2. Calculations for Morphology Assessment

In order to study building morphology selection, it is necessary to comprehend the concept of form factor, as stated in Chapter 1, so that better energy efficiency is achieved. We know from the State of Art that minimal surface area reduces heat transfer, while the opposite increases heat transfer. With this information, the first phase of this stage of the research is to test various shapes/volumes. The first attempts are done experimenting with four shapes/volumes: a square prism, a rectangular prism (the length dimension being twice the width dimension), a semi-sphere volume and a semi-ellipsoid volume. All forms vary in size, to comprehend and analyse their form factor variations. For this stage, the floor-to-ceiling value of the square and the rectangular shapes/volumes are kept always at 2.20 m. Regarding the semi-sphere, 2.20 m is the value for half the radius (in the horizontal direction), which means that only 25% of the floor area of the volume has at least the 2.20 m in floor-to-ceiling height; the rest is lower, as the sphere's surface curves. In order to ensure those minimal 25%, the central floor-to-ceiling height is first set at 2.54 m, getting higher every time the sphere's enlarged, as all dimensions augment equally. For the last volume/shape, the semi-ellipsoid, the height of 2.54 m considered for the base semi-sphere is used for the central point in all volume variations, remaining stable throughout. So, for this specific part of the research, only the sphere rises in height (see Image 3.1).

The process starts with the semi-sphere, considering the first height dimension of 2,54 meters at the centre, and then increasing the axis by 10% throughout. In order to be able to compare all the shapes/volumes, all calculations are based on the same variation used for the spehere. While for the sphere the axis variation of 10% causes all the volume to grow larger, so that it remains a sphere, on the other shapes the 10% increment is only done to the base, so that the floor area rises, but not the height, as it is unnecessary. The objective is to compare all different form factors for the exact same floor area available, depending on the exterior shape. The final set of tested shapes/volumes prefaces 13 S/A (envelope surface area divided by treated floor area) form factor values and 13 S/V (surface area divided by volume) form factor values, per shape/volume. This results in a total of 104 form factor values, for 52 different tested shapes/volumes, as each shape/volume has two form factor values. This process is conducted in a simple computational spreadsheet with the use of Microsoft Excel, which can be seen in Anex A.

This experiment is conducted to figure out which shape would be the best for the lowest form factor. Both alternatives to calculate form factor (S/A and S/V) are considered. Regarding the shape/volume with the square floor area, both values of form factor decrease, as it would be expected. The first values (S/A) range between 3.95 to 2.75, while in the other they range from 1.80 to 1.25. For the prismatic floor area, the values range between 4.07 to 2.66, for the

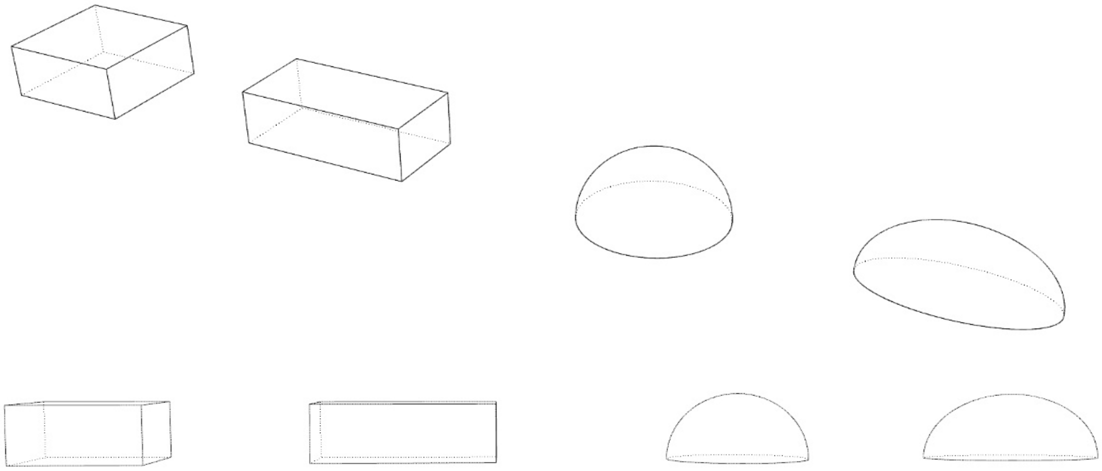


Image 3.1 – 3D views of the basic architectural shapes: a prism with a square floor area, a prism with a rectangular floor area, a semi-sphere and a semi-ellipsoid.

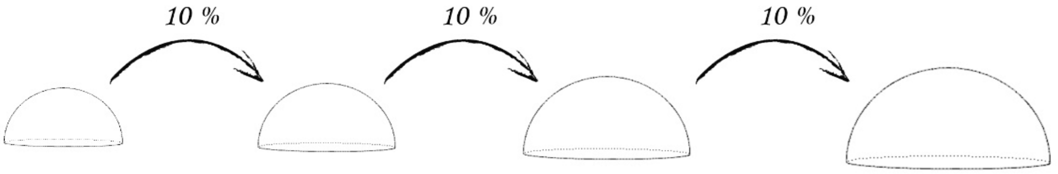


Image 3.2 – Example of the increments of the sphere’s axis, which increases 10% throughout, relative to the previous semi-sphere.

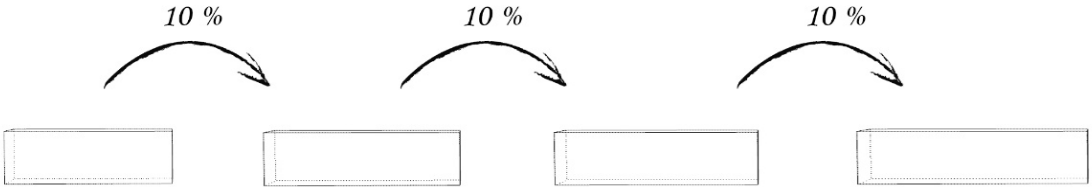


Image 3.3 – Example of the increments of the prism’s base axis, which increase 10% throughout, relative to the previous prism. However, the height is always maintained, the height only varies in the semi-sphere.

first, and 1.85 to 1.21 for the second. For the semi-ellipsoid shape/volume, the values vary from 2.13 to 1.23 for the first, and 1.26 to 0.72 for the second. Finally, in case of the semi-sphere, the first form factor value is always the same, 2, and the values range between 1.18 to 0.38 for the second form factor. These results are better analysed through the graphics shown below, in Image 3.4 and 3.5.

The results show that regardless of which form factor vale is used, they all tend to an asymptotic value, which brings us to the conclusion that passing a certain floor area dimension,

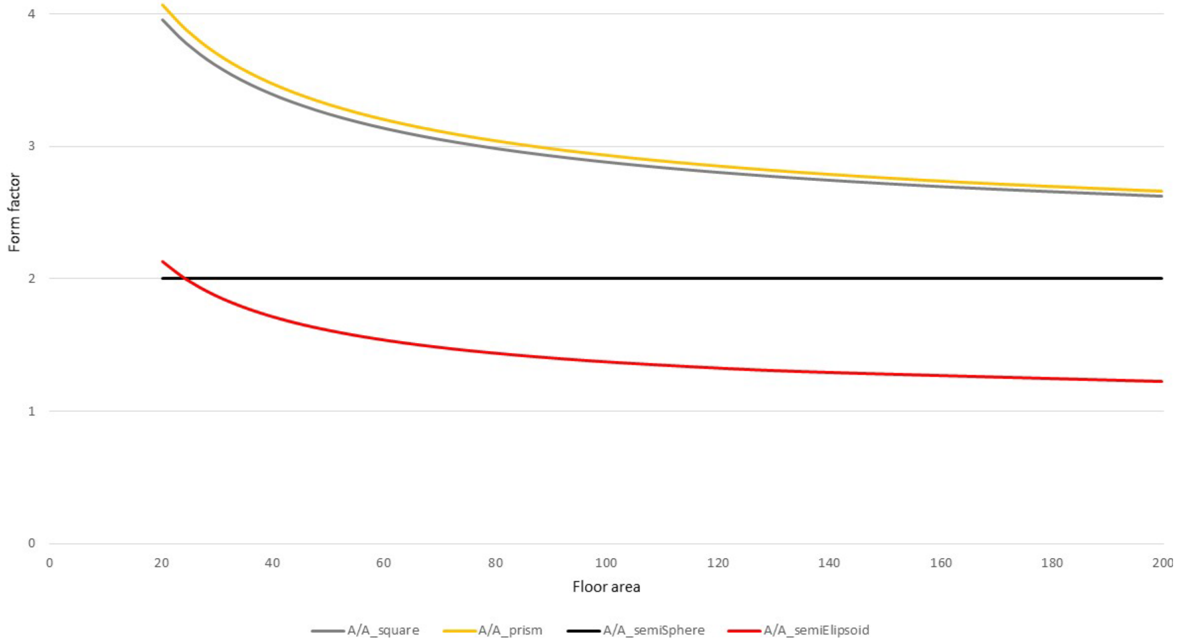


Image 3.4 - Variation of the S/A Form Factor as a function of the floor area *(Domingos & Rato, Optimization of living spaces morphology for extreme climates, 2019).*

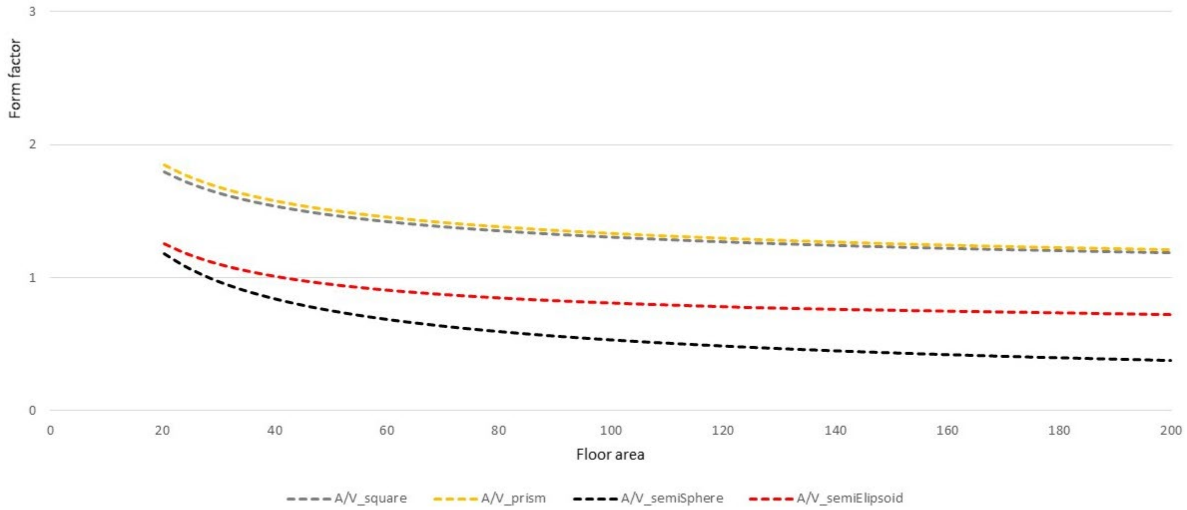


Image 3.5 - Variation of the S/V Form Factor as a function of the floor area *(Domingos & Rato, Optimization of living spaces morphology for extreme climates, 2019).*

its increase does not alter the relationship between the shape's surface area and the treated floor area, or the shape's volume. It is however important to notice that this asymptotic value does not appear on the extent of the floor area values that are considered in this specific experiment.

Other conclusions that are possible to take from this experiment are that, between the square and prismatic floor area shapes/volumes, there are no significant differences, in both Form Factor values, so there does not seem to be a great advantage in picking one or the other, as an optimal form factor building shape. Regarding the semi-sphere, the first form factor value (S/A), is always 2 because the shape's dimension and volume increase in a proportional way, thus provoking no difference in the values. Still, its value is still better than the square and prismatic floor area shapes' values. It has the lowest (S/V) form factor in all cases, but this also brings issues, as the usable floor area is reduced, when compared to the other options, as the sides of the semi-sphere offer little height. Lastly, the semi-ellipsoid presents better values of the S/A form factor, as they are the lowest of all the tested shapes/volumes, except the first shape, where it rates slightly higher (worst) than the semi-sphere, at 2.13. However, on the other variations the semi-ellipsoid rates lower (better) than all.

Through the analyses of the results, it is possible to conclude that the semi-ellipsoid seems to be the best building shape for the lowest possible form factor, amongst the four tested shapes/volume types. This means the semi-ellipsoid seems to be the most effective for lowest energy transfer, as well as available treated floor area. Therefore, this option is later analysed thoroughly, in comparison to the other shapes, through energy simulations.

Although this first experiment offers preliminary results, it allows for further steps to be taken in the scope of this research, to comprehend what would be the best architectural shape for the lowest form factor possible, making it as compact as possible, to reduce energy transfer. This also helps to understand how to bring together the architectural morphology with the minimal areas and spatial configuration principles, which is presented in the next chapter. Having the basis defined of what the best architecture morphology would be, allows to better direct the research, knowing that whatever shapes were experimented, they should be compared with the semi-ellipsoid.

3.3. Prism Simulations to Understand Variations in Temperature due to Architecture Morphology

The second phase of this research task is focused on utilizing computational tools to address what was analysed on the previous experiment, and compare it with actual interior comfort temperatures for specific shapes/volumes, in the chosen extreme environments, indicated previously. Although the semi-ellipsoid did present itself as the best option to make regarding a shape/volume for the lowest form factor, in order to have a comparison base, it is necessary to study the consequences of morphological changes in a prism, in terms of form factor, interior comfort temperatures, and energy use, in what can be considered a simpler shape than a semi-ellipsoid, as it is easier to test, build and replicate a prismatic shape/volume. This allows to effectively compare the influence of form factor in the internal comfort conditions, and how much energy is needed to keep these shapes comfortable, when dealing with extreme temperatures in extreme climates.

The computational tools used for this stage of the research are parametric 3D modelling software Rhinoceros 3D, and plug-in Grasshopper, using LadyBug and HoneyBee in order to connect with the simulation engine of the software EnergyPlus. All these tools have been previously mentioned in the State of Art. It is first necessary to build the 3D models of the various shapes in Rhino, so that they can be imported into Grasshopper, a generative parametric design tool plug-in. After the geometry is imported into Grasshopper, it is necessary to create digital surfaces, on the script, so that they can be read and used by the simulation engine. 3D surfaces existing solely in Rhino do not run in Grasshopper. In order to achieve this, Honeybee, a plug-in that exists within Grasshopper, that communicates with EnergyPlus in order to populate the geometry with materials, schedules, loads, and other necessary information to run a successful simulation (for energy, daylight, temperature and humidity), is also used.

The 3D Rhino surfaces are modelled and imported, then connected to HoneyBee commands, which make the designed building imputable into the essential simulation command node for Energy Simulation, together with the required weather file from EnergyPlus. LadyBug, on the other hand, is the plug-in that is used to download, analyse, and visualize weather data, which is required to run energy and temperature simulations. LadyBug commands are used to retrieve weather files from the EnergyPlus website or from the user’s computer, which is then connected to the essential command node for energy simulation mentioned previously. On the other hand, LadyBug also processes simulation results by creating visual outputs, so that data can be analysed in an easier and faster way. The necessary weather files of Yakutsk and Needles are obtained from the on-line library of the USA Department of Energy, which is run by the software EnergyPlus.

The defined base prism for this experiment is the prism presented below, in Image 3.6, with interior dimensions of 11.80 meters long, 4.80 meters wide and 2.40 m high. It is created following the guidelines from NASA, presented in chapter 1, with minor changes. These changes relate to removing the EVA suits area, as we are dealing with an earthly environment and, as such, areas required for outer space exploration are not necessary. These changes result in a prismatic volume with a total interior area of 56.64 m^2, including divisory walls (being 11.80 m long and 4.80 m wide), divided between Sleeping Quarters (12.50 m^2), Work Area (12.85 m^2), Hygiene Quarters (6.25 m^2) and Social Area (23.52 m^2). The reasons for why the interior spaces are designed and distributed this way will be assessed in the next chapters, regarding Interior Spatial Configuration. Since gravity is also not a concern, opposite to the example presented on the State of Art, having a specific minimal volume is not necessary, as all human activity happens at floor level. Thus, the height of the habitat can be defined at 2.40 meters. This value is chosen as it is the minimal value for residential buildings in Portugal (Ministério Público, 1951), and the minimal value is chosen because, as stated earlier, the building should be as compact as possible, to maximise energy efficiency.

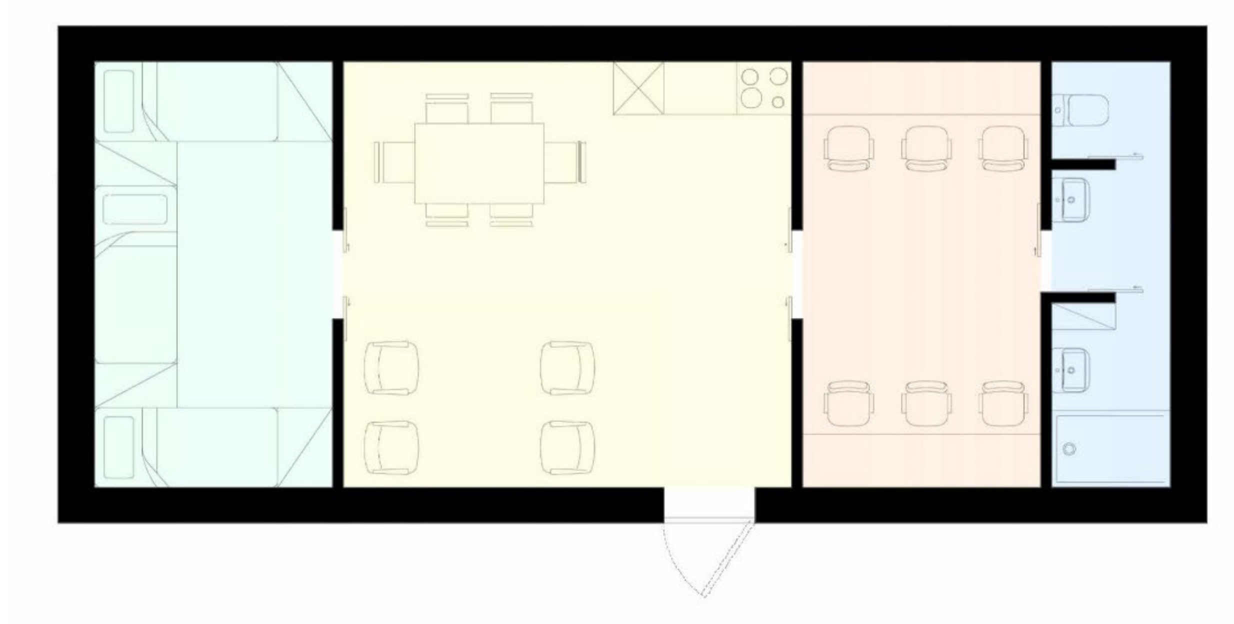


Image 3.6 - Example of a 6-people habitat based on the guidelines from NASA *(NASA Human Research Program, 2015)* divided by spaces: Sleeping Quarters (green), Social Area (yellow), Workspace (orange) and Hygiene Quarters (Blue).

It is important to mention that no openings such as windows or doors are considered for the simulations, because the goal is to comprehend only the influence of the form, and not consider energy transfer through thermal bridges, or different materials. That part of the study is presented further on. To study the shape/volume's form factor influence on the internal thermal comfort among the prisms, sizing variations are also performed. The first group of variations is a scaled augmentation in all the axis of the prism, by one meter. Which results in three prisms with 5.80x12.80x3.40 m, 6.80x13.80x4.40 m and 7.80x14.80x5.40 m. The second group has an augmentation in the height axis, the base axis remaining stable at 11.80 meters and 4.80 meters. This results in other three prisms with 4.80x11.80x3.40 m, 4.80x11.80x4.40 m and 4.80x11.80x5.40 m. Lastly, the third group has an augmentation in both base axis, but the height remaining stable at 2.40 m, resulting in more three prisms of 5.80x12.80x2.40 m, 6.80x13.80x2.40 m and 7.80x14.80x2.40 m. As the compactness of the building changes, the goal of the experiment is to comprehend the influence of the shape's form factor in the energy performance of the tested volumes. To better analyse this data, all the volumes are indicated by numbers, 1 being the base prism, numbers 2 to 4 are the augmentations in all axis, 5 to 7 the height augmentation and lastly, 8 to 10 the base augmentations. All the shapes/volumes are indicated in table 3.

Table 3.1 – Prism variations with dimensions, areas, and volumes.

Prism Variations	**1 (Base)**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Side 1 (m)	4.80	5.80	6.80	7.80	4.80	4.80	4.80	5.80	6.80	7.80
Side 2 (m)	11.80	12.80	13.80	14.80	11.80	11.80	11.80	12.80	13.80	14.80
Height (m)	2.40	3.40	4.40	5.40	3.40	4.40	5.40	2.40	2.40	2.40
Base Area (m^2)	56.64	74.24	93.84	115.44	56.64	56.64	56.64	74.24	93.84	115.44
Volume (m^3)	135.94	252.42	412.90	623.38	192.57	249.22	305.86	178.18	225.22	277.06

For the computational simulations, as it is intended to experiment the shapes/volumes in the most extreme temperatures of the chosen climates above, only specific months of the year are used. For the hot climate, Needles in California, only the summer months are used (between June and August), and for the cold climate, Yakutsk in Russia, only the winter months are used (between December and February). This is defined through the use of a LadyBug analysis component, that allows the user to analyse specific time periods within the year. The user defines from what month, day and hour does the simulation begin, and in which month, day and hour does it end. Also, as explained previously, as only the building morphology is being evaluated, the generic material assemblies from EnergyPlus are used for the building's external envelope. In order to conduct the simulation, it is necessary to devise a visual script in plug-in

Grasshopper, using both HoneyBee and LadyBug. To conduct a proper simulations, it is also necessary to define building loads and schedules. HoneyBee is used to define occupation and schedules, and then communicates with the engine of EnergyPlus. The first component is used to feed the second, an occupation of six people is defined, for the full daily 24 hours, as in such an extreme environment, it is most likely that people remain within the building, during the whole day. Zone Loads are also be defined, which are then connected to the previous command node. LED lights are chosen (to achieve best energy efficiency), with a value of 3 W/m^2 (lightning load per square meter of floor), and a machine quantity equivalent of between a single laptop and a heavily equipped office (the mid-point of the default scale of energy load per square meter of floor, used by the software, 7 W/m^2), this decision is made as the building includes a workspace. It is also necessary to inform the software of the number of people per area, this number is defined by people per square meter. Taking total area into account and the six people that would inhabit it, this results in a value of 0.1059. This specific value is variable depending on the analysed prism, as although the number of people remains the shame throughout (6 people), the floor area is altered, and as such the final value is modified.

Two types of simulations are performed: the first relates to internal free-floating temperature throughout all the prism variations, for both the cold and the hot climates. The second one relates to cooling energy demand (for the hot climate), and to heating energy demand (for the cold climate). The desired interior comfort temperatures are defined through the use of a HoneyBee command, where the user defines heating and cooling setpoints and setbacks, allowing the definition of maximum and minimal comfort temperatures to be considered for the building in study. These comfort temperatures are defined at 26º to 28º degrees Celsius, for the hot climate, and 16º to 18º degrees Celsius for the cold climate. These ranges are defined as they match the limit threshold for comfort interior temperatures (Thomsen, et al., 2014), taking into account these are very extreme climates and require a lot of energy to stay comfort, keeping temperatures at threshold limit seems the most adequate decision.

This information is also input to Grasshopper, LadyBug and HoneyBee to perform the simulations accordingly. For the simple free-floating interior temperature simulation, the node script for comfort is just turned off, so as to not to be considered by the engine, allowing the simulation to obtain temperatures without any interior thermal control.

For this specific experiment, regarding results, some interesting questions come up. Firstly, regarding free-floating internal temperatures, for Needles, the average indoor temperatures vary between 42 and 43.5 degrees Celsius among all the volumes. The lowest temperature belongs to the tallest volume with the constant base (number 7), and the highest temperature to the largest volume and constant height (number 10). For Yakutsk, the average indoor temperatures range between -35.6 and -36 degrees Celsius, among all volumes. Although it is a very low variation, the lowest temperature belongs to the largest volume with the constant height (number 10), and the highest temperature to the highest volume with the constant base (number 7). This showed an opposite tendency to what happens in Needles, which shows the consistency between these two extreme environments, regarding interior free-floating temperature. The relation between the interior free-floating temperature (left axis), and the volume's form factor values (right axis), of all 10 volumes can be observed below (see image 3.7).

Regarding the form factor values of the two mentioned volumes above, number 7 and number 10, they have the limits of the results range of form factor values of the whole sample. Number 7 has a form factor of 4.17 and number 10 of 1.94. These are the highest and the lowest form factor values of the whole sample. This is opposite to what the tendency was expected to be, as previous research states that lower form factors result in more compact buildings, and therefore there is less heat transfer, making the volume more comfortable to people that inhabit it. What is presented however, shows that the more comfortable temperatures, warmer in the cold climate and colder in the hot climate, belong to the volumes with the biggest form factors of all. The possible explanation for this is that a higher form factor (allowing for more heat transfer), causes a building to lose a lot of heat during night-time, which would be possible in Needles, since night-time temperatures lower down to 16 ºC, so there is a very large temperature range. This would result in a colder temperature, which would be more comfortable to inhabit in. Another reason to consider is that smaller roof areas allow for lesser solar gains through that surface, so it would make sense that the highest volume with the smallest floor area would be more comfortable (Mahmoodzadeh & Fatehi, 2018). This question is also confirmed by the fact that the temperature gets lower from volume number 5 to volume number 7, as the building gets higher.

This, however, also causes the form factor to rise, giving it a higher value as well. For the Yakutsk results, no reason is found to explain the tendency verified in a cold climate, being that higher form factors lead to more comfortable interior temperatures (warmer), even though the variations are very small.

When it comes to the second set of simulations, which focusses on energy demands to keep interior comfort temperatures, it is clear that the cold climate requires much more energy to warm up the volumes as opposed to the hot climate. This makes sense as it is necessary to withstand a temperature difference, between the external and the internal environments, of 52 ºC, while this difference amounts to 18 ºC for the hot climate. Regarding the Needles climate results, the highest total energy load for the three tested summer months is 8997.49 kWh. This value is achieved in volume number 4, which is the biggest one of all, augmented in all axes. The volume with the lowest energy load, 4003.45 kWh, is prism number 1, which is the smallest volume of all, the base prism.

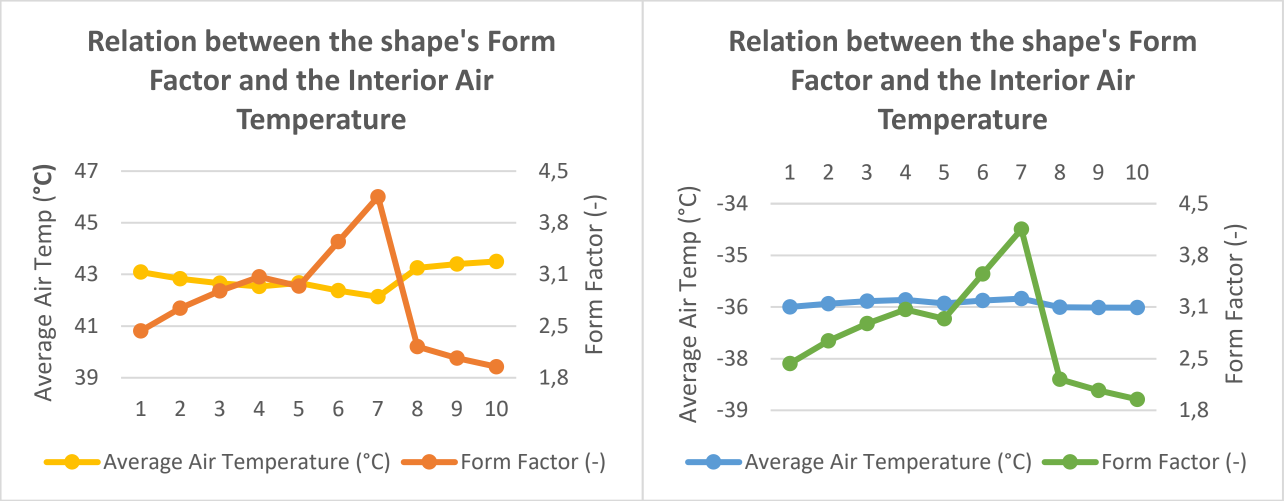


Image 3.7 – Relation between the interior free-floating air temperature and the volume's form factor values in all prisms (1 to 10) in Needles (left) and Yakustsk (right) *(Domingos & Rato, Optimization of living spaces morphology for extreme climates, 2019)*.

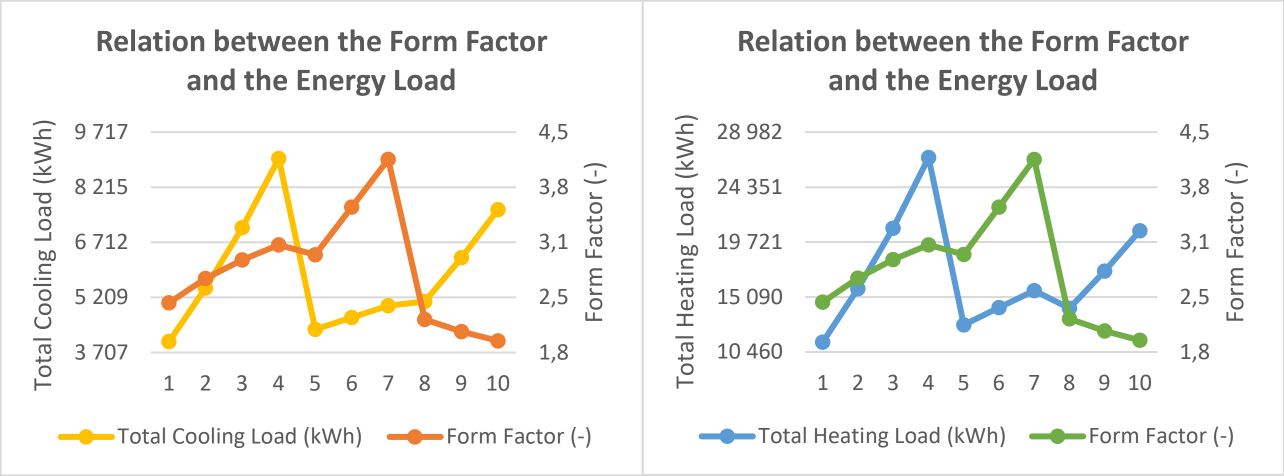


Image 3.8 - Relation between the form factor values and the energy loads in all prisms (1 to 10) in Needles (left) and Yakustsk (right) *(Domingos & Rato, Optimization of living spaces morphology for extreme climates, 2019)*.

For the Yakutsk climate, the volume with the highest energy load is also volume number 4 (the largest one of all), reaching 26834.82 kWh, and the one with the lowest energy load is also volume number 1 (base prism, the smallest of all), at 11296.48 kWh. So, the results for both Needles and Yakutsk, regarding which volumes allow for highest and lowest energy loads, are the same. These two prisms have form factors of 2.40 (number 1) and 3.11 (number 4), which are not in the limits of the form factor values of the whole set of volumes. It seems that these results are not achieved through form factor, but instead through the building/shape volume, as it relates to the total volume of internal air to be brought to comfort temperatures (by heating or cooling). The relation between the various volumes (right axis) and the energy loads (left axis) can be seen in image 3.9.

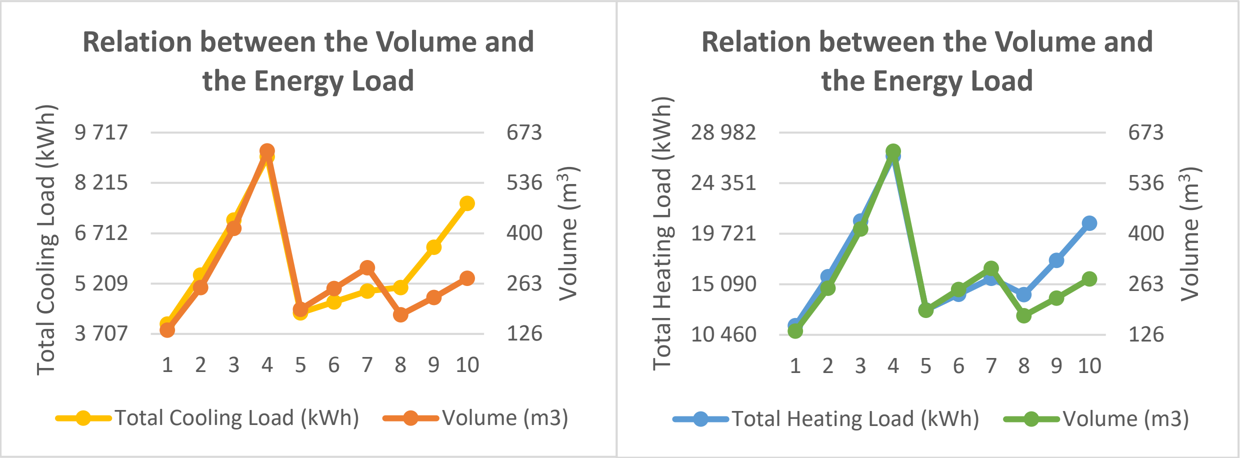


Image 3.9 – Relation between the total energy load and the volumes of all prisms (1 to 10), in Needles (left) and Yakutsk (right) *(Domingos & Rato, Optimization of living spaces morphology for extreme climates, 2019)*.

These results show that when it comes to energy demand in the set of shapes that are tested, it is not form factor that seems to be the determining force defining which shapes have higher or lower energy loads, but the shape's volumes instead. This results in the smaller volume of all (base prism) having the lowest energy loads, and the biggest (number 4) having the highest energy loads, in both Needles and Yakutsk climates. These results supply a first preliminary insight into building behaviour for internal free-floating temperature and energy demands in environments with such extreme conditions, and how their shape, either through form factor values, or volume, influences a building's performance. It is likely that as these environments have such extreme temperatures, the relationships between form factor and heat loss are not as significant as what would be expected in other more mild environments, as the usual relationship between the two does not seem to be according to what would be normally expected. These can be seen in the results presented above regarding free-floating interior temperature. When it comes to energy loads however, even though it seems to relate to volume instead of form factor, buildings in this type of environment do benefit from being as small as possible, as less energy is used in order to make them comfortable enough to be inhabited. There is also the question that it seems that the smaller the roof surface is, the least heat the building accumulates in the hot climate. The relationship between the roof surface and the facade surface also seems to be essential, as a larger roof will absorb more heat than a smaller roof. This is further explored on the tasks ahead. The essential values of Average Interior Free-Floating Temperature, Energy Loads, Volumes, Surface Areas and Form Factor values, obtained from the simulations for all ten prism variations can be found on table 3.2.

Table 3.2 - Relations between Average Interior Free-Floating Temperatures, energy loads, volumes, surface areas and form factor for all 10 prisms and in both environments, Needles and Yakutsk.

Prism Variations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Average Interior Free-Floating Temperature (Needles) (ºC)	43.105	42.84	42.67	42.545	42.68	42.385	42.145	43.27	43.415	43.515
Average Interior Free-Floating Temperature (Yakutsk) (ºC)	-36.245	-36.16	-36.1	-36.06	-36.15	-36.08	-36.03	-36.255	-36.26	-36.265
Energy Load (Needles) (kWh)	4003.45	5465.93	7113.36	8997.49	4334.5	4659.62	4983.5	5093.93	6294.5	7606.02
Energy Load (Yakutsk) (kWh)	11296.48	15780.59	20894.15	26834.82	12747.62	14192.84	15634.3	14148.4	17275.2	20676.99
Volume (m^3)	135.94	252.42	412.90	623.38	192.57	249.22	305.86	178.18	225.22	277.06
Surface Area (m^2)	136.32	200.72	275.12	359.52	169.52	202.72	235.92	163.52	192.72	223.92
Form Factor (A/A)	2.41	2.70	2.93	3.11	2.99	3.58	4.17	2.20	2.05	1.94

These results allow for a preliminary view of the influence of morphology in interior temperatures when working with extreme environments, and also allow for learning and gaining experience with the simulation engine to perform better and more accurate energy simulations. All of the data can be seen in Anex B. One of the challenges encountered was that the EnergyPlus engine does not run curved surfaces, thus, for a while it was impossible to run simulations with a semi-ellipsoid for comparison, as it has been previously concluded that it was the best form possible for these types of environments. This issue is addressed through using Rhinoceros 3D to divide the surface of the semi-ellipsoid in various polygons, so that there are no pure curved surfaces, to then be able to run the energy simulations. These simulations are presented further in the research, as they are used to compare the various proposed morphologies.

3.4. Proposed Morphology Design Solutions

In order to comprehend and assess the various morphology types and their thermal performance, four different architecture morphologies are considered in the scope of this research. This way, it is possible to determine which type of building form is better, depending on the climate it's built on. While the previous sub-chapter focused essentially on only one morphology (the prism), which then suffered variations in terms of axis dimensions and overall floor area and volume, this part of the research presents the possibilities of other types of morphologies, such as semi-circular forms (semi-ellipsoids), and then accesses the possible behaviour of these forms in terms of extreme climates. In terms of this research, morphology is understood as the structural efficiency and the architectural appearance of a building form **Invalid source specified.**. These structural forms start from a geometry-based shape, which in this case is either a rectangle or an ellipse, which forms the basis of the building structure. This shape ends up defining the overall shape of the building and its internal configuration.

The first proposed architecture morphology is the same that has already been studied throughout this research: the prismatic habitat based on the guidelines of NASA (seen image 3.6). It is a prismatic habitat which is 4.8 meters wide and 11.75 meters long. For this research, this volume represents a building which is a low-rise prism. The second morphology, on the other hand, is a prismatic habitat but that is larger in height, making it a high-rise prism. This allows to understand whether a tall prism, or a low-height prism, is more adequate, depending on the weather conditions of temperature. This second prism has a base of 5.8 meters wide and 4.8 meters wide, and 8 meters in height, as opposed to the 2.40 meters high of the low-rise prism. This height allows this prism to have several floors inside, instead of just a ground floor. The spatial organization and space divisions within the volumes are addressed in the following chapter.

The other two proposed architectural morphologies are semi-ellipsoids. Following the same train of thought as the previous examples, a low-rise semi-ellipsoid is proposed, as well as a high-rise semi-ellipsoid. The first semi-ellipsoid uses the area of the first prism as reference. In order to ensure that all areas have the minimal required height, the prism is inserted into the shape of the semi-ellipsoid. This way, the essential area is guaranteed to have the minimal height, and the extra area on the sides can be used for other purposes, such as storage space. The central area also ends up having more height, due to the shape of the semi-ellipsoid. The shape ends up being 11.77 meters long and 9.38 meters wide, with a central point height of 3.04

meters. The last and fourth morphology proposal is a high-rise semi-ellipsoid, which is also designed over the high-rise prism. The difference is, as it doesn’t need to ensure a minimal height for the essential area, because it’s divided into various floors, and already ensures that minimal area, it’s no longer necessary for the high-rise semi-ellipsoid morphology to be matched by inserting the full size of the high-rise prism. However, its shape ensures that it maintains the high prism’s floor area in its base, for the same reason as the previous prism, ensuring the necessary area has the minimal height at the first level. Due to this, the high-rise semi-ellipsoid has the same height as the prism, 8 meters, and its base is 8.70 meters long and 6.54 meters wide. The representation of these changes and morphology shapes can be seen in the following Images. The blue line drawn over the prisms represents the semi-ellipsoids shapes.

After defining the four proposed examples of architecture morphology, it is necessary to digitally simulate them, in order to obtain more accurate specific results, instead of using solely computacional spreadsheet-based calculations, or only simulating prismatic shapes. For the digital simulations ran in Grasshopper, all the shapes are designed in Rhinoceros 3D and then imported into Grasshopper. In the beginning of the research, simulating semi-ellipsoid volumes was challenging. This was due to the fact that the EnergyPlus engine, which Grasshopper uses to do the energy simulations, doesn’t run curved surfaces, it isn’t programmed with that purpose. This ended up being a handicap of the software. To solve this question, it is necessary to transform the shape’s 3D surface into a geometrical mesh, which is then reformed into a surface build out of very small planar surfaces. This allowed the 3D volume to keep its initial curved shape, but being now divided into small planar surfaces, the EnergyPlus engine can already work with it, and thus being able to perform the required energy simulations.

In order to run adequate simulations for accurate results, it is necessary to input into Grasshopper a series of energy loads and, also, construction materials. As this will be approached in a following chapter in more detail, this chapter is focused solely on the preliminary results obtained related to morphology.

It is important to note that the floor surfaces of all models are considered to be adiabatic, due to this, energy transfer through the floor is not considered, as it can provide less accurate results, because this energy transfer is dependable on the type of material that the building is set on, natural ground material, and one of the purposes of this study is to comprehend the impact of the buildings morphology and construction material. Turning the floors into adiabatic allows for a research more focused on the two questions mentioned earlier.

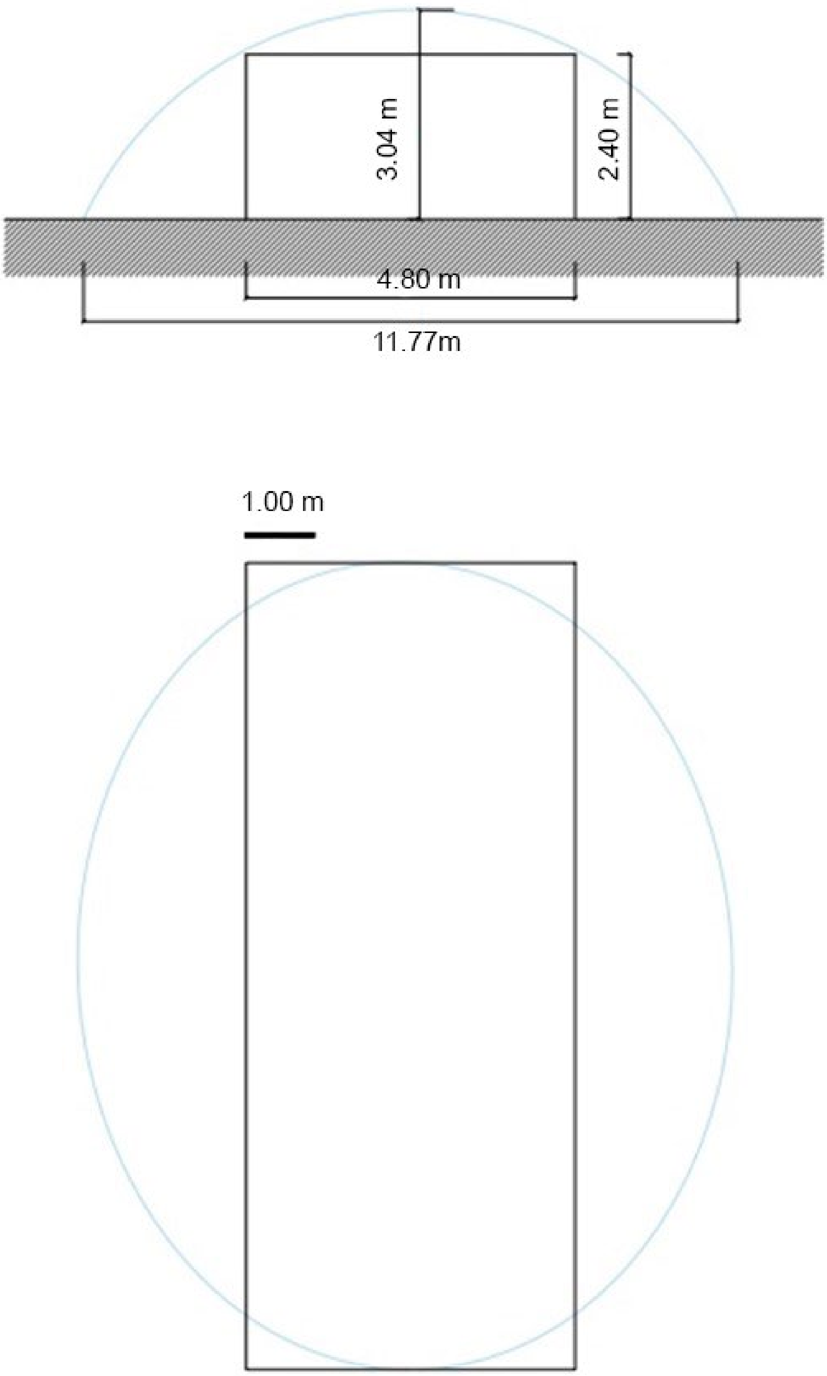


Image 3.10 – Outline of the semi-ellipsoid’s shape over the outline of the prismatic habitat. Ensuring that the whole prismatic volume (except edges) fit into the semi-ellipsoid’s shape allows to keep the essential usable area.

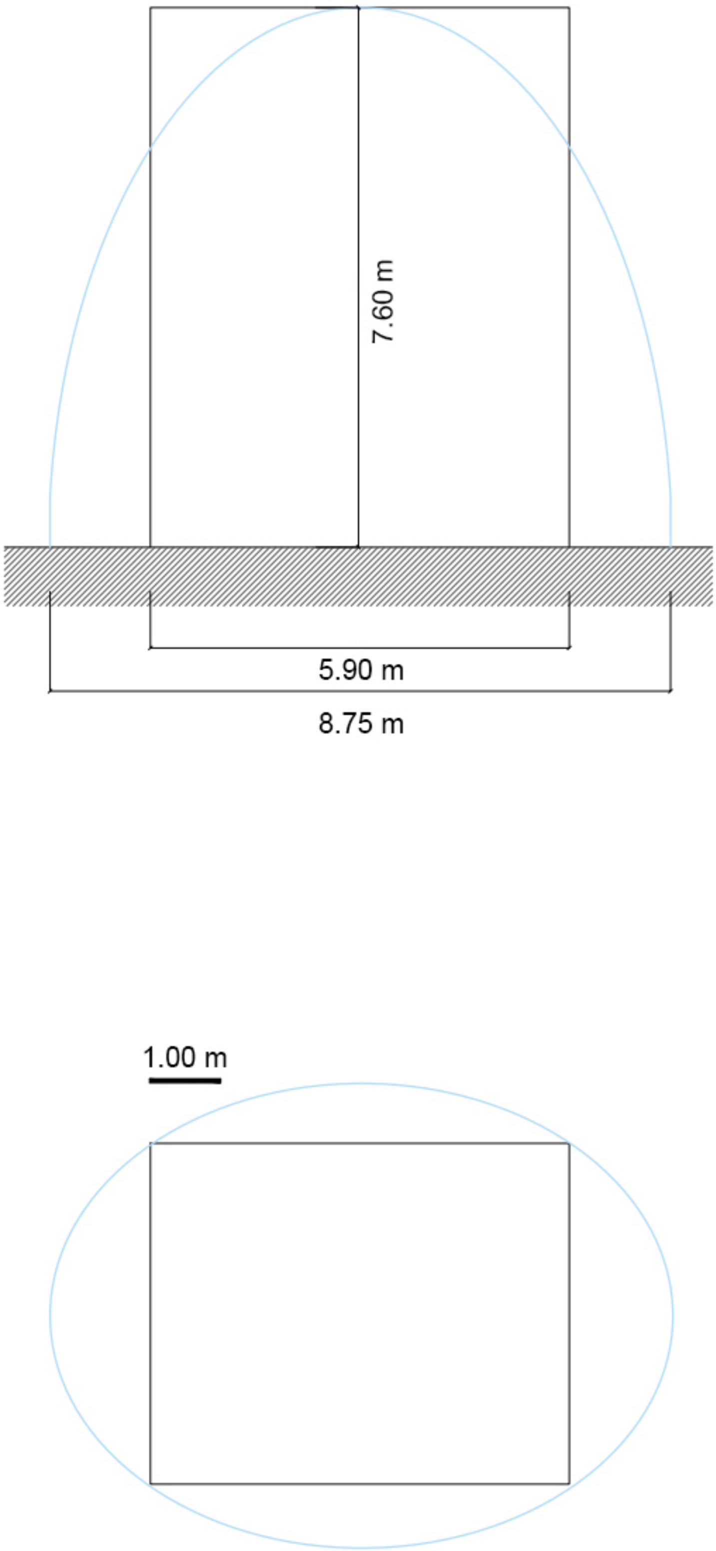


Image 3.11 - Outline of the high semi-ellipsoid’s shape over the outline of the high prism habitat. Ensuring that the main prismatic volume (except edges in height) fit into the semi-ellipsoid’s shape, as the base grows in area, this allows to keep the essential necessary usable floor area.

The parameters of these simulations are explained further in the "Material Selection" chapter, but, the preliminary conclusions that are possible to retrieve from this part of the study was that for Yakutsk, the very cold climate, both the low-rise semi-ellipsoid, and the low-rise prism, present better values in terms of energy, as they require less daily energy to keep warm, within previously defined comfort temperatures. However, if daily energy demand per unit floor surface area is considered, the volume that requires less energy is the high-rise ellipsoid, and the low-rise ellipsoid. For the very hot climate, Needles, if energy per day is considered, the best volumes are the low-rise prism and the high-rise prism, the low-rise ellipsoid rating the worst, with a very large difference from the others. If daily energy demand per unit floor surface area is considered, the volume that rates the best is the high-rise prism, and the high-rise ellipsoid, this is coherent as they have more area. The results regarding energy demand for this simulation can be seen in table 5. All the parameters of this simulation are explained in the next chapter regarding material selection. These results allow to comprehend that, for a very cold climate, the best options morphology wise seem to be a high-rise ellipsoid, as it requires the least amount of energy to be kept comfortable, both in terms of absolute daily energy demand and in daily energy demand per unit floor surface area. The low-rise semi-ellipsoid also seems to be a good option, as it rates best in energy needs per day per area, or a low-rise prism, rating better in energy needs per day, but rating the worst in energy needs per day per area. When it comes to the very hot climate, the best architecture morphology seems to be either the low-rise prism, rating better in energy needs per day, followed by the high-rise prism, and next by the high-rise semi-ellipsoid, which has the best rating in energy needs per day per area.

Table 3.3 - Inserted values of each proposed architecture project on each criterion for the MCDA model, quantitative and qualitative, for the environment of Yakutsk and Needles.

Projects (Yakutsk)	Energy (KWh/day)	Energy In (KWh/day/m^2)	**Projects (Needles)**	Energy (KWh/day)	Energy In (KWh/day/m^2)
Low-rise Prism	53.18	0.939		20.27	0.358
High-rise Prism	59.70	0.703		20.33	0.239
Low-rise Ellipsoid	53.51	0.623		41.31	0.481
High-rise Ellipsoid	53.09	0.526		27.95	0.277

This seems to show that the semi-ellipsoid shapes are better for very cold climates, and the prisms are better for very hot climates. The reasons for this are discussed further in the research, when the nuances of the simulations are explained further on.

CHAPTER 4

Spatial Configuration Design Principles

4.1. Minimal Areas & Organization Proposals

Based on the previous information presented on the State of Art, minimal areas are defined through the study of NASA's habitat proposal, for six people to inhabit, as well as all the other recommendations regarding space usage, presented in the literature. However, considering this first proposed habitat, some changes are possible if an earthen environment is considered, instead of an outer space one. Spaces such as an EVA suits storage room become useless, thus making it possible to remove it from the list of required spaces. This change results in a building with minimal areas divided as follows: social area (23.52 m^2), work area (12.48 m^2), hygiene quarters (6.24 m^2) and sleeping quarters (12.48 m^2), this volume has a minimal internal floor area of 54.72 m^2. These are the minimal values proposed by NASA, so all proposed habitats should at least ensure these indoor areas, as well as the total interior floor area. For a question of practicability, a couple of interior organizations are also changed, to better accommodate living on earth, and the living experience of the people that can use the building. This organization is according to the first morphology examples proposed previously, the low-rise prism, where there is only one ground floor.

These are changes such as the division of the hygiene quarters into two parts, so that one person could shower, while another uses the toilet, making the hygiene quarters more flexible. Also, due to the fact that there is no lack of gravity, as there would probably be in other planets and definitely in outer space, volume is not an issue, as it is only possible to utilize floor area to move around. Ceiling height is therefore defined by the minimum height allowed in Portugal for living spaces in residential buildings (Ministério Público, 1951), 2.40 m. Regarding organization, and following the recommendations defined in the literature, the social area is placed in the middle of the volume, the sleeping quarters are on the opposite side of the workspace and the hygiene quarters, due to noise reduction. The example of a habitat with these areas and organization was demonstrated previously, in Image 3.6., in chapter 4.

The same guidelines are then applied to the other proposed morphology examples. The general principles are: the main, largest area should be the social area, and preferably it should be placed in the centre of the building/project. The area for sleeping should either be a more private area, or one should be able to close this space-off, so that the inhabitant is allowed more privacy. The work and hygiene quarters should be farther away from the sleeping areas so that noise is not an issue, if an inhabitant is in her/his resting period. This low-rise prism, which the floor plan was presented previously, resulted in an architecture project as follows.

Image 4.1 - Floor plan and elevations of the prismatic proposal of a habitat for extreme environments, using a wood derivate material such as OSB panels for the walls.

Windows are located in the volume following directions from literature, presented previously in Chapter 1. Larger windows are located in the social area, and in the work area, as views of the outdoors are important for the inhabitant's well-being, as well as having daylight and well-lit spaces, particularly where they work or engage in social activities. Smaller windows are located next to each bed in the sleeping quarter, so that every inhabitant has its own window and can observe the outside environment, without having too much glass surface, which leads to higher heath transfer, thus making the building less energy efficient.

The second proposed architecture morphology form, the high-rise prism, is designed in order to experiment and comprehend the behaviour of a higher prism with a smaller base. Having another type of prism allows to observe the performance differences between the two and understanding how much of an impact more height has simulation wise, and if it could even be more beneficial, for one of the studied environments. In order to create this prism, it's base is designed by dividing the floor area of the original prism into half, thus turning the ground floor into the social area, ensuring that the access to the building is done through this area, similarly to the low-rise prism, where the entrance is directly to the social area. This also ensured that the noisiest division remains in the lower floor. With this design, the social area ends up having 23.40 m^2, having the largest social area of the two prisms. The access to the next floor is made through the stairs located in the left side of the room, which are accessible directly from the entrance of the building. The second floor is comprised of the workspace, which has 14.20 m^2, and the hygiene quarters, which have 6.25 m^2 and are divided into two rooms, as it was done in the previous project. One division has a shower and a cabinet, and the other has a toilet and a cabinet. The access to the third floor is made through stairs equal to the ground floor. The last floor is comprised of the sleeping quarters, the beds were planned as bunk beds, as they were in the first prism, to allow for more room within the sleeping quarters. However, this disposition allows for more area within the quarters, which can be used as a storage space, or even as an entertainment area, making it a changeable and adaptable space. This results in the sleeping quarters having a total area of 19.77 m^2, about 5 m^2 larger than the low-rise prism. There is also some remaining area in correspondence to the stairs, in the second and third floors, which are turned into storage spaces.

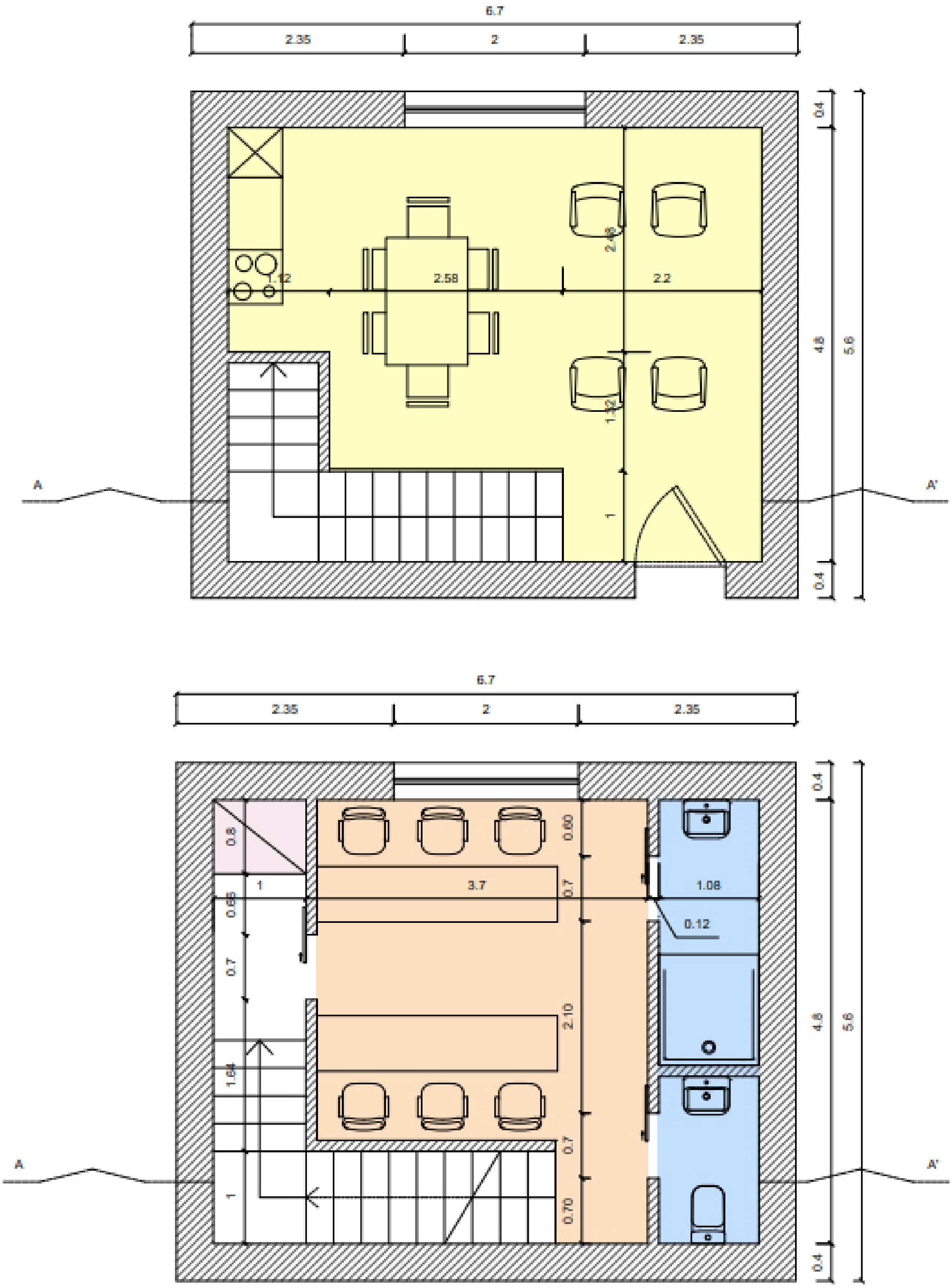


Image 4.2 - Floor plan of the first and second floors of the third exploratory architecture project, a high prism divided into three floors, with the definition of the different areas, social area in yellow (first floor), workspace, in orange, and hygiene quarters, in blue, (second floor) sleeping quarters in green (third floor), and storage space (in pink).

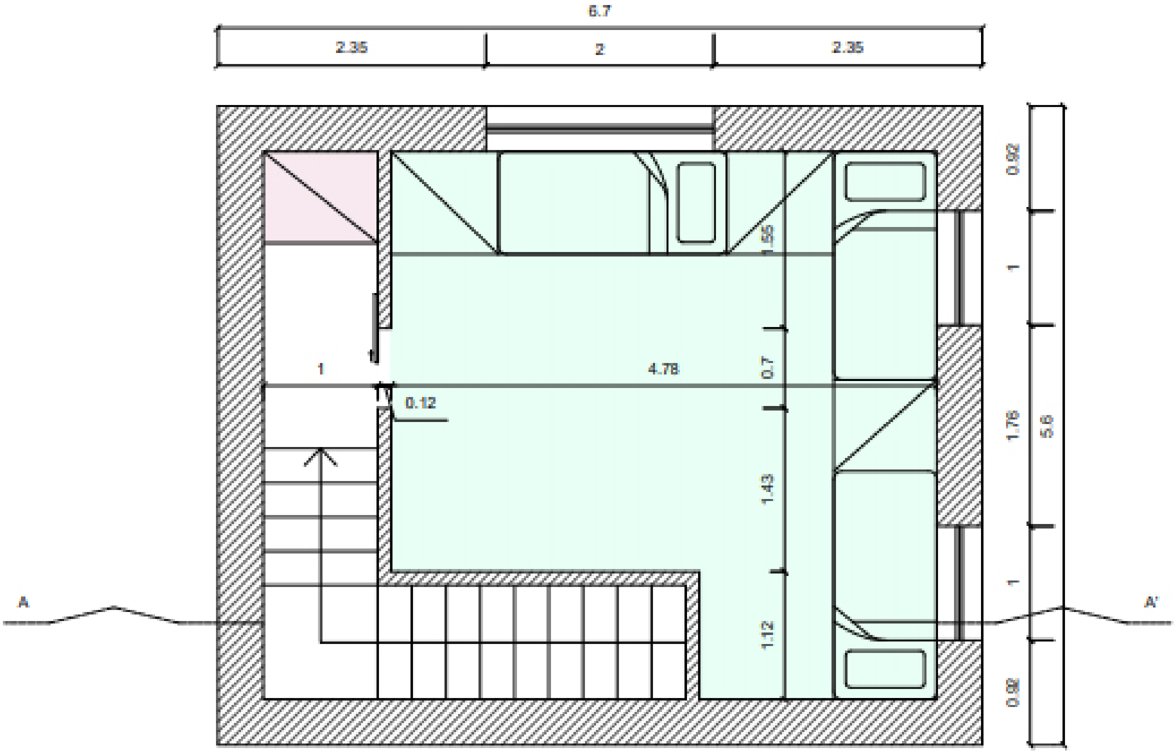


Image 4.3 - Floor plan of the third floor of the third exploratory architecture project, a high prism divided into three floors, with the definition of the different areas, sleeping quarters in green (third floor), and storage space (in pink).

These storage spaces can also be used to instal required machinery to keep the building comfortable. Although natural ventilation could be ensured for air renovation, that is never considered for these projects, due to the fact that the outside temperatures are just too dangerous to humans. Allowing air from the outside to enter the building, without being climatized, would create large temperature differences between the temperature the air is outside, and the comfortable interior temperature the building needs to be. Due to this, a large amount of energy would be necessary just to compensate that temperature difference, making the building much less energy efficient. Such climatization requirements require specific systems which must be installed in these buildings. This high prism allows for more area than the minimal recommended by NASA, which the first prism follows, thus also allowing for more flexibility for the installation of these systems, as there is more space to spare, than just the minimal required for people to inhabit.

This makes the buildings inherently more comfortable, by allowing that flexibility. Regarding the windows for this project, the same guidelines used for the first prism were followed, one large window for the social area, one large window for the workspace, and six smaller windows, one located over each bed, so that the inhabitants can be resting and enjoying the outdoor view. As this proved to be important to people's well-being (please, refer to chapter 1). The floor plans of this project can be seen in Image 4.2, 4.3, 4.4 and a section in Image 4.5.

The interior spatial organization of the proposed projects changes when it comes to the third proposed architecture morphology for this research, which would be a low-rise semi-ellipsoid, as it has a very specific shape. This shape allows for extra area for storage spaces, as the semi-ellipsoids line extend over the prism's shape, as shown previously on Image 45, in Chapter 3. The building envelope of the semi-ellipsoid, having a much lower height than the rest, makes it impossible to make them into living spaces, however, a storage space is created along the outline of the whole semi-ellipsoid.

On the left side of the habitat, sleeping quarters are created following a half-moon shape; there would be a division between the beds and the social space, through a panel which can be closed and opened, according to the level of privacy desired by each user. Should they want to be in their beds but engaged into the activities of the social area, it would be possible.

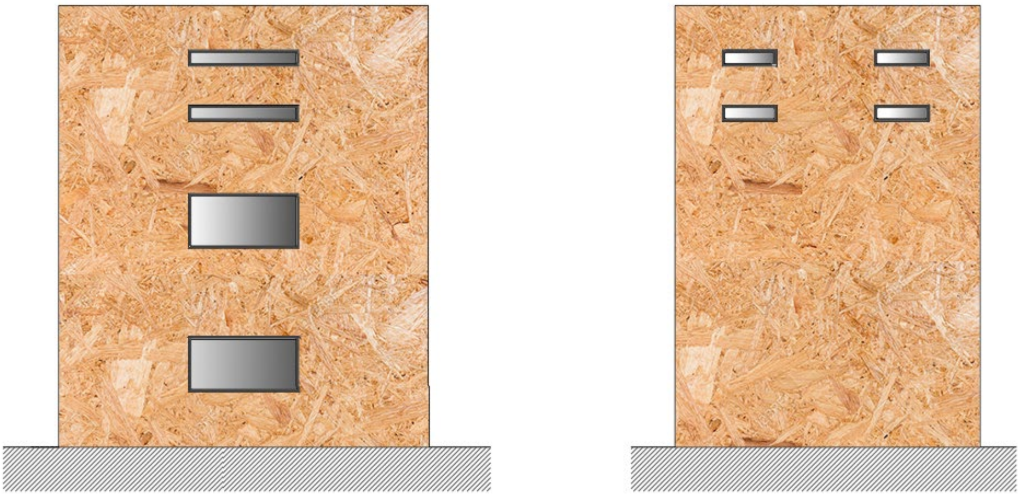


Image 4.4 - Side views of the high prism proposed project, from the right side and the back, where the windows can be seen. In the back the windows of the social area, workspace and sleeping quarters can be seen, and from the right-side view, only the windows for the individual beds can be seen, on the third floor.

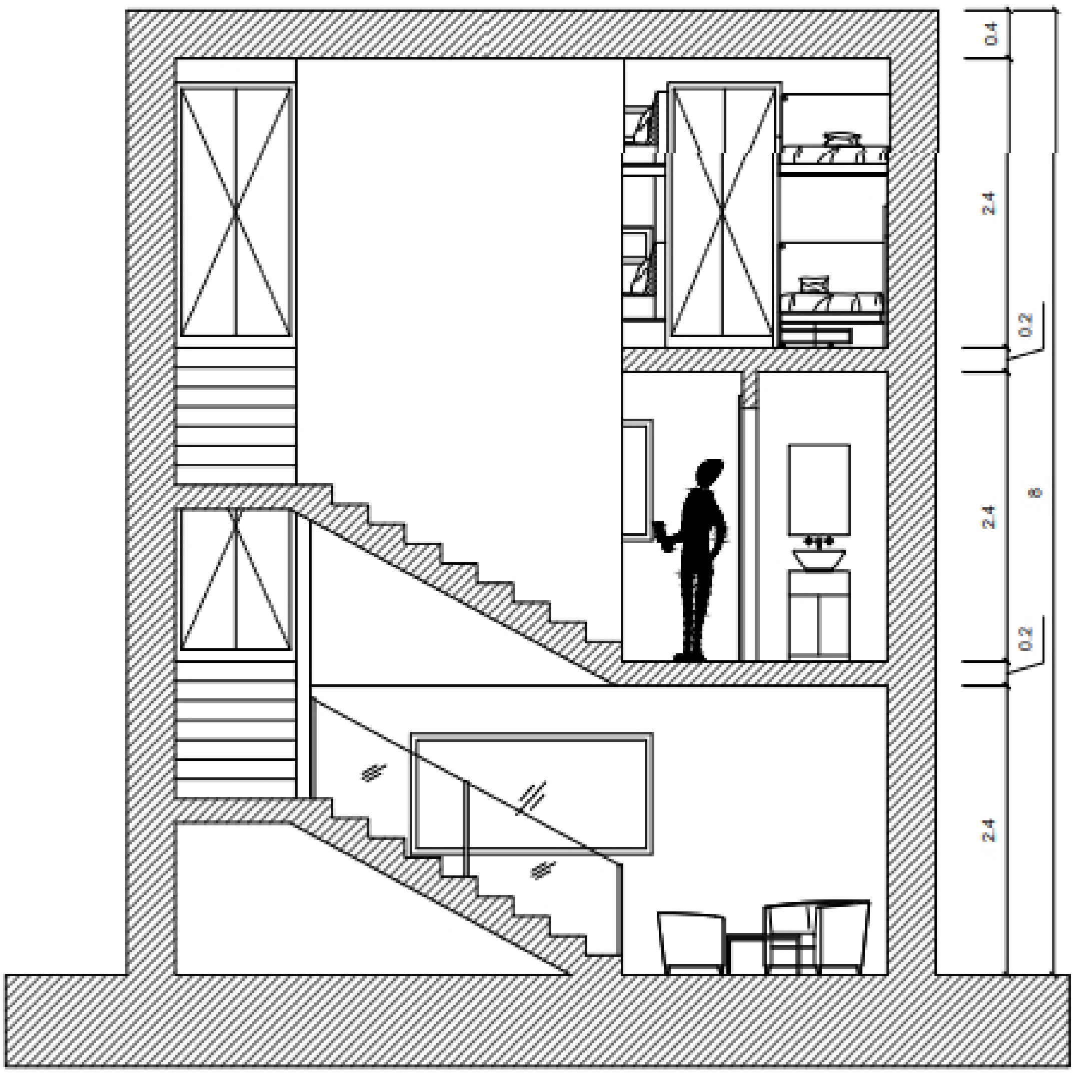


Image 4.5 - Section AA’ of the high prism proposed project volume, in the section it’s possible to see the social area (first floor), the stairs, a part of the workspace, the hygiene quarters (second floor), and the sleeping quarters (third floor), as well as storage cabinets in the stairs access area and the sleeping quarters.

If not, the panel could be closed for more privacy and rest. The social area occupies the centre of the project, where it is also the main entrance to the building, with a little corridor, similar to the corridor created in igloos, to separate the immediate outdoor environment with the interior. The workspace is also accessible through the social area and has the largest storage area of all the divisions, as digital and work equipment may occupy a large amount of space.

Lastly, the hygiene quarters are on the opposite side of the building’s sleeping area, and are divided into two rooms, similarly to the prism: a room with a shower and cabinet and another with a toilet, a cabinet, and a storage space. The other room also has space for the storage space to be added if desired. With this distribution, the sleeping quarters have a total of 15.60 m^2, the social area 19.45 m^2, the workspace 12.85 m^2, and the hygiene quarters 10.25 m^2. All the proposed areas are larger than the minimal areas presented on the low-rise prism because the morphology of the building allows for it, it also allows for a large and specific area for storage space.

Due to its shape, the window's distribution is different than the prism's. Because there are storage spaces at a lower height, a single sleek window goes all the way from one point of the habitat to the other (stopping at the hygiene quarters), allowing for light to get in, and for the inhabitants to look outside, but at a higher height than would normally be considered for a regular window. In order to look through this window, a person has to be standing up. This allows for the storage spaces to always stay below window-height, as well as providing almost all the spaces of the building with an outdoor view. The drawings for this proposed habitat can be seen in images 4.6 to 4.8.

Lastly, the fourth proposed architecture morphology shape is a high-rise semi-ellipsoid. It is designed the same way the first semi-ellipsoid is, by ensuring that the floor area of the corresponding prism fitts within the dimension of the ellipse, and also that a height of 2.4 meters could be assured for the floor area where main functions are located. As it is a semi-ellipsoid, more floor area is achieved, while allowing for more space with the necessary height, as opposed to the first semi-ellipsoid. This question ensures that the necessary area for people inhabiting the building is guaranteed by the first two floors, instead of three, as the high-rise prism does. Due to this, this semi-ellipsoid is able to have the same height as the prism, instead of it having to be slightly higher, and the third floor, as it is very small, can serve as an extra space, for various uses (this can be seen in images 55 to 59).

Regarding the project itself, similarly to the previous presented projects, the entrance is done through the social area, the kitchen/cooking zone is located to the left and the social zone to the right. This is also where it is possible to access the spiral staircase that leads to the next floors, which is located in the middle of the building. Next to the social area is located the workspace, which is a separate room, accessible through double doors. As the windows of this project are located just on one of the sides of the building, and are prolonged to the next floors, both the social and work areas have access to daylight and an outside view. The sleeping quarters are located on the second floor, in similar arrangement as the previous semi-ellipsoid: the beds snug to the walls of the building, in this case with 3 bunk beds, with the same panels for privacy that are devised for the previous semi-ellipsoid.

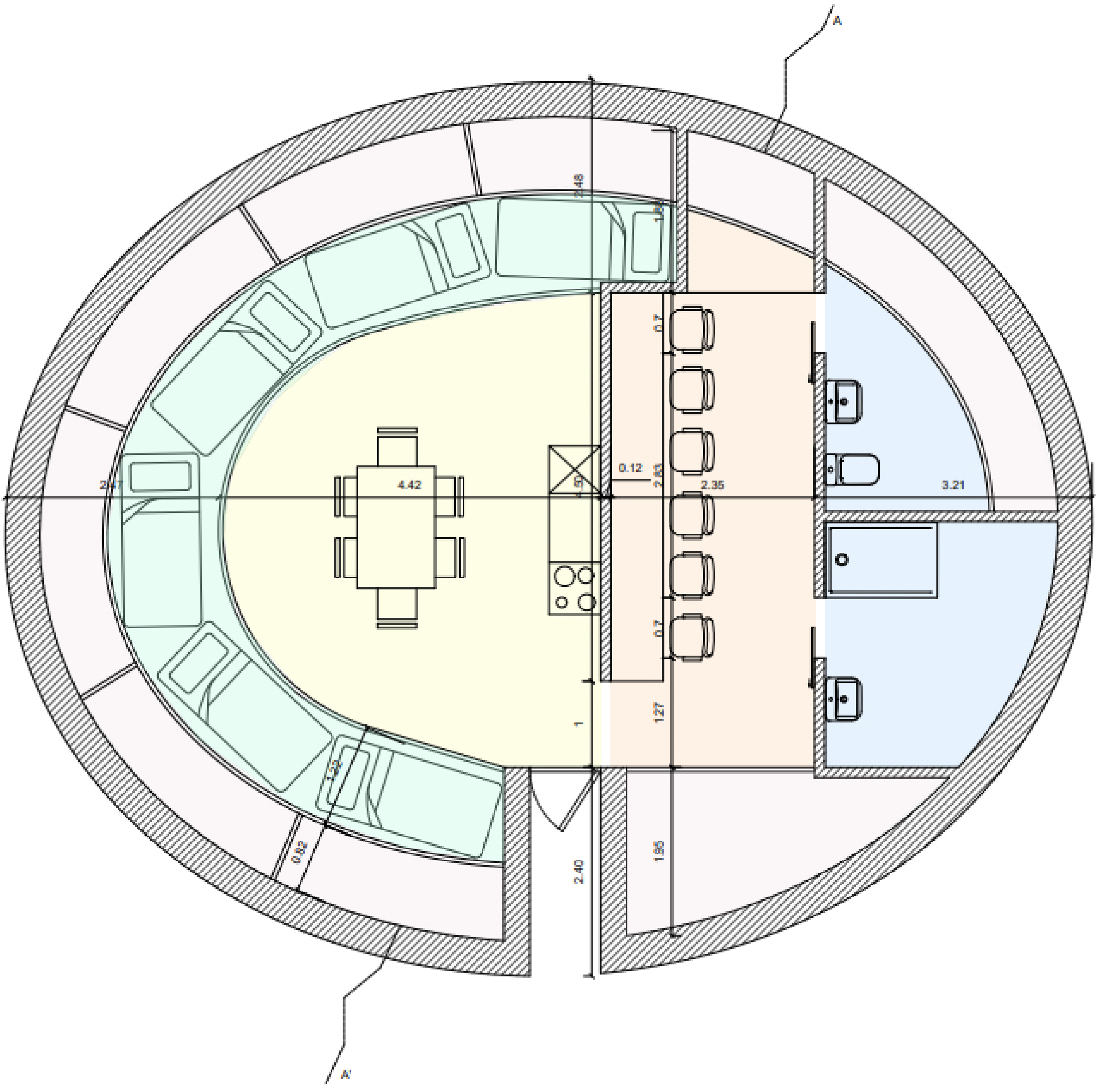


Image 4.6 - Floor plan of the semi-ellipsoid project proposal, with the definition of the various areas: sleeping quarters (green), social area (yellow), workspace (orange), hygiene quarters (blue) and extra storage space (pink).

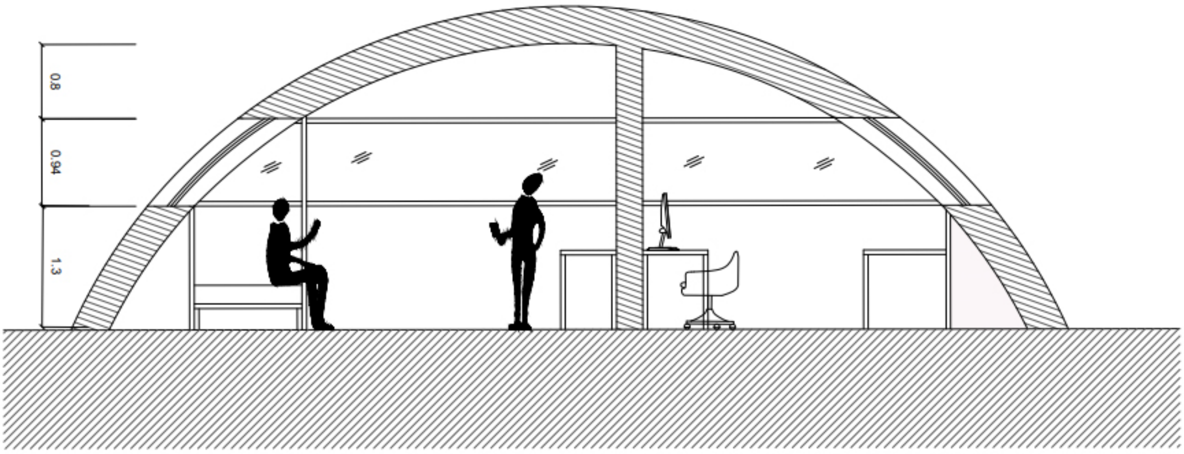


Image 4.7 - Section AA’ of the semi-ellipsoid project. On the section it is possible to see the low in height storage areas just below the window surface, as well as the sleeping area (where the division panels to the social area can be closed and opened), the social area, and the workspace.

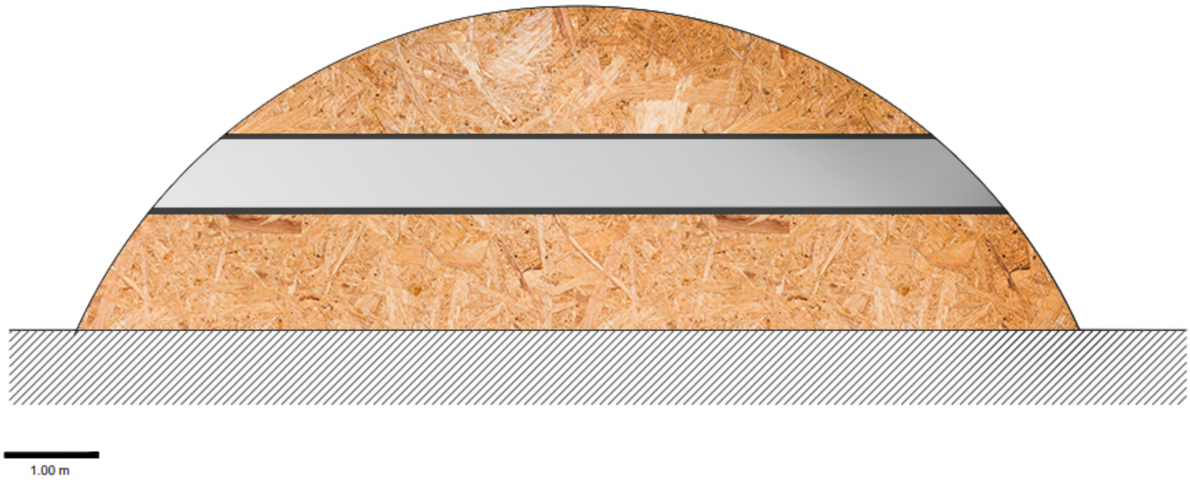


Image 4.8 - Section AA’ and side view of the semi-ellipsoid project. On the section it is possible to see the low in height storage areas just below the window surface, as well as the sleeping area (where the division panels to the social area can be closed and opened), the social area, and the workspace.

The staircase is once again directly accessible in the middle of the room where it rises another floor. By walking to the other end of the floor, the inhabitants can access the hygiene quarters, which are divided into three zones: the entry zone that also has a cabinet, a division with the toilet, and another one with a cabinet and a shower, similarly as the previous projects. The window allows the entrance of daylight on the right side of the room, while the same space on the left side, as it has no window, is perceived as a storage area. The last floor, as it has very a small area where the 2.40 meters height is guaranteed, is devised as a flexible zone, it can either be a storage room, or a small place to relax or even work. As the window rises in height, it diminishes in width. However, the last floor will still be daylit, and being at the highest point of the building, it probably also offers a great view.

Once again, due to the shape of the building, it offers larger areas than those of the low-rise prism (1st project) for instance. The social area comprises of 29.18 m^2, the workspace of 12.50 m^2 (it ensures the minimal required), the sleeping quarters of 25.45 m^2 and lastly, the hygiene quarters of 8.75 m^2.

These four architecture morphology examples allow to evaluate whether a less conventional form (such as a semi-ellipsoid), is a better option for extreme environments, when compared to more traditional forms (such as a prism). It's also able to show how can an architecture project adapt to these types of shapes and distributions, while still following the adequate guidelines for buildings in these types of environments. These four projects all present different spatial configurations while still following those same guidelines. Others could be suggested, planned and designed, but for the scope of this research the focus is on these four, which are used to validate the final evaluation methodology for architecture in extreme environments. In table 4.1 it's possible to see all of the data regarding the morphology values for the four architecture projects.

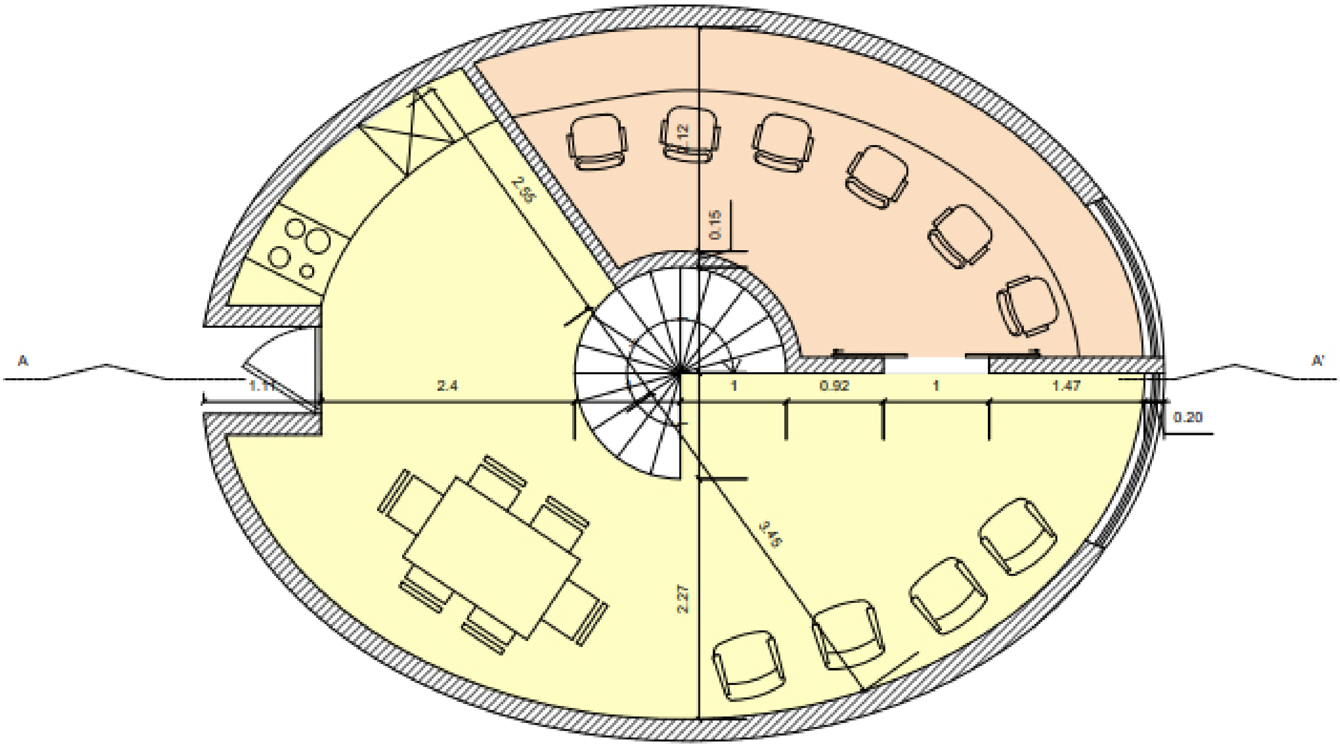


Image 4.9 – Ground floor plan of the high semi-ellipsoid proposed project, with the definition of the various areas: social area (in yellow), workspace (in orange), both on the first floor.

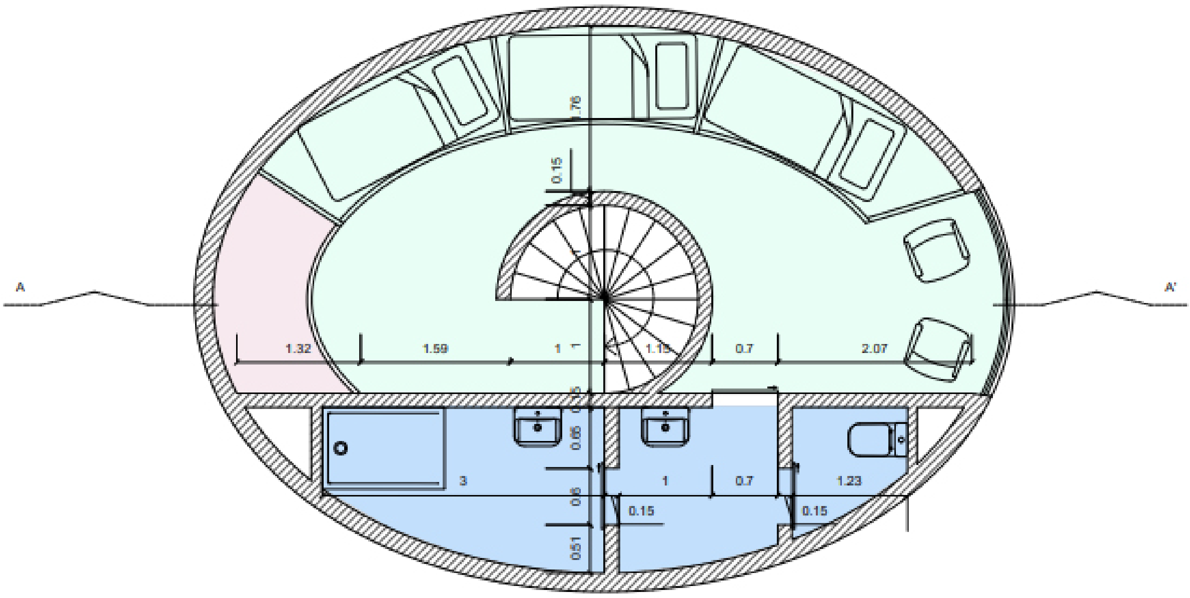


Image 4.10 – Floor plan of the second floor of high semi-ellipsoid proposed project, with the definition of the various areas: sleeping quarters (in green), hygiene quarters (in blue), and a flexible space, here marked as storage (pink).

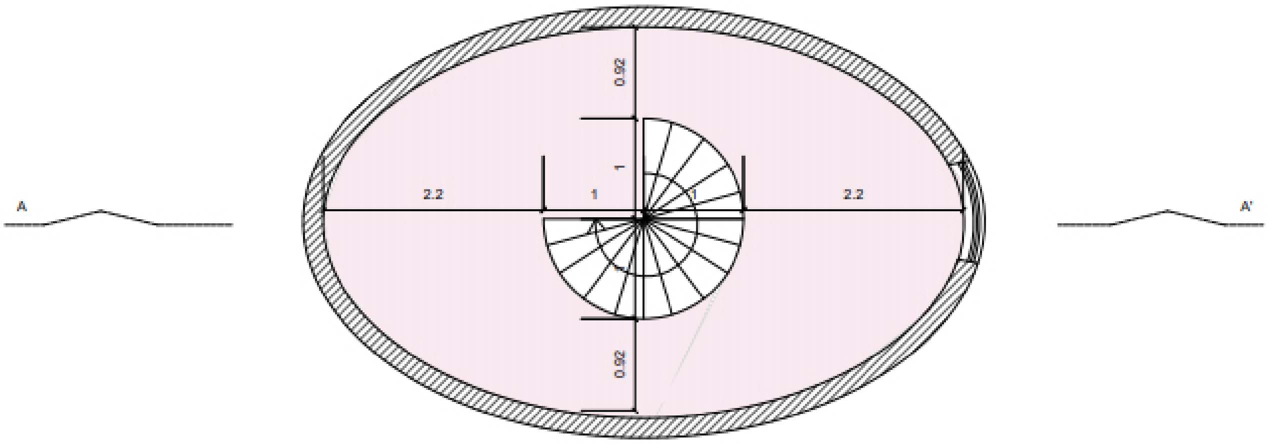


Image 4.11 - Floor plan of the third floor of high semi-ellipsoid proposed project, with the definition of areas: a flexible space, marked as storage (pink).

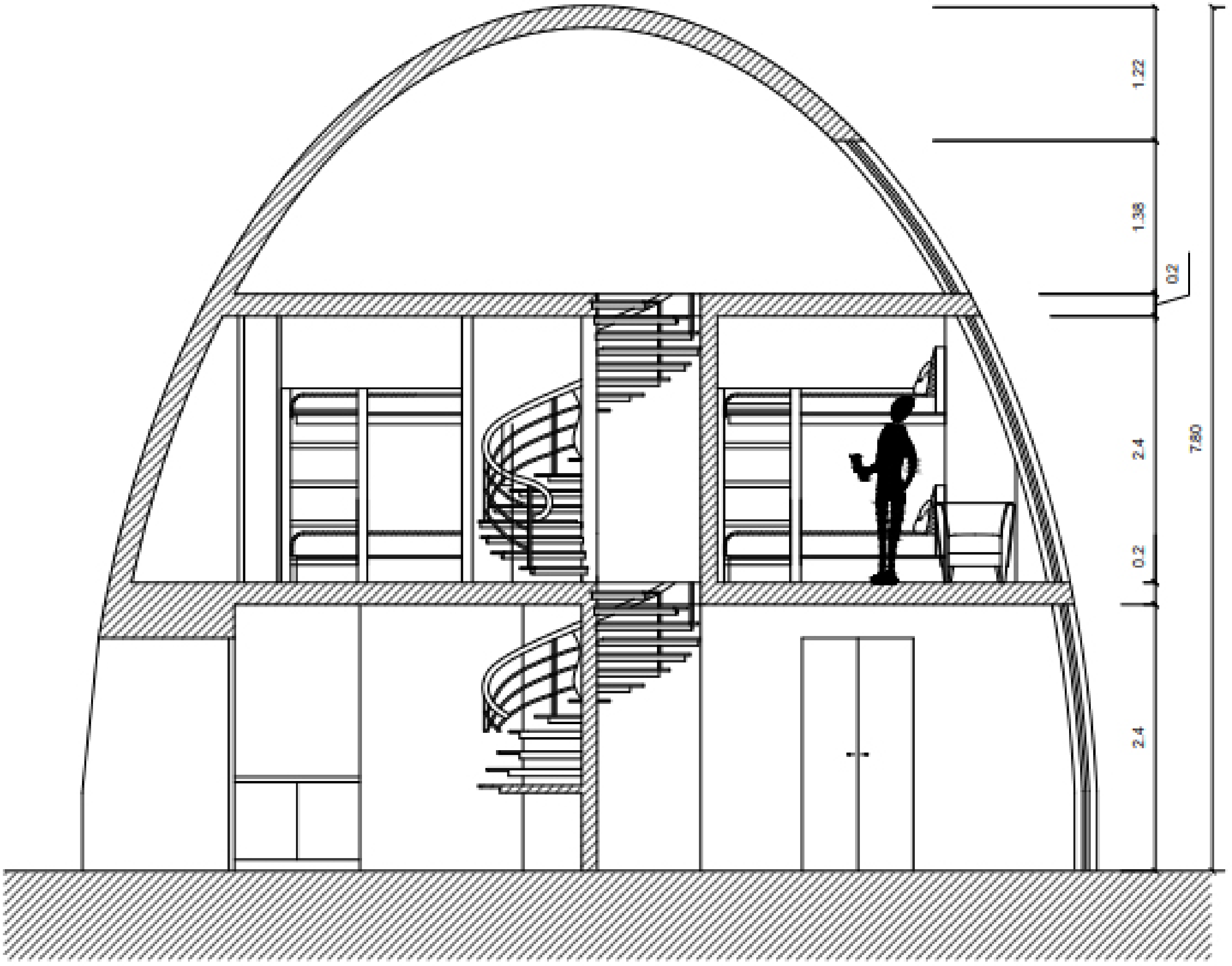


Image 4.12 - Section AA' of the proposed high prism project, which cuts through the entrance and the social area, which also shows the entrance to the workspace, on the second floor the sleeping quarters are represented, with the bunk beds, which can be covered with a panel, and on the third floor the flexible space is represented, which can serve as both a storage area and a second social/work area.

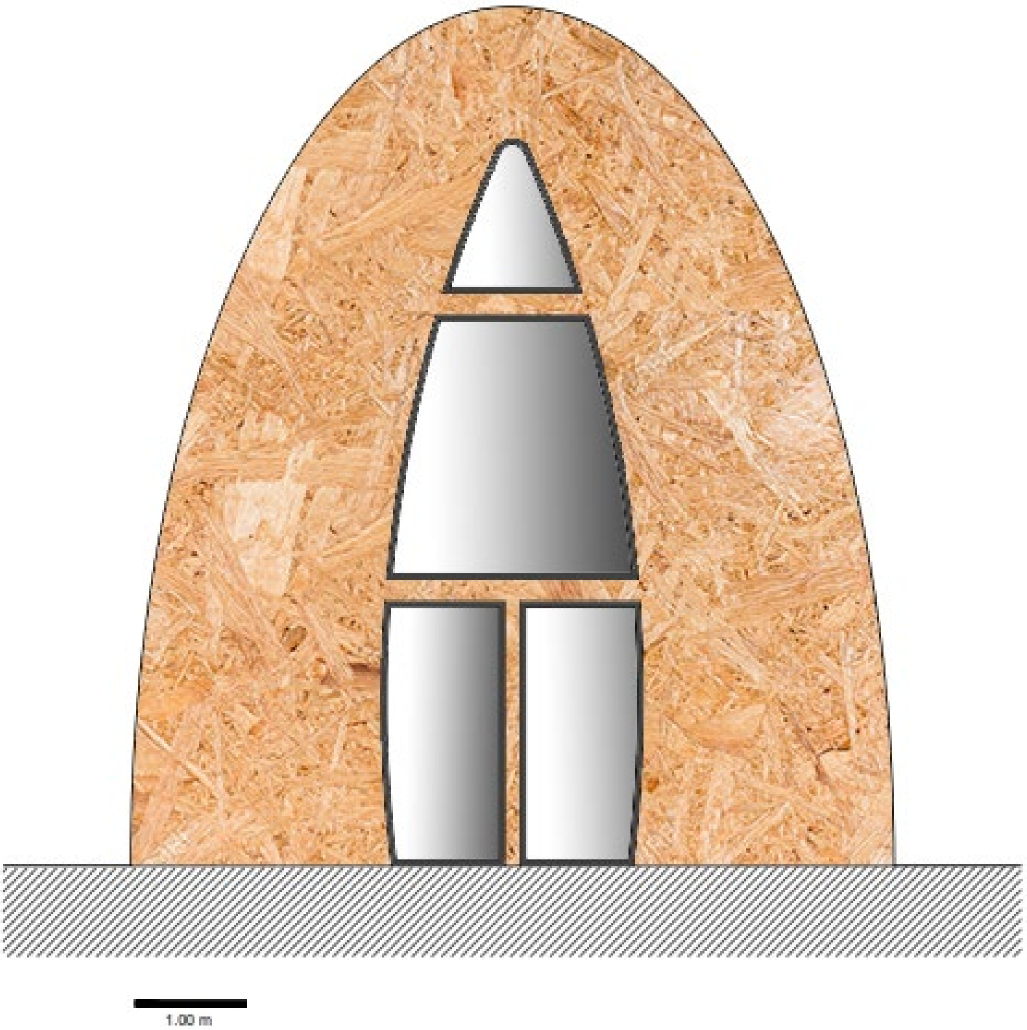


Image 4.13 - Elevation of the high prism proposed architecture project, from the right side, where all windows are located, the first two are for both the social area and the workspace, the second one for the sleeping quarters area, and the third one for the flexible storage/social/work area, on the last floor.

Table 4.1 – Architecture morphologies dimensions and form factor values.

Architecture Morphologies	Floor Area (m^2)	Surface Area (m^2)	Volume (m^3)	Form Factor (S/A)	Form Factor (S/V)
Base Prism	56,64	136,32	135,94	2,41	1,00
High Prism	84,96	190,96	215,23	2,25	0,89
Semi-Ellipsoid	85,83	126,14	179,12	1,47	0,70
High Semi-Ellipsoid	100,84	148,85	207,63	1,48	0,72

CHAPTER 5

Material Selection

When designing and building for extreme environments, the goal is to provide the most comfortable indoor temperature possible, as well as the lowest possible energy consumption, and to achieve this, materials are an essential question. Regarding the material choice for buildings in this type of environments, bio-climatic architecture shows up as an important reference, as explored in the State of Art. Research tells us that architecture that is adapted to its surrounding climate should use proper, and preferably native materials, with eco-construction criteria. The goal of this stage of the research is to define a self-proposed construction assembly, which would be adequate to build in the two extreme environments, while also being energy efficient and structurally sound.

5.1. Definition of Criteria

In order to achieve the above-mentioned goal, it is necessary to make a material library, that allows to define the most adequate type of construction material for the environments in question. A first draft of the library is created using commonly used construction materials (aluminium, bricks, concrete, soda glass, steel, PS, PVC, PU foams and wood), as well as other materials that might prove useful in the context of extreme environments (such as cardboard, teflon, nylon, neoprene, rubber, silicone and kevlar), and natural materials (straw bale, hemp, flex, jute and kenaf) . All the info regarding the materials is retrieved from two main references from the same renowned researcher in order to achieve coherent results and data (Ashby M. , 2013) (Ashby & Johnson, 2014). This first draft of a materials set has 52 materials, divided into twelve categories: biopolymers, ceramics, concrete, elastomers, glass, metals, natural fibres, polymers, polymer foams, stone, wood and wood derivatives.

Regarding the selection criteria, in the beginning, eight material properties are defined for this part of the study, to understand how these materials would behave in such extreme conditions. These properties are divided into categories of thermal, mechanical, and ecological. The thermal category includes thermal conductivity (heat transfer), thermal effusivity (thermal inertia), linear thermal expansion (thermal stability) and service temperature (the minimum and maximum temperature the material can withstand without changing its physical or chemical properties). The mechanical category is defined by fracture toughness. This is the property that can best deal with very different materials in respect to their mechanical performance, such as natural fibres, concrete or metal. Fracture toughness allows to characterize structural failure (as assessed by crack propagation) comparing materials with very different compressive and tensile strength. Lastly, the ecological category includes the recycle potential of the material, as well as the embodied carbon (as it accounts for climate change potential). This made possible to consider the environmental impact of each material in the library. The set of materials types, properties and criteria can be seen in image 5.1.

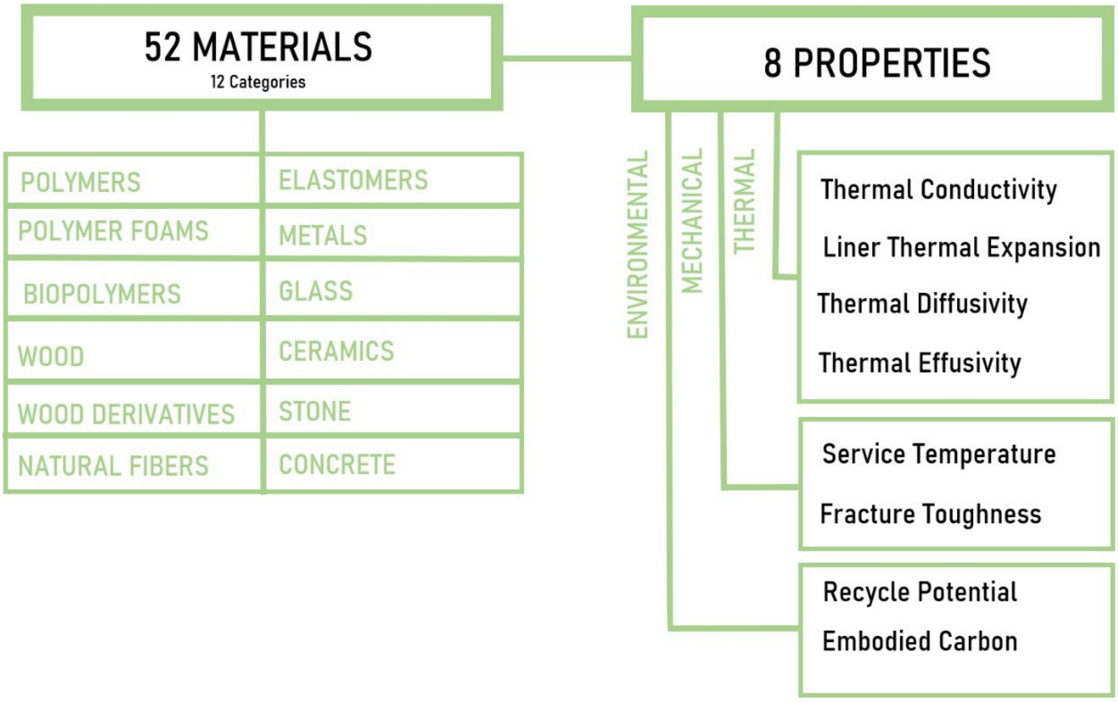


Image 5.1 – Representation of the type of materials presented in the material library and the defining eight properties that were researched.

About the service temperature as a criterion, specifically, a preliminary analysis of the whole set of materials shows that all materials endured a temperature higher than the maximum value of the climate considered, and therefore it is redundant as a criterion for very hot climates. This property is therefore only used for extreme cold climates.

In order to access which material was better in terms of the first draft of the material library, an MCDA model is created, using the properties addressed previously. This way, it is possible to understand which group of materials would be a better option for construction, depending on each of the two extreme climates.

5.2. M-MACBETH model for preliminary material selection in the context of extreme environments

The goal of the following multi-criteria decision analysis (MCDA) model is to select the most suitable material to use in extreme environments, from the first draft of the material library. An MCDA model is generally used to develop comparative analysis of various options in solving complex problems that involve a set of several and different (sometimes even opposite) criteria (Mustajoki & Marttunen, 2013). In the case of this research, conflicting objectives in the material selection may be lightness for ease of transportation and construction versus mechanical strength or versus environmental impact. On the other hand, a MCDA model allows for very effective scenario representation by changing the relative weight of the criteria. The specific MCDA method used throughout this research is MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique), through the software tool M-MACBETH. This method exists since the early 90's, which uses non-numerical judgements and asserts weights for all the criteria in MCDA. These judgements are defined by the user by asserting qualitative differences of attractiveness, given to each pair of criteria. The software then generates a numerical scale with the user's judgments as its base (Costa, De Corte, & Vansnick, 2003). This selection method was chosen as it has been proved effective in multiple research areas, and it can include a large number of options and criteria with high flexibility for characterization and judgements. This allows for an accurate representation of different scenarios by altering the differences of attractiveness among the criteria and/or the levels of a specific criteria in order to better tune the analysis. This allows to create various different scenarios with the same model, in case the user wants to give more importance to a set of criteria or another, to create scenarios focused on environmental impact, or on mechanical performance, changing the relative importance between the criteria.

Two different MCDA models are created, one for the extreme low temperature climate, and one for the extreme high temperature climate. For the first one, the most important priorities considered are high resistance to low temperatures, as a material needs to be able to keep performance levels in those harsh conditions, and thermal conductivity, the two with the same weight. Next, environmental impact is considered, with embodied carbon and recycle potential receiving the same weight and with low difference of attractiveness between these and the options before. Fraction toughness and linear thermal expansion are granted the next priority level, with moderate difference of attractiveness regarding the other options. The remaining criteria, thermal effusivity and thermal diffusivity are ignored for the extreme cold climate, as they are not essential to provide comfort in these conditions. Due to this option, these criteria have extreme difference of attractiveness towards the other options in the model, as they are not important.

Regarding the extreme hot temperature climate, the model does not include the criterion of resistance to extreme cold temperatures, as this is not relevant in this case. The defined top criteria for this model are thermal effusivity, thermal diffusivity and thermal conductivity,

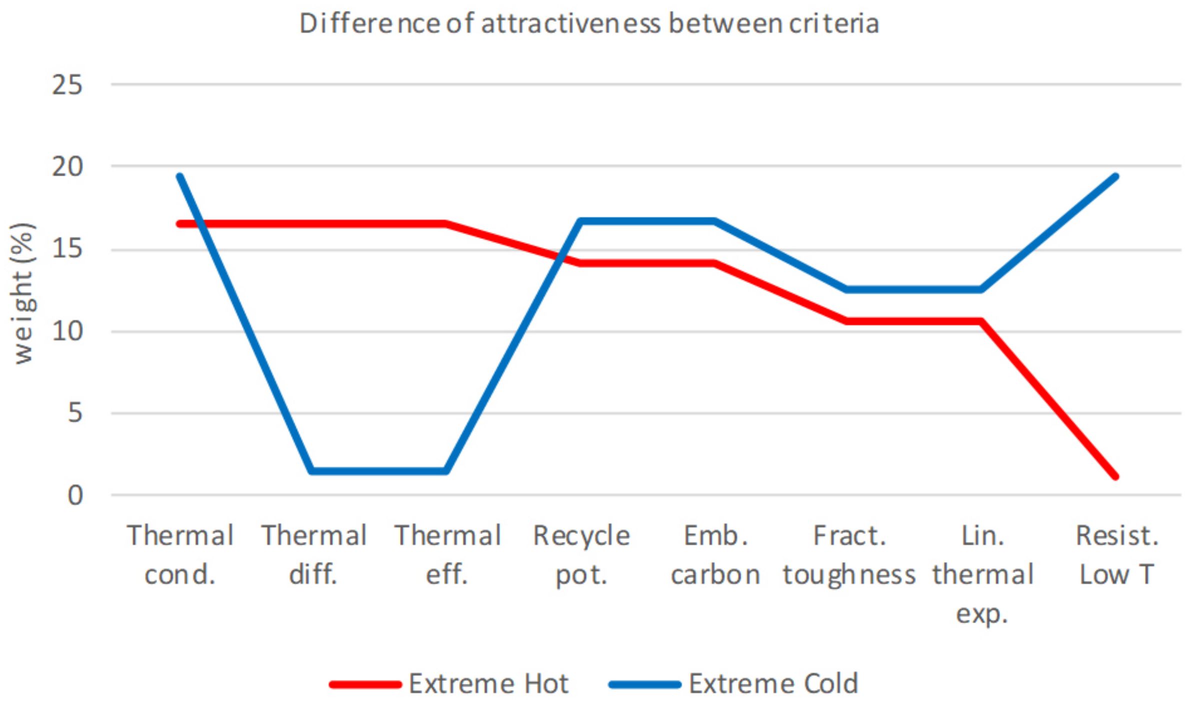


Image 5.2 – Difference of attractiveness between the eight criteria of the two base MCDA models (extreme hot temperature climate in red, and extreme cold temperature climate in blue).

as thermal inertia is key to achieve comfort in very hot climates. The next defined priority levels and attractiveness differences are the same as the extreme cold temperature model.

Regarding both models, all but two criteria are given quantitative numerical characterization levels. The exceptions are resistance to extreme low temperatures and recycle potential, which are rated qualitatively between High, Medium and Low. The values used as upper and lower references (corresponding to 100% score and 0% score, respectively) in the quantitative characterization of options are the limits of the range of values of the whole set of materials. The practical implication of this option is that materials are compared within the set and no other specific reference is used. Image 5.2 and table 5.1 show the two main models (extreme hot climate and extreme cold climate), with all the criteria and priority levels (table 7), as well as the difference in attractiveness between the different criteria.

Table 5.1 – Priority Levels and Criteria for the 2 MCDA models, for an extreme hot climate and an extreme cold climate.

PRIORITIES / MODELS	Extreme Hot Climate	Extreme Cold Climate
LEVEL 1	Thermal Conductivity	Thermal Conductivity
	Thermal Diffusivity	Resistance to Extreme Low Temperatures
	Thermal Effusivity	
LEVEL 2	Recycle Potential	Recycle Potential
	Embodied Carbon	Embodied Carbon
LEVEL 3	Facture Thoughness	Facture Thoughness
	Linear Thermal Expansion	Linear Thermal Expansion
Not Significant	Resistance to Extreme Low Temperatures	Thermal Diffusivity
		Thermal Effusivity

Two more models are added afterwards to the first two, to represent a scenario focused on the environmental impact of each material, as represented by the criteria embodied carbon and recycle potential. In order to achieve this, the difference of attractiveness among each criterion characterization levels is changed. In these scenarios, the difference of attractiveness of the options' characterization levels of those two criteria is not linear, as in the previous models. Instead, the levels corresponding to the lower reference are given an extreme difference of attractiveness against the upper reference levels, creating a relative weight bias for values close to the upper reference.

The charts of images 5.3 and 5.4 show the difference in attractiveness attributed to the characterization levels of the environmental impact criteria in the base models and the eco-models. In these environment-focused models, the difference of attractiveness among criteria remains the same. The four created models are named "cold", "hot", "cold-eco" and "hot-eco", the first two being the base models for the two climates, and the last two being models that address more specifically the environmental impact of the set of materials.

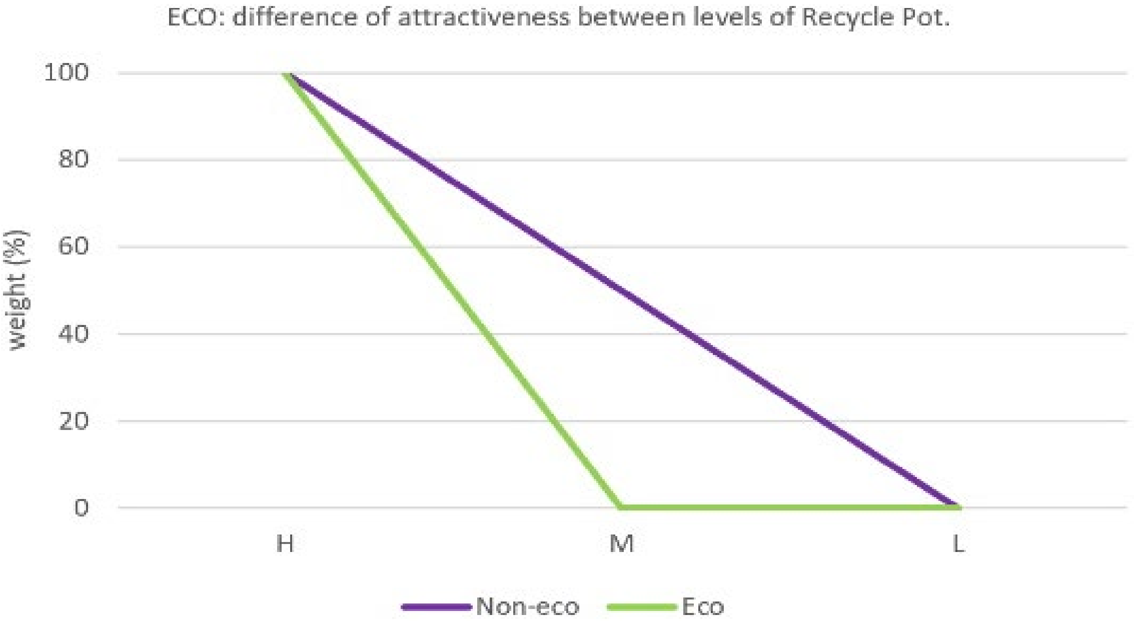


Image 5.3 - Difference of attractiveness between levels of Recycle Potential between the base model (non-eco, in purple) and the environmental impact model (eco, in green).

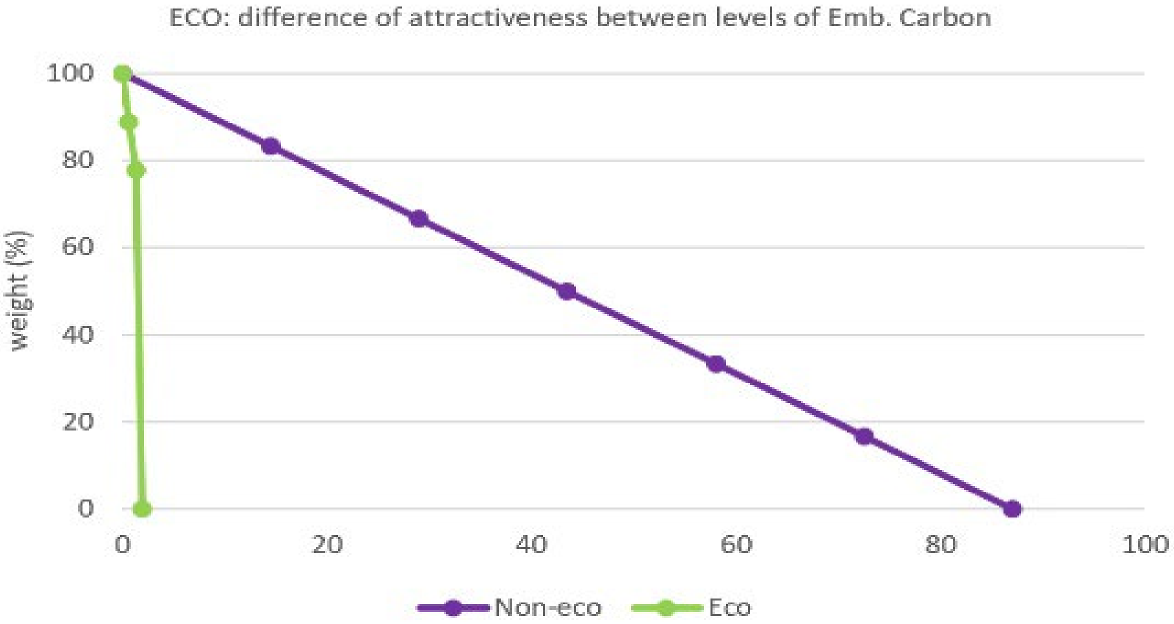


Image 5.4 - Difference of attractiveness between levels of the criterion Embodied Carbon, between the base model (non-eco, in purple) and the environmental impact (eco, in green)

5.3. Preliminary Results for the MCDA Material Selection in the context of Extreme Environments

Regarding the base scenarios, the best ranked materials for the extreme cold climate are polymers, polymer foams, glass, biopolymers, wood, and wood derivatives. Stone and metals rate the worst, with ceramics and concrete rating poorly as well. The best ranked material is Polytetrafluoroethylene (PTFE), also known as Teflon[1]. The maximum rating is 66.48 (out of 100), which in reality shows that no material performs exceptionally well in extreme cold climates when taking all criteria into account. Although the material ranking is important to have a general idea of the behaviour of these materials, individual analysis of each specific criteria is necessary to do a better-informed choice, depending on the purpose the material is selected for.

In the case of the extreme hot temperature climate, the best materials are polymers, biopolymers, polymer foams and glass, the highest ranked material being polyethylene terephthalate (PET), with a maximum score of 48.04. It is again evident that no material can answer satisfactorily to the demands of this climate. The worst rated materials are also metals,

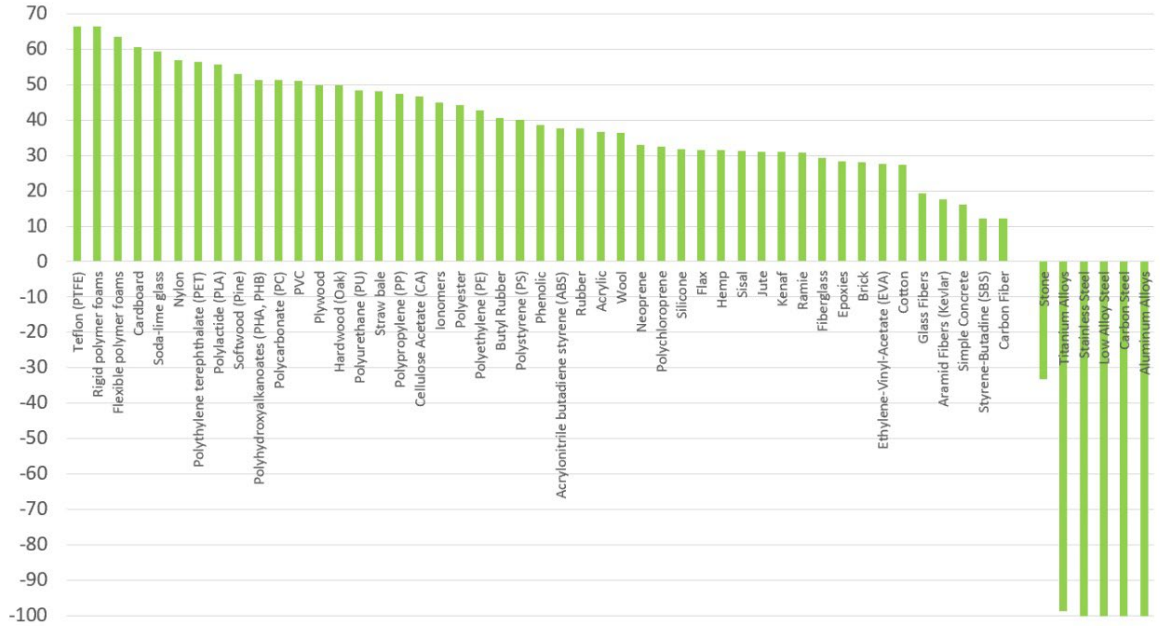


Image 5.5 - Material Performance of all 52 library materials according to the MCDA Model, for the extreme cold temperature's climate base model.

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[1] Teflon is a trademark of PTFE-based products from Chemours Company FC, LLC (formally part of DuPont)

while wood, ceramics, concrete and natural fibres perform poorly. The material performance between the two different climates is presented in Images 5.5 and 5.6.

It is important to note that although cardboard shows up as a material in the library and the charts, rating highest in the hot climate, it was not been considered in the results analysis as it comes with a lot of issues such as being very vulnerable to humidity, and having very little mechanical strength, therefore making it almost impossible to be adequately used as a building material, especially in itself, i.e., without being part of a composite system. However, it does show that materials that are cellulose based are a very valid option; this will prove useful when it is necessary to create a self-proposed material for construction in these extreme environments. This will be explained in the next sub-chapters

Regarding the two "eco" scenarios, the results are different, even though the general tendencies are maintained. However, the highest rated materials are now natural fibres, wood, and wood derivatives, in both climates. These results are different from the previous, since the differences of attractiveness between the characteristic levels for environmental impact is changed and, as such, materials that ranked worst before, now rank better. The presented results suggest that it might be possible to use the same construction material for both climates. Wood, or wood derived materials, could be used to create a construction assembly that would work in both very hot and very cold environments. Adjustments regarding insulation thickness would be necessary due to the difference between temperatures, but the type of construction material

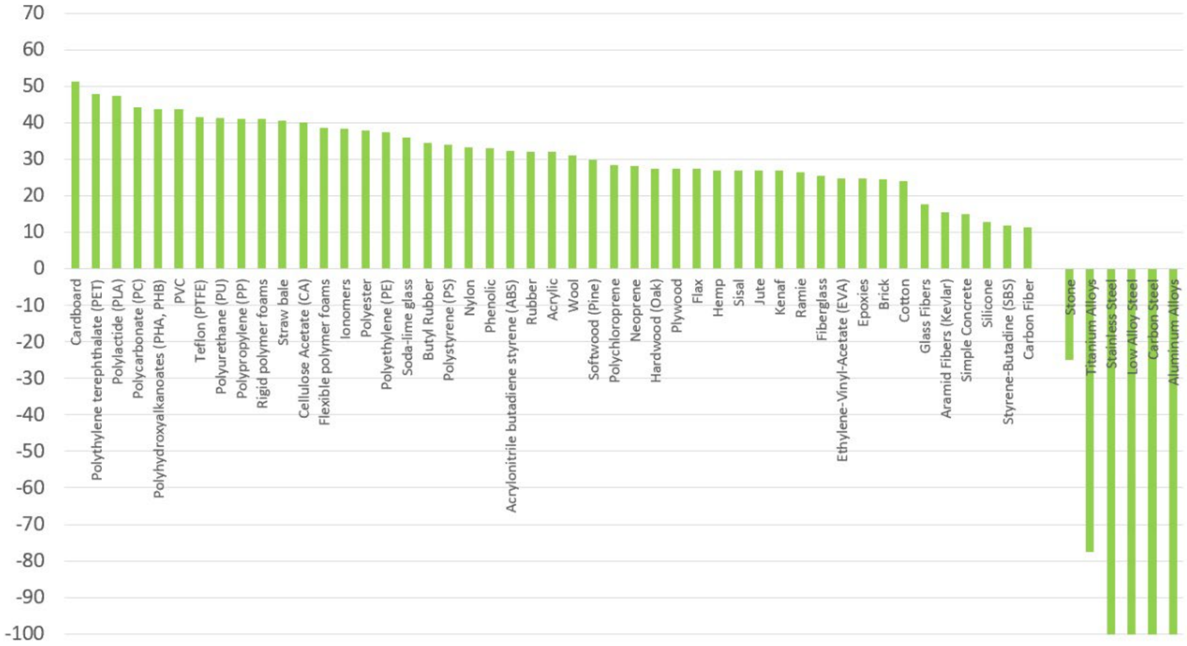

Image 5.6 – Material Performance of all 52 library materials according to the MCDA Model, for the extreme hot temperature's climate base model.

could be the same. A couple of conflicts in these results can be found though, as some criteria objectives contradict others. This is the case with mechanical properties and thermal insulation, as the materials with a lower thermal conductivity have a lower fracture toughness, and also with thermal insulation and thermal storage, as materials that share heat with their environment have a moderate to high thermal conductivity. It also seems all materials fairly rate well in linear thermal expansion, meaning that this criterion does not contribute effectively to the analysis and can thus be excluded from the evaluation process in the future. Images 5.7 and 5.8 show how all materials rate in the "eco" MCDA Models.

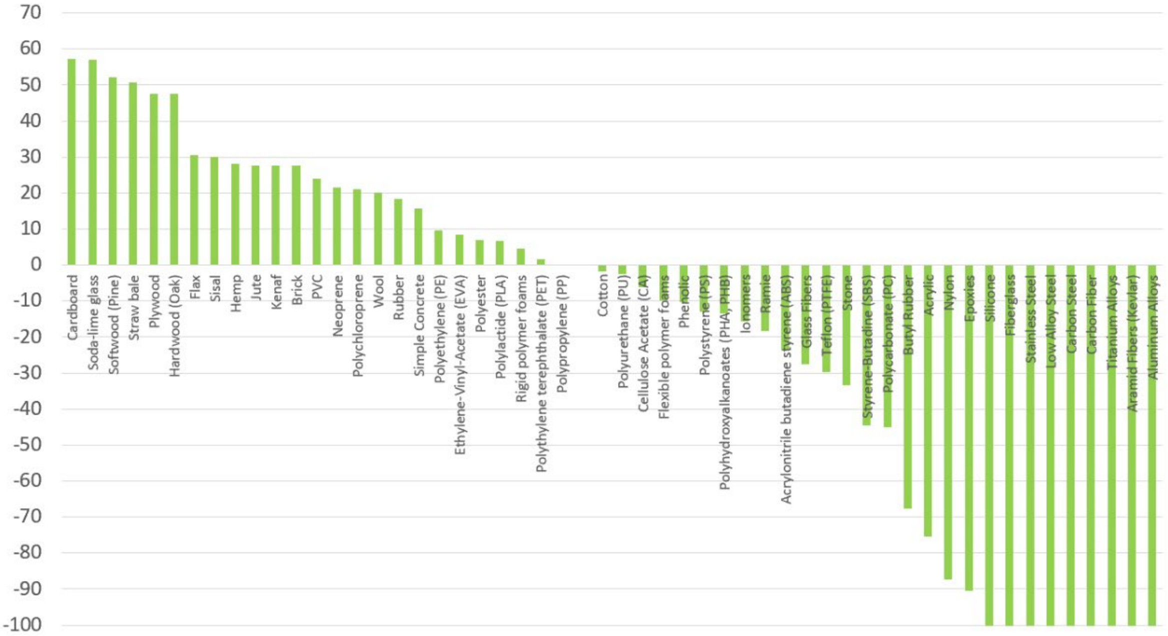

Image 5.7 - Material Performance of all 52 library materials according to the MCDA Model, for the eco cold temperature's climate base model.

Through these analyses, it is concluded that the best possible materials for these extreme climates seem to be materials that mix the properties of polymers, but without having a large environmental impact, probably natural fibres or materials such as biopolymers might be adequate choices. Innovative materials such as mycelium (Heisel, et al., 2017/18), as seen in the State of Art, might be possible choices, but it would require further research on the matter, especially on the field of material engineering.

This material preliminary study proved essential to start comprehending how materials can behave in such extreme and demanding environments, as well as to get a first experience with MCDA models, which can aid greatly the research process when selection processes are required. It is important to note that wood and wood derivative materials rate highly in both environments on the eco models, which means they can be effective construction materials without having a big environmental impact. This is interesting as it may indicate that a similar construction material can be used for both climates. It also seems that biomaterials may be an adequate future option, as material research develops. These biomaterials should combine high thermal insulation, exceptionally low environmental impact, and high mechanical strength. Material choice is adamant when it comes to building for climates with such extreme conditions, to provide thermal comfort to people inhabiting them, keeping high performance levels regarding other requirements such as mechanical strength. Once again, the option of using cellulose-based and wood-based materials seems to be a very strong one.

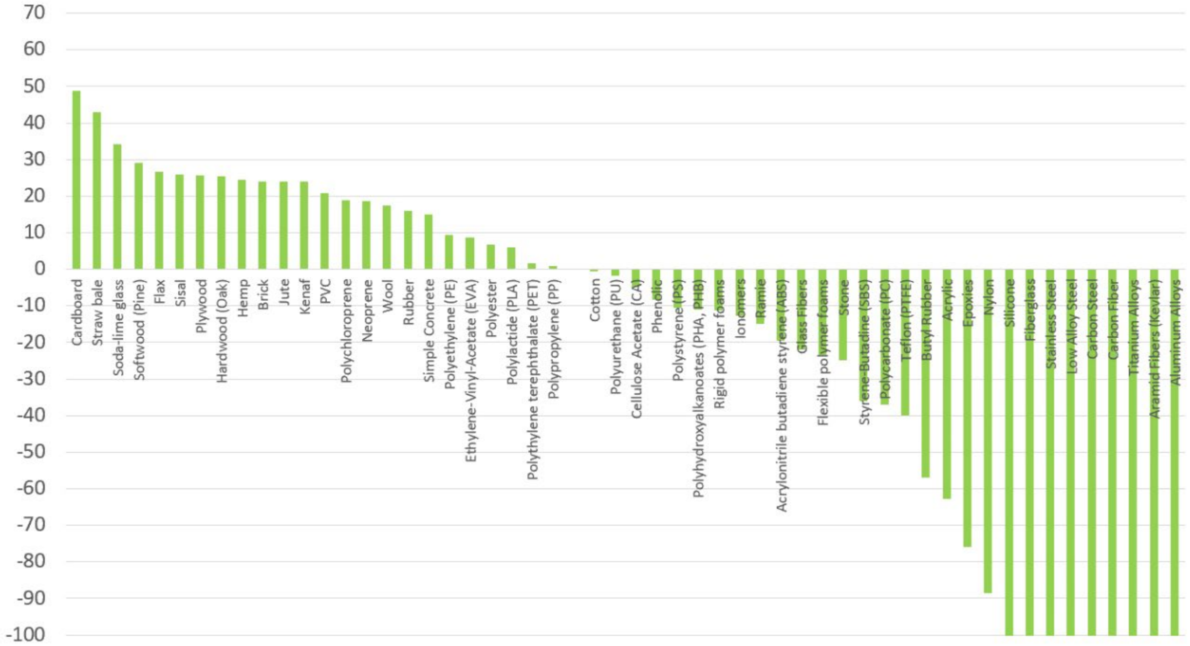

Image 5.8 - Material Performance of all 52 library materials according to the MCDA Model, for the eco hot temperature's climate base model.

5.4. Glass Material Selection for Windows

Although the material library that was presented previously contained the Soda-Glass material, it is important to do a more in depth research regarding types of glasses, that can be used for construction in extreme environments. For this, a specific library is created containing only low-e glasses (chosen as they would be more energy efficient than regular glass), which range from manufacturers Pilkington (Pilkington, 2021), AGC (AGC, 2021) and Guardian Glass (Guardian Glass, 2021). The glass database includes 32 triple glasses and 58 double glasses, with a total of 90 glasses.

For this selection, material properties is taken into question, such as thickness, solar transmittance, solar reflectance, visible light transmittance, visible light reflectance, front emissivity, back emissivity, thermal conductivity and Solar Heat Gain Coefficient (SHGC), which defines the solar radiation transmittance. Also, all glasses have either one or two layers of argon between them, instead of regular air, to make them more efficient.

In order to conduct the energy simulations to define what would be the better type of glass for each environment, four glasses are retrieved from the database, two double and two triples. These are chosen also based in their characteristics, as a double and a triple were chosen with high SHGC and Visible Transmittance, and the other double and triple with low SHGC and Visible Transmittance, to see how it would impact the internal temperature of the building, and the energy requirements. The characteristics of the four preliminary chosen glasses can be seen in table 5.2.

In order to pick just one glass for each environment, to make the solutions as effective as possible, simulations are run using the first prismatic proposed habitat, shown in Chapter 4, section 4.1, created having as base the guidelines from NASA.

Table 5.2 – Material characteristics of the four chosen glasses for simulations in extreme environments.

Glass	**Thickness (m)**	**Solar Transmittance (%)**	**Solar Reflectance (%)**	**Visible Transmittance (%)**	**Visible Reflectance (%)**	**Front Emissivity**	**Back Emissivity**	**Conductivity (W/m2K)**	**SHGC**
Double Optitherm S1A	0.004+0.016 (a)+0.004	55	36	76	16	0.02	0.02	1	0.55
Double Suncool Optifloat Clear 30/16	0.006+0.016 (a)+0.004	18	40	30	25	0.02	0.02	1	0.18
Triple Suncool Optifloat Clear + Optitherm S3 One 30/21	0.006+0.012 (a)+ 0.004+0.012 (a)+0.004	18	34	27	31	0.02	0.02	0.7	0.18
Triple Glazing Iplus advanced 1.0 #3	0.006+0.012 (a)+ 0.006+0.012 (a)+0.006	36	48	68	22	0.02	0.02	0.68	0.5

The thermal simulations are performed on the low-rise prism volume, and the results of the four main studied glasses are shown in table 9 and 10. The glasses with the “Suncool” standard perform better in Needles, a very hot climate, allowing for there to be lower temperatures within the building, and also, the most comfortable average indoor temperature. Also, these two glasses have low SHGC (0.18 for both), and low visible transmittance (0.3 and 0.27), as opposed to the other two glasses. On the other hand, the glasses that best perform in Yakutsk have high values of SHGC (0.5 and 0.55) and visible transmittance (0.68 and 0.76), showing that a higher solar heath gain coefficient is better to warm up a building, as necessary in a very cold environment such as Yakutsk.

The analysis of these simulations allowed the selection of only two glass materials for the habitat's constructions, as they provide the best results in terms of the amount of heating/cooling load. These are the two triple glass windows, the Triple Suncool Optifloat Clear with Optitherm S3 One 30/21 from Pilkington for Needles, and the Triple Glazing Iplus Advanced 1.0 #3 from AGC for Yakutsk.

Table 5.3 - Simulation results for the 4 glass materials in the two extreme environments of Needles and Yakutsk, regarding windows facing North and South directions. The data shows the indoor average temperature of the building in free-floating temperature, without comfort standards

Glass	Average Indoor Temperature Needles (windows North)	Average Indoor Temperature Needles (windows South)	Average Indoor Temperature Yakutsk (windows North)	Average Indoor Temperature Yakutsk (windows South)
Double Optitherm S1A	51.26º C	51.68º C	-31.22º C	-27.9º C
Double Suncool Optifloat Clear 30/16	47.36º C	47.47º C	-31.77º C	-30.65º C
Triple Suncool Optifloat Clear + Optitherm S3 One 30/21	48.08º C	48.18º C	-31.45º C	-30.3º C
Triple Glazing Iplus advanced 1.0 #3	51.61º C	52º C	-30.95º C	-27.84º C

Table 5.4 - Simulation results for the 4 glass materials in the two extreme environments of Needles and Yakutsk, regarding windows facing North and South directions. The data shows the Total Cooling and Heating Load necessary to keep the building comfortable in terms of interior temperatures.

Glass	Total Cooling Load Needles (windows North)	Total Cooling Load Needles (windows South)	Total Heating Load Yakutsk (windows North)	Total Heating Load Yakutsk (windows South)
Double Optitherm S1A	8259.23 (kW/h)	8297.43 (kW/h)	43818.11 (kW/h)	43529.13 (kW/h)
Double Suncool Optifloat Clear 30/16	7940.46 (kW/h)	7948.41 (kW/h)	43866.35 (kW/h)	43768.96 (kW/h)
Triple Suncool Optifloat Clear + Optitherm S3 One 30/21	7919.78 (kW/h)	7927.19 (kW/h)	43665.73 (kW/h)	43569.13 (kW/h)
Triple Glazing Iplus advanced 1.0 #3	8186.62 (kW/h)	8220.37 (kW/h)	43611.17 (kW/h)	43350.72 (kW/h)

The analysis of these simulations allowed the selection of only two glass materials for the habitat’s constructions, as they provide the best results in terms of the amount of heating/cooling load. These are the two triple glass windows, the Triple Suncool Optifloat Clear with Optitherm S3 One 30/21 from Pilkington for Needles, and the Triple Glazing Iplus Advanced 1.0 #3 from AGC for Yakutsk.

5.5. Building the first general MCDA model to access construction assemblies

In order to produce more accurate results and further improve the MCDA models for the material selection, simulations for the low-rise prism are made, using materials from the EnergyPlus material library. These materials are used in regular construction and match the guidelines of the ASHRAE Standard 189.1-2017, which provides guidance for designing and operating high-performance green buildings (ASHRAE, 2017). This task is important to further assess which type of material is more adequate, through the results of energy performance simulations , instead of just through the study of material properties. These results allow to have a more accurate understanding of which materials are better, in the context of extreme environments, and made it possible to propose a construction assembly, specific to this research, which consists essentially of cellulose and wood-based materials, the assembly being both effective in terms of energy and toughness, as well as environmentally, having a negative carbon footprint. This decision is aided by the results that are achieved from this selection task.

According to previous research from the State of Art and previous stages of this work, a total set of 11 criteria are defined, divided into four categories. The first category, energy efficiency, is divided into two criteria: energy consumption and free-floating interior temperature. This data is retrieved from the simulations done in Rhinoceros 3D, with plug-ins Grasshopper, LadyBug and Honeybee. For the purpose of this study, energy consumption relates to the energy required to cool (in the hot climate) or to heat (in the cold climate) the studied volume, and keep the temperatures between comfortable limits for humans to inhabit it.

These interior comfort temperatures are defined at 16 to 18 degrees Celsius, for Yakutsk, the cold climate, and 26 to 28 degrees Celsius for the hot climate, Needles, as mentioned previously. The energy consumption is considered for the 3-months period of summertime (for the hot climate) and the 3-months period of wintertime (for the cold climate), per surface area unit [kWh/m^2]. The next criterion, internal free-floating temperature, relates to the interior temperature that the volume gets to, when there is no heating or cooling systems operating. This will of course depend on the building's morphology and the materials or construction assemblies that are used, and the data was retrieved from the digital simulations which were ran on Grasshopper. Regarding the schedules, space usage (amount of people inhabiting the building), lights and equipment load for the simulation, the same inserted data from the simulations ran previously for the morphology chapter, as well as for the glass material simulations above. These specifics can be seen in image 5.9, although they will be explained in more detail in the following chapters regarding the final simulations. Results are exported to excel spreadsheets, analysed, and inserted into the MCDA Model. A scheme explaining the criteria of this group and the simulation inputs can be seen bellow.

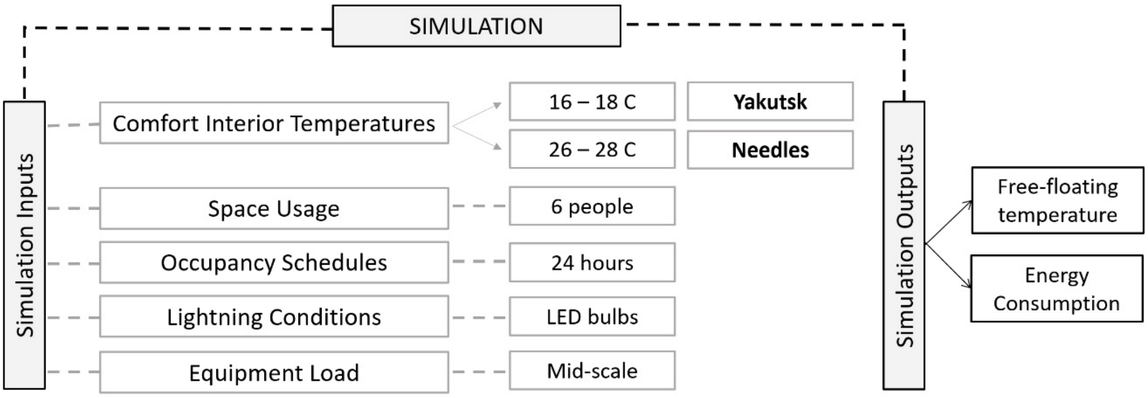

Image 5.9 – Scheme showing the inputs and outputs of the comfort simulations performed in Ladybug and Honeybee for the first group of criteria for the MCDA model.

The second group of criteria is about material performance. It consists of five criteria. The first is Service Temperature, a criterion only used for the very cold climate, as all the materials could handle the extremely hot temperatures, but not the extremely low temperatures. In fact, it is a necessary requirement for these types of environments that a material is highly resistant to cold temperatures. For the MCDA model, the criterion for resistance to extreme low temperature was defined qualitatively between Low, Medium and High. The next criterion is fracture toughness, to access the mechanical strength and durability of the material. Data is retrieved from the previously created material library, and a qualitative rating is given to the used construction assemblies for this study, these assemblies rated from "very low" to "very high", in 5 levels of importance. The next criterion is the weight of the materials; this is achieved by calculating the total weight of each material layer, using the density data from the EnergyPlus library and the volume of material used. It is a quantitative criterion, for the total weight of each construction assembly [kg]. For the fourth criterion, Carbon Footprint, it is defined as the total embodied greenhouse gas emissions of each assembly [kgCO$_2$e]. These values are retrieved from the Inventory of Carbon and Energy, from the University of Bath (Hammond & Jones, 2011). Finally, the last criterion, end-of-life, which relates to the recycle potential of each construction assembly, a qualitative scale is also used, ranging between Low, Medium and High.

The third group of criteria is related to Architectural Performance, and it is constituted by three different criteria. The first, related to Minimal Areas, is defined as a qualitative criterion, which rates between Low, Medium and High. The minimal necessary area for a habitat with 6-people is ensured by the base prism, which rates High. So, in this model, all options rate "High" for this criteria. For the models which include more than one type of volume, this criterion will be changed posteriorly. The second criterion relates to height, and it follows the same rational as the previous one: as 2.40 meters is the minimal height, comfort is guaranteed in all the options and, as such, it always rates High. Lastly, the third criterion, Space Organization, is qualitative and it also ranges between Low, Medium and High, being that the example used for this specific task (the low rise prism) rates High, as it ensures all the organizational principles required and defined in the SoA. In the scope of this research, Space Organization is defined as the group of design principles required for a good interior design, in buildings for extreme environments. These principles are defined in Chapter 1, in section 1.4.1. and further explored in Chapter 4: the interior spaces must be personalizable, and have possible alternated uses; the use of coloured spaces must be considered; the building must ensure the inhabitants physical safety; the sleeping chambers cannot be next to the hygiene chambers, so that noise is reduced; there must be a separation between private and social areas, and the social area should occupy the central and bigger part of the habitat; and lastly, the habitat must have windows that allow the inhabitants to view the outdoors, and also allow for daylight to enter the building.

The fourth group of criteria is named "Circularity", and it is an index-type assessment, through an MCDA sub-model, which rates between 0 and 100, and englobes the criteria of "Carbon Footprint", "End-of-Life", "Energy Consumption" and "Internal Free-Floating Temperature". A representation of the general MCDA model's organization and the described criteria can be seen in image 5.10.

The model’s options are also defined in the EnergyPlus system’s construction assemblies: “Generic”, “Mass”, “Metal” and “Wood”. These assemblies are retrieved from the EnergyPlus material library, as explained previously, and are also chosen accordingly to their specific climate zone, which are climate zone 2 for Needles and climate zone 8 for Yakutsk (ASHRAE, 2017). ASHRAE standards define specific climate zones to inform builders of the construction requirements of different climates.

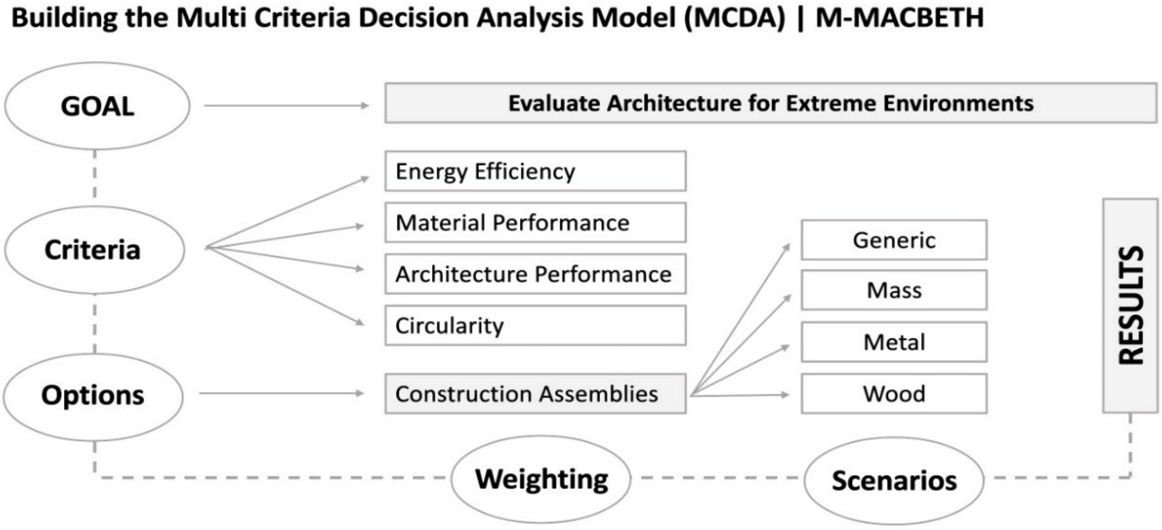

Image 5.10 – Scheme of the construction of the MCDA Model with each criteria category (groups) and the options (construction assemblies).

Depending on whether the climate is too hot or too cold, needs for insulation and material thickness change accordingly. ASHRAE defined 8 climate zones, using the USA map as a reference: 1 – hot-humid, 2 – hot-dry, 3 – mixed-dry, 4 – mixed humid, 5 – marine, 6 – cold, 7 – very cold and 8 – subarctic. Needles is located in the USA, so its climate zone is clearly defined, for Yakutsk, although it is in Russia, the coldest climate zone was used, as it is the most accurate for that extreme cold climate. The ASHRAE map of the climate zones can be seen in Image 5.11.

Finally, how each construction assembly option rates according to each criterion can be seen in tables 5.5 and 5.6.

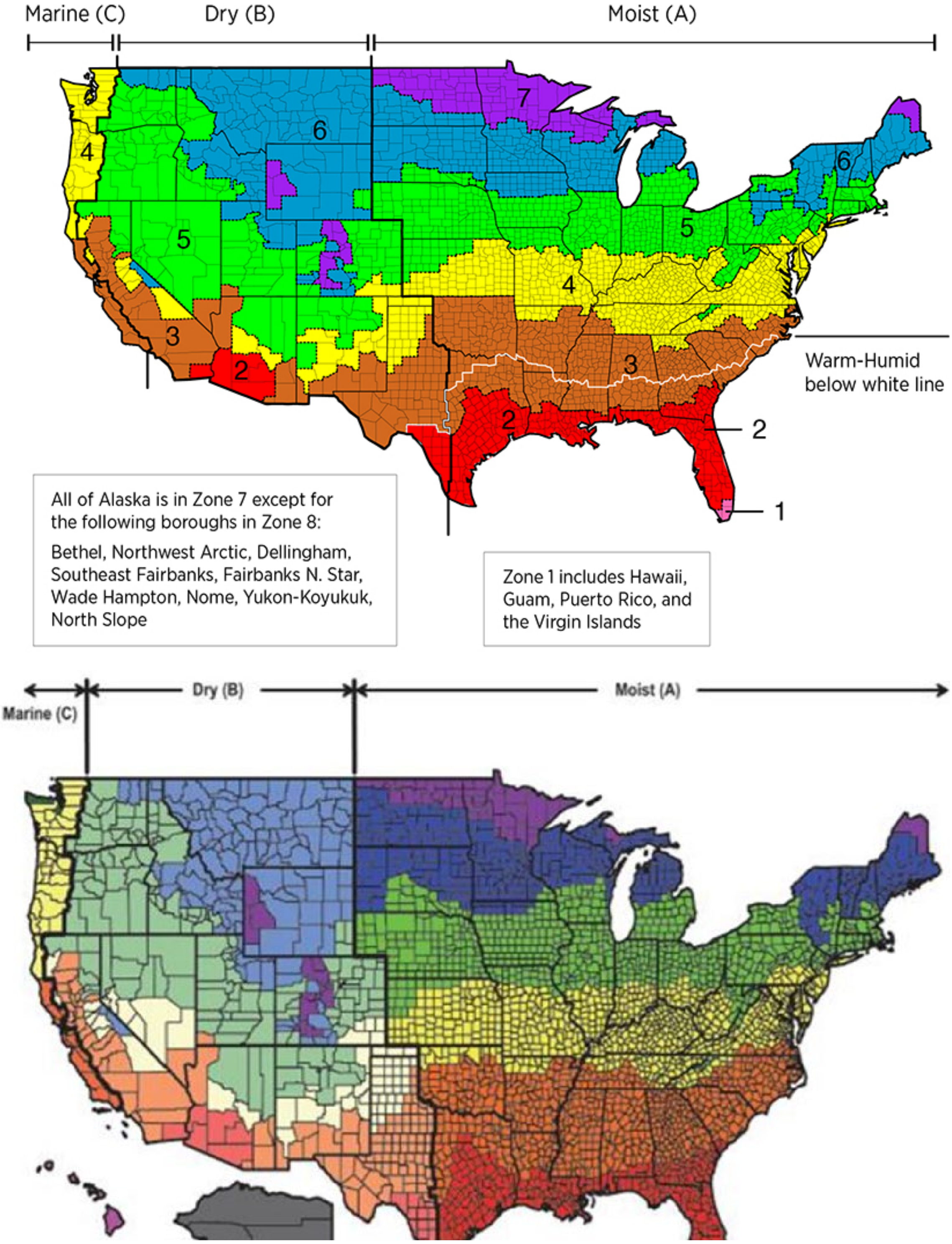

Image 5.11 – The first ASHRAE map for climate zones definition, in 2004 (above), and the new altered one in 2016 (below). The map was altered in 2016 to reflect the effects of climate change (ASHRAE, 2020).

Table 5.5 - Construction Assemblies from the library of EnergyPlus with detailed materials for Climate Zone 2 (Needles).

Construction Assembly	Exterior Wall	Exterior Roof	Exterior Floor
“Generic”	100mm brick	100mm lightweight concrete	200mm heavyweight concrete
	200mm Heavyweight concrete	Ceiling air space resistance	50mm insulation board
	50mm Insulation	Acoustic Tile	
	Wall air space resistance		
	19mm gypsum board		
“Mass”	25mm Stucco	Roof membrane	AtticFloor Insulation
	200mm heavyweight concrete	Roof Insulation R-21 [1]	12.5mm gypsum
	Wall Insulation R-35	Metal Decking	
	12.5mm gypsum board		
“Metal”	Metal Siding	Metal Roofing	AtticFloor Insulation
	Wall Insulation R-32	Roof Insulation R-22	12.5mm gypsum
	12.5mm gypsum board	Metal Decking	
“Wood”	Wood Siding	Metal Roofing	Attic Floor Insulation
	Wall Insulation R-34	Roof Insulation R-22	12.5mm gypsum
	12.5 gypsum board	Metal Decking	

Table 5.6 – Construction Assemblies from the Library of EnergyPlus with detailed materials for Climate Zone 8 (Yakutsk).

Construction Assembly	Exterior Wall	Exterior Roof	Exterior Floor
“Generic”	100mm brick	100mm lightweight concrete	200mm heavyweight concrete
	200mm Heavyweight concrete	Ceiling air space resistance	50mm insulation board
	50mm Insulation	Acoustic Tile	
	Wall air space resistance		
	19mm gypsum board		
“Mass”	25mm Stucco	Roof membrane	AtticFloor Insulation
	200mm heavyweight concrete	Roof Insulation R-26	12.5mm gypsum
	Wall Insulation R-44	Metal Decking	
	12.5mm gypsum board		
“Metal”	Metal Siding	Metal Roofing	AtticFloor Insulation
	Wall Insulation R-38	Roof Insulation R-27	12.5mm gypsum
	12.5mm gypsum board	Metal Decking	
“Wood”	Wood Siding	Metal Roofing	Attic Floor Insulation
	Wall Insulation R-43	Roof Insulation R-27	12.5mm gypsum
	12.5 gypsum board	Metal Decking	

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[1] The “R” value, is related to the American Standart from the Department of Energy which defines the R-Value of a certain insulation material. The value following the “R” is related to the inches of the insulation material. Example, an “R-13” value corresponds to a material that is 4.75 inches thick, and a value of “R-60” corresponds to a material that is 19.50 inches thick (USA Insulation, 2021).

Table 5.7 - Options performance in each criterion for the hot climate (Needles).

Criteria / Assemblies	Generic	Mass	Metal	Wood
Energy Consumption (kWh/m^2)	70.7	61.4	46.6	45.9
Free-floating temperature (°C)	42.6	46.4	44.7	46.3
Fracture Toughness (-)	VL	VL	VH	VL
Weight (kg)	86865	45898	7239	6904
Carbon footprint (kgCO$_2$e)	21800	17379	9184	7805
End-of-life (-)	L	L	M	M
Minimum Areas (m^2)	56.64	56.64	56.64	56.64
Height (m)	2.40	2.40	2.40	2.40
Space Organization (-)	H	H	H	H
Circularity (-)	25%/5%	17%/12%	71%/48%	63%/48%

Table 5.8 - Options performance in each criterion for the cold climate (Yakutsk).

Criteria / Assemblies	Generic	Mass	Metal	Wood
Energy Consumption (kWh/m^2)	202.5	65.4	61.5	55.6
Free-floating temperature (°C)	-38	-32	-33	-32
Service Temperature (-)	L	L	H	H
Fracture Toughness (-)	VL	VL	VH	VL
Weight (kg)	86865	45898	7239	6904
Carbon footprint (kgCO$_2$e)	21800	17379	9184	7805
End-of-life (-)	L	L	M	M
Minimum Areas (m^2)	56.64	56.64	56.64	56.64
Height (m)	2.40	2.40	2.40	2.40
Space Organization (-)	H	H	H	H
Circularity (-)	0%/0%	55%/27%	80%/56%	88%/59%

Four variations of the base MCDA model are created. The first one, base model, is defined as “A”, where all criteria groups have the same importance, 25% for each of the four groups, this way the weight of the group is divided between the number of criterions within the group. If a group has more criteria, each of those criterions will be worth less, than a criterion within a smaller group. For the second model, model “B”, European energy standards are used regarding energy consumption, instead of just having the highest and lowest limit values of the energy performance simulation results. The reference of 11 kWh/m^2 final energy is used for the highest possible score. This reference value is the result of applying an average conversion factor for the portuguese energy mix (Panão, 2016) to the maximum primary energy allowed for residential buildings in the danish regulation (Thomsen, et al., 2014) (considered as one of the best standards in the EU). The third and fourth models, “C” and “D”, represent an evolution from the general evaluation methodology to a more specific, and realistic approach for selecting architecture for extreme environments. In both cases, the criterions of “free-floating operative temperature” and “circularity” are discarded. This option is related to the fact that as the internal free-float temperatures are so extreme that it would be impossible for a human to dwell in them, thus making them useless for a more realistic scenario. On the other hand, the temperature differences are too small to be of importance (they range between limits for about 6 degrees Celsius). Regarding the "circularity" criterion, this is removed as the difference of attractiveness between criteria now adapts to real life scenarios, and so it becomes redundant to use "circularity" as an independent criteria group, as the criterions that are a part of it are already considered within other criteria groups.

Another change that is made on these two latter models, on the scenario of Yakutsk, is that the criterion of resistance to extreme low temperatures (service temperature) is modified, so that options that rated "low" or "medium" now rate 0, as what would be truly necessary, in a real-life scenario, is an option that would be resistant enough for these temperatures. Model "C" is a model where major priority is defined as environmental impact, providing more weight to the environmental criteria, such as carbon footprint, end-of-life and energy consumption. Regarding Model "D", priority is given to the option's weight and mechanical strength, to assess the ease of transportation and durability. This would be essential for an extreme environment scenario as it is necessary to have a resistant habitat, that is also light enough to be transported and easy to assemble. The representation of all four models, "A", "B", "C" and "D" are presented in image 5.12 and 5.13.

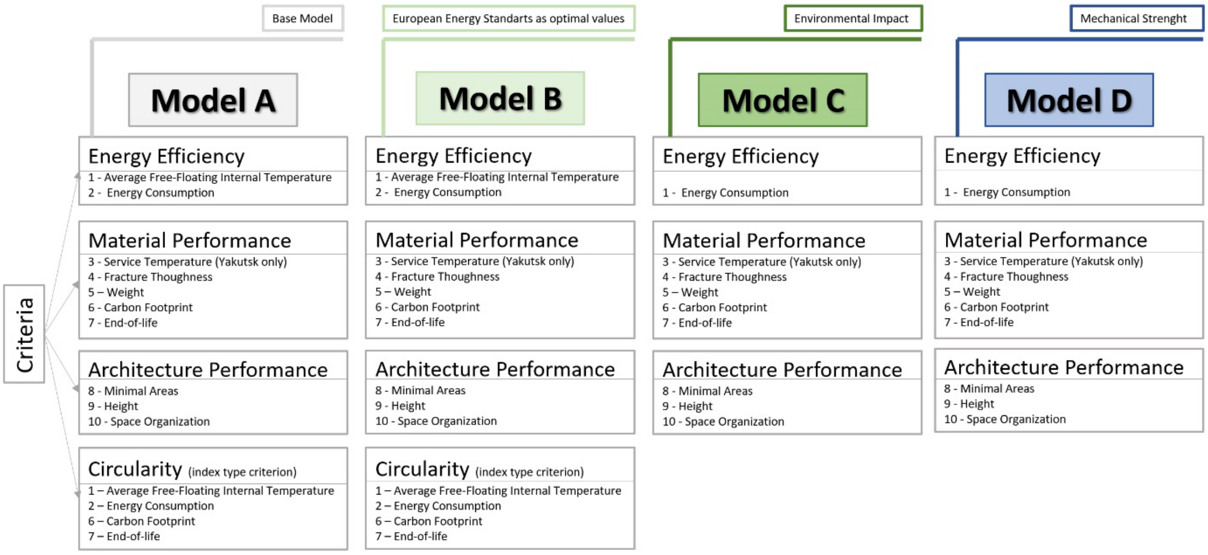
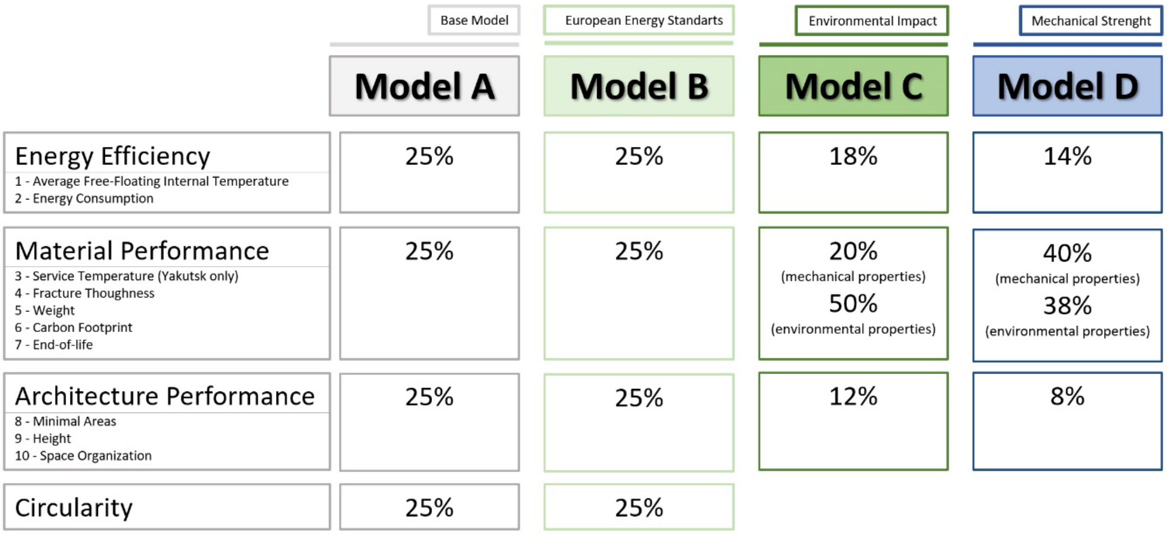


Image 5.12 - Scheme representing the four MCDA Models, the criteria groups and individual criterions, and the differences in terms of criteria organization between the models.



	Base Model Model A	European Energy Standarts Model B	Environmental Impact Model C	Mechanical Strenght Model D
Energy Efficiency 1 - Average Free-Floating Internal Temperature 2 - Energy Consumption	25%	25%	18%	14%
Material Performance 3 - Service Temperature (Yakutsk only) 4 - Fracture Thoughness 5 - Weight 6 - Carbon Footprint 7 - End-of-life	25%	25%	20% (mechanical properties) 50% (environmental properties)	40% (mechanical properties) 38% (environmental properties)
Architecture Performance 8 - Minimal Areas 9 - Height 10 - Space Organization	25%	25%	12%	8%
Circularity	25%	25%		

Image 5.13 – Scheme representing the weight of the criteria groups in the four MCDA Models.

Table 5.9 - Ratings of the four construction assemblies in all the MCDA models, for the hot climate, Needles.

Needles	Model A	Model B	Model C	Model D
Generic	25%	15%	11%	10%
Mass	19%	16%	31%	31%
Metal	76%	64%	85%	91%
Wood	61%	53%	77%	67%

Table 5.10 - Ratings of the four construction assemblies in all the MCDA models, for the cold climate, Yakutsk.

Yakutsk	Model A	Model B	Model C	Model D
Generic	1%	1%	9%	8%
Mass	56%	42%	30%	28%
Metal	85%	73%	88%	92%
Wood	87%	73%	83%	76%

The results regarding the options (construction assemblies) ratings (0-100%), for the four MCDA models indicated above, for the hot climate (Needles) and the cold climate (Yakutsk) are represented respectively below, in tables 5.9 and 5.10, and images 5.14 and 5.15.

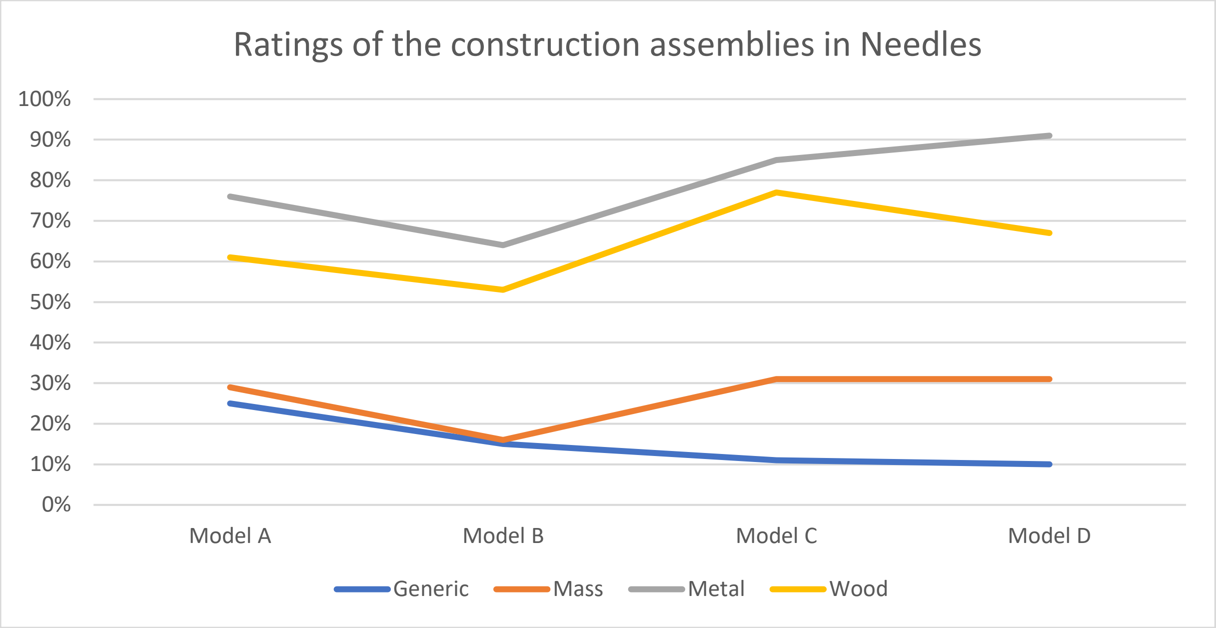


Image 5.14 – Chart representing the ratings of the construction assemblies in the extreme hot climate of Needles.

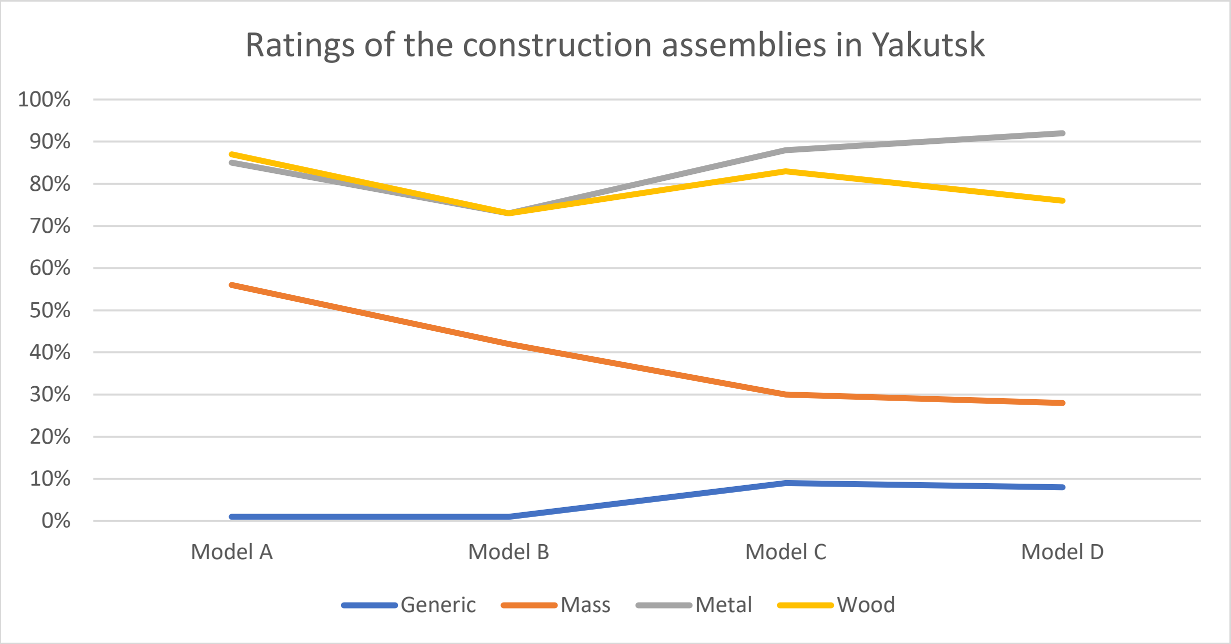


Image 5.15 - Chart representing the ratings of the construction assemblies in the extreme cold climate of Yakutsk.

Regarding the results for Model “A”, where all criteria groups have the same importance between them (25%), these differ between the Needles and the Yakutsk climate. While the “metal” assembly rates higher for the hotter climate, followed by “wood”, “generic” and “mass”, the “wood” option rates higher for the colder climate, then followed by “metal”, “mass” and finally “generic”. For model “B”, all options had lower ratings than in model “A”, but the relative positions of these options are the same. Regarding models “C” and “D”, the options rate in a very similar way in both environments, they also had the same organization for the options rating wise, “metal” rated highest, then “wood”, “mass” and “generic”.

The first conclusion that can be retrieved from these results, is that the construction assemblies for “mass” and “generic” are the worst for these types of climates. Although “mass” does rate higher in Yakutsk than in Needles, its performance is still undesirable for what these environments demand. For the Needles results, the construction assemblies of “metal” and “wood” always rate higher, although “metal” seems to be preferable. This happens due to the fact that mechanical resistance is a priority in this case, and metal has a higher fracture toughness than wood. In model “C”, where “wood” rated higher, this happens due to the fact that wood is preferable to metal when it comes to environmental impact, with the criterions of end-of-life and embodied carbon rating much higher with a construction assembly of wood than a metal based one. For the Yakutsk results, the construction assembly of “wood” rates higher in model “A”, and in model “B” both “wood” and “metal” have very similar rates. In models “C” and “D”, the same tendency of Needles is observed, where “wood” rates higher in model “C”, due to environmental impact, and “metal” rates higher in model “D”, due to mechanical performance. These models allowed experimentation with default construction assemblies from EnergyPlus, helping to further validate and advance the MCDA model and the list of criteria used, so that it could be used afterwards in the final simulations stage[1].

5.6. Self-Proposed Construction Assembly

For a Self-Proposed Construction Assembly, it is necessary to return to the results that were previously presented both for the material library and the simulations ran with generic materials from the EnergyPlus software. For both, materials created from cellulose and derivatives of wood rate high, and specifically for the part of the research presented in PLEA2020, the higher rated construction assemblies are either metal or wood. However, the MCDA models which give more importance to environmental impact, seem to gravitate more towards wood, due to its carbon footprint and recycle potential. Due to this, the construction assembly developed

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[1] The models created for this part of the research were presented in the PLEA2020 Conference and presented themselves as a valid framework (Domingos, Rato & Laureano, 2020)

specifically for the further development of this research is composed of wood and wood derivatives. It is composed of a timber frame structure, OSB wall panels, and wood fibre insulation boards. In order to create this assembly in the simulation software however, and due to the fact it includes a timber frame, which makes the material layers different depending on different parts of the wall, and that cannot be adequately translated into the software, it is necessary to calculate a weighted average value to represent the performance of the whole system. This way, it is possible to insert into the software one single material, with the required thickness, that encompasses the required values of all layers of the wooden wall. The material characteristics that are required to input into the software are thickness (m), density (Kg/m^3), specific heat capacity (J/Kg.K), thermal conductivity (W/m.K), roughness (between very rough or very smooth), thermal absorptance (between 0 and 1, 0.9 is common for most non-metallic materials), solar absorptance (between 0 and 1, 0.7 is common for most non-metallic materials) and visible light absorptance (between 0 and 1, 0.7 is common for most non-metallic materials). Environmental characteristics are also considered, although not necessary for the simulation software, they need to be inserted later into the final MCDA model. These are values of embodied carbon (kgCO$_2$/m^2). The values for embodied carbon (by kilogram of material, kgCO$_2$/kg) are retrieved from the Inventory of Carbon and Energy from the University of Bath, which offers the values of embodied carbon for various materials, from cradle-to-gate[1] (Hammond & Jones, 2011). In order to obtain the total value of embodied carbon for the construction assembly, this unitary value is used to calculate the amount of superficial embodied carbon, the weight of embodied carbon per square meter (kgCO$_2$/m^2)

In order to understand what the adequate thickness of the wall would be, and insulation requirements, a total of eight construction assemblies are proposed: number 1 and 2 were generic, number 3, 3.1 and 3.2 are designed for the hot climate alone, and number 4, 4.1 and 4.2 for the cold climate alone. To comprehend which would be more adequate depending on the climate, simulations are performed to understand which would allow for better energy performance results, also allowing to evaluate how much of an impact the thickness of the insulation has in energy transfer. All of these construction assemblies are presented below.

For the first proposed assembly, a wall is devised comprising of an OSB panel, wood frame, wood fibre insultation, and another OSB panel. However, this solution doesn't guarantee that

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[1] "Cradle-to-grave is the full life cycle assessment from resource extraction ("cradle") to the use phase and disposal phase ("grave"). Cradle-to-gate is as assessment of a *partial* product life cycle from resource extraction (cradle) to the factory gate (ie, before it is transported to the consumer)." (Guiot & Cramer, 2016).

adequate insulation is achieved because the wooden plumbs are directly into de OSB panel, creating a thermal bridge. Due to this, it is discarded and substituted by proposed assembly 2 (Image 5.16).

To conduct proper energy performance simulations, the software requires an input of the layers of materials that the wall is built with. However, this process is not a viable solution for this research, as the proposed construction assemblies are not homogeneous solutions. These construction assemblies are comprised of areas with wooden plumbs (for structure), without wooden plumbs, with glass windows, and so on. Due to this, representing a singular type of wall by inputting singular materials on the software would not adequately represent a real solution, or a real wall that can be built. To solve this issue, mathematical calculations are run for each construction assembly, to achieve the necessary performance values, and then a single material is created, which has the same properties (with weighted values) as the construction assembly, with the same thickness. This allows to artificially generate a hypothetical material, with just one layer, that has the same properties as the proposed construction assembly and can thus be input into the software. The properties values presented next are the values referent to that hypothetical material, which represents the studied construction assembly, and is posteriorly used in the simulation software.

Assembly 2, is comprised of the same elements as solution 1 (as are all the solutions), and has a specific heat capacity of 1936 J/Kg.K, a thermal conductivity of 0.043 W/m.K, an average density of 130 Kg/m^3, a value of embodied carbon of -18 kgCO$_2$/m^2, and a thickness of 0.327 m. The first set of new simulations is done solely with proposed construction assembly 2. However, it is important to note, these simulations are done without windows, so there is no solar heat gains through window surfaces.

The simulations are run with and without ventilation. The ventilation rate values are set for laboratory areas and places where dust contamination is a concern, with a value of 0.0025 cubic meters per second per square meter of floor (m^3/s-m^2). In a later stage, it is acknowledge that the ventilation rate can be lowered to typical residential values and is adjusted for the minimal values of comfort for 6 people; which are 0.0001 m^3/s-m^2, and 0.0014 m^3/s per person (0.0083 m^3/s in total). However, for these preliminary simulations, it allows to uncover interesting results. Due to the very harsh climates (Yakutsk and Needles), the inlet of very cold or very hot air into the building through ventilation augments massively the energy required for thermal comfort, within the comfort ranges previously specified. In the case of Yakutsk, it is ten times the required energy without ventilation, and for Needles about six times. With these results, it became necessary to comprehend if such a massive need for energy can be diminished using more, or less insulation, and what results could come of simulations performed with different construction assemblies. Less insulation could be an adequate answer only in the very hot climate, as more insulation could cause the building to overheat, since it won't allow the transmission of heat from the inside to the outside, during the night-time. This wouldn't allow for the building to cool down during the night, requiring more energy to keep it cool. To achieve these results, three solutions are created specifically for Needles (no. 3, 3.1 and 3.2) and three solutions are created for Yakutsk (no. 4, 4.1 and 4.2).

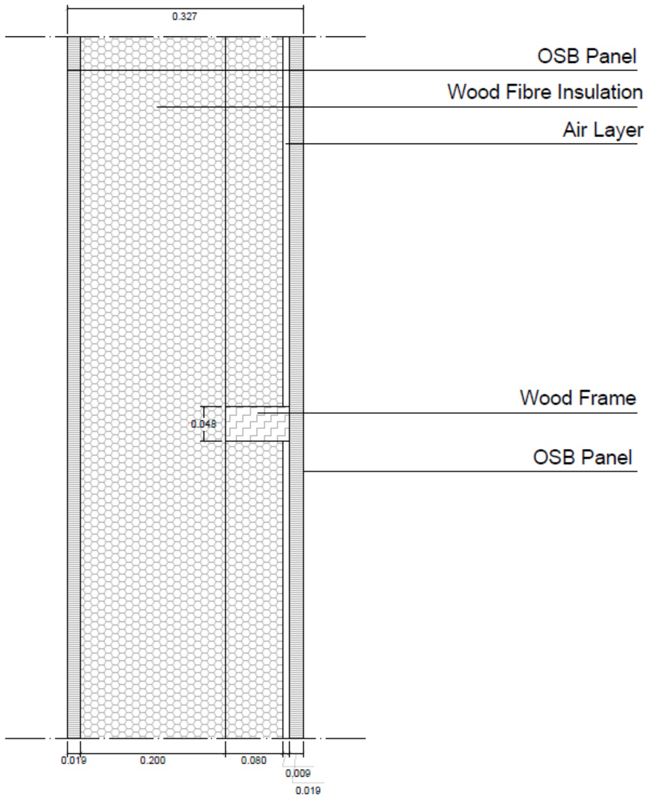


Image 5.16 – Proposed Construction Assembly. 2.

Construction assembly 3 is 0.137 m thick, and consists of the same elements as construction assembly 2, except the thickness of insultation is reduced to 0.080 meters (instead of 0.280 meters). It has a Specific heath capacity of 1756 J/Kg.K, a thermal conductivity of 0.059 W/m.K, and a density of 237 Kg/m^3. Construction assembly 3.1 has the same thickness, but almost all insulation is removed, counting only for 0.030 meters of the wall. It has a Specific heath capacity of 1740 J/Kg.K, a thermal conductivity of 0.110 W/m.K, and a density of 221

Kg/m^3. The last specific construction assembly thought for Needles is 3.2, in this case all insulation is removed, so that it could be studied what would be energetic behaviour of an habitat that has no insulation, and so has a lot of heat loss, which can be beneficial in a very hot climate like Needles. As explained previously, less insultation could be beneficial for the very hot climate, as it would allow heat losses during the night, cooling down the building. This specific construction assembly is designed to comprehend what would happen if there was no insulation, if it could actually be more or less beneficial, in comparison to a construction assembly with insulation. This construction assembly has a thickness of 0.127 meters, Specific heath capacity of 1697 J/Kg.K, a thermal conductivity of 0.260 W/m.K, and a density of 227 Kg/m^3. These three construction assemblies are represented in image 5.17.

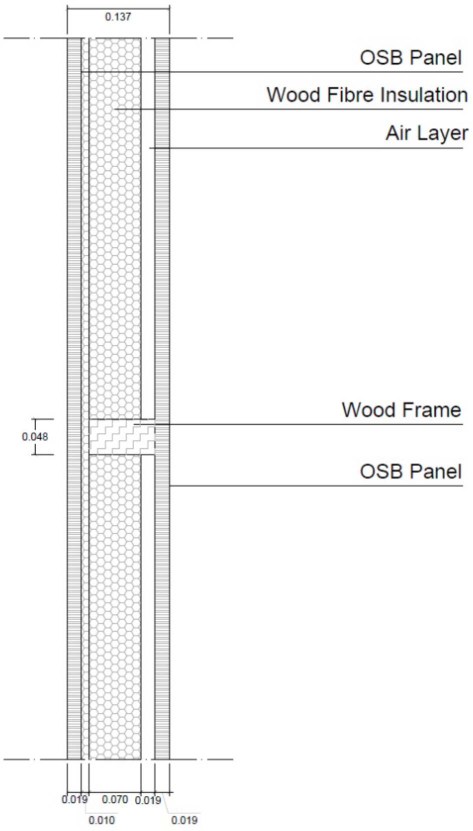
Simulations are performed for the environment of Needles, for the volume of the low-rise prism, with construction assemblies 2, 3, 3.1 and 3.2. With construction assembly 2, the total cooling load (for the three summer months, June, July and August), without ventilation, is 1274 kWh; with construction assembly 3, 2473 kWh; with construction assembly 3.1, 3634 kWh; and with construction assembly 3.2, 6169 kWh. In this aspect, it is possible to see that the less insulation there is, the most energy is needed, as it seems the volume heats throughout the day and without air circulating the insulation seems to be able to stop the heat from entering the habitat. The same tendency is observed in the results which consider ventilation. Once again, the cooling load, when considering ventilation, is much higher than the results without ventilation, with construction assembly 2 is 6367 kW/h, with construction assembly 3, 8935 kW/h, with construction assembly 3.1, 10108 kW/h and with construction assembly 3.2, 12951 kW/h. The tendency, however, is the same. The least insulation the habitat has, the more energy it will be necessary to keep it, in this case, cool. With these results in mind, it is appropriate to assume that construction assembly no. 2 rates higher for energy savings in Needles and is thus the most appropriate assembly. The hypothesis that a solution with less insulation could be more adequate for Needles, ensuring a more comfortable interior environment due to larger heat losses during the night-time, is not verified and, as such, this option is discarded, in favour of construction assembly 2.

Regarding Yakutsk, three new construction assemblies are also proposed, 4, 4.1 and 4.2. These assemblies have much greater amounts of insulation material, and very large thickness. It is important to note that even if these larger walls are much more energy-efficient, they would also be much heavier, making them harder to transport, so the difference would have to compensate for the other disadvantages. Construction assembly 4 has a thickness of 0.527 m, a specific heath capacity of 1975 J/Kg.K, a thermal conductivity of 0.041 W/m.K, and a density of 99 Kg/m^3. Construction assembly 4.1 has a thickness of 0.627 meters, Specific heath capacity of 1988 J/Kg.K, a thermal conductivity of 0.040 W/m.K, and a density of 92 Kg/m^3. Lastly, construction assembly no. 4.2 has a thickness of 0.927 meters, Specific heath capacity of 2013 J/Kg.K, a thermal conductivity of 0.040 W/m.K, and a density of 78 Kg/m^3. These three construction assemblies are represented in Image 5.18.

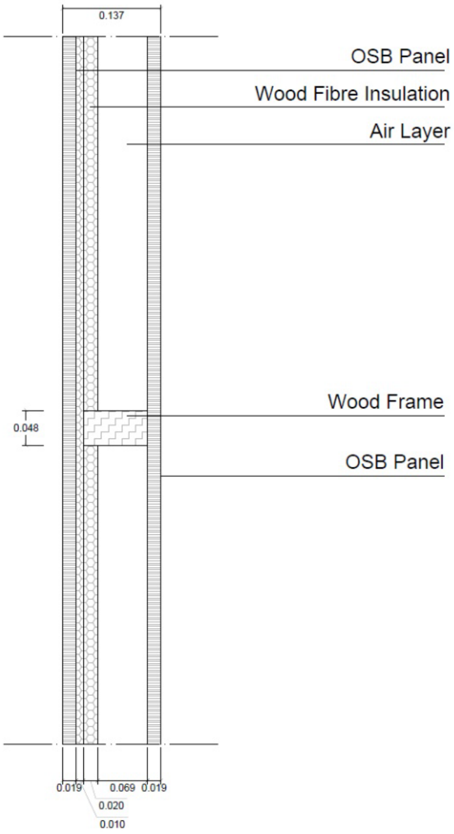
The results of the simulations for Yakutsk present very different data with and without ventilation, opposed to the ones from Needles. When ventilation is not considered, construction assembly 2 has a total heating load (for the three winter months, December, January and February) of 2194 kWh. Construction assembly 4 has 1106 kW/h, no. 4.1, 809 kW/h and 4.2, 387 kW/h.

However, when it comes to the results with ventilation, which are the more accurate ones as people to inhabit the habitat will need ventilation, the differences are not that noticeable at all, as construction assembly 2 needs 27862 kW/h, construction assembly 4, 27404 kW/h, construction assembly 4.1, 27108 kW/h, and construction assembly 4.2, 26659 kW/h. This happens as the outside air that enters the building can be at less than -50º C, and thus a massive amount of energy is necessary to heat it up until it reaches comfort temperatures. For the low difference in energy savings, a solution such as 4.2, with a wall that's one meter wide, doesn't seem to justify the cost in extra materials and the weight it would be necessary for the structure to handle. The characteristics of all construction assemblies and simulation results can be found in tables 5.10 and 5.11.

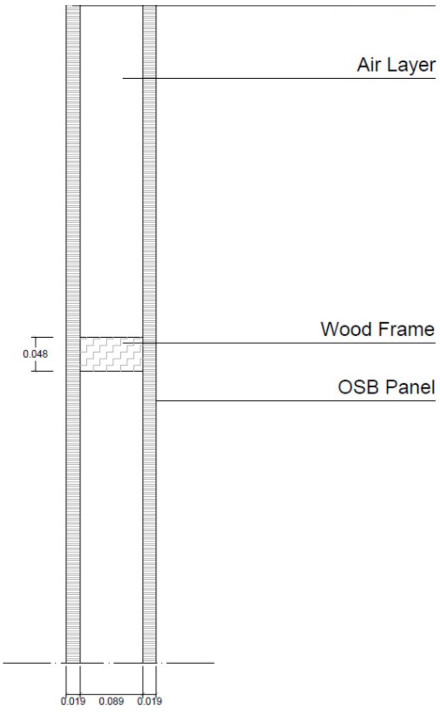
These preliminary simulations allow for conclusions to be made regarding the construction assembly chosen to experiment and simulate in the last stage of the research, with other exploratory architectural proposals, instead of just the base prism. Construction assembly 2 rates higher in Needles. On the other hand, this assembly does not rate the highest in Yakutsk, but the other ones with more insulation had very close energy demand results when the simulation is performed with ventilation, which means that it probably wouldn't be preferable as they would be more expensive and heavier. Thus, it is concluded that the same construction assembly can be used for both extreme environments, and that while some insulation is a positive point for very hot climate, after a certain amount of insultation, for very cold climates such as Yakutsk, it does not make a significant difference to have even more (as construction assembly 4.2 has 0.80 meters of insulation).



Assembly no.3

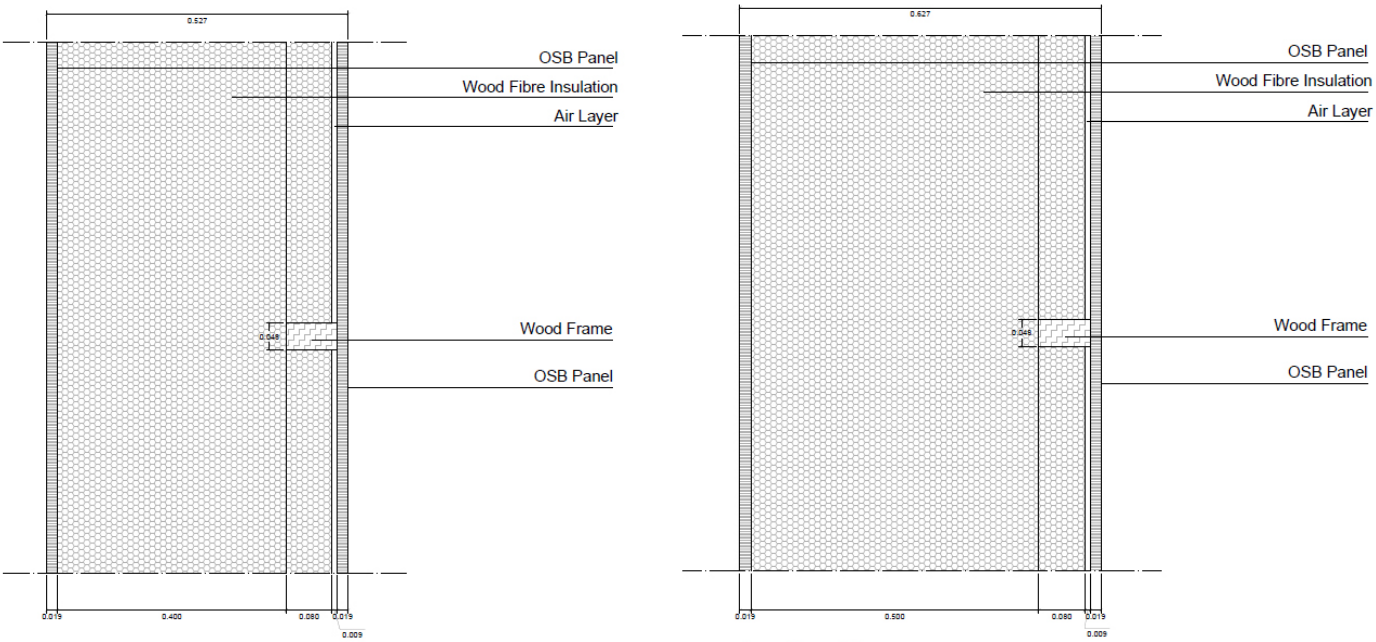


Assembly no. 3.1



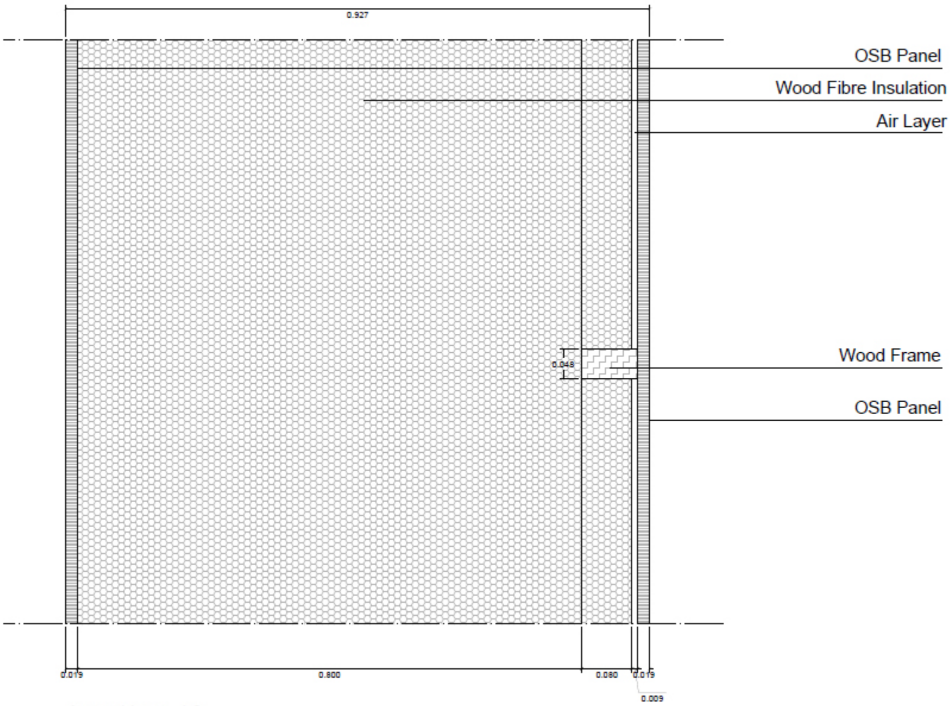
Assembly no. 3.2

Image 5.17 – Specifically defined construction assemblies no. 3, 3.1 and 3.2 for the extreme hot climate of Needles.



Assembly no. 4

Assembly no. 4.1



Assembly no. 4.2

Image 5.18 – Construction assemblies specifically designed for the cold climate of Yakutsk, no. 4, 4.1 and 4.2.

Table 5.11 - Material Properties required by the software to create the materials for the energy simulations of all seven proposed construction assemblies.

Construction Assemblies	**Thickness (m)**	**Specific Heat Capacity (J/Kg.K)**	**Thermal Conductivity (W/m.K)**	**Density (Kg/m^3)**	**Roughness (qualitative)**	**Thermal Absorptance (0-1)**	**Solar Absorptance (0-1)**	**Visible Light Absorptance (0-1)**
No.2	0.327	1936	0.043	130	Medium	0.9	0.7	0.7
No.3	0.137	1756	0.059	237	Medium	0.9	0.7	0.7
No.3.1	0.137	1740	0.110	221	Medium	0.9	0.7	0.7
No.3.2	0.127	1697	0.260	115	Medium	0.9	0.7	0.7
No. 4	0.527	1975	0.041	99	Medium	0.9	0.7	0.7
No.4.1	0.627	1988	0.040	92	Medium	0.9	0.7	0.7
No.4.2	0.927	2013	0.040	78	Medium	0.9	0.7	0.7

Table 5.12 - Simulation results for cooling and heating loads with and without ventilation of the seven construction assemblies, in the climates of Needles and Yakutsk.

Energy Loads (kW/h)	**Needles (without ventilation)**	**Needles (with ventilation)**	**Yakutsk (without ventilation)**	**Yakutsk (with ventilation)**
No.2	1274	6367	2194	27862
No.3	2473	8935	-	
No.3.1	3634	10108	-	-
No.3.2	6169	12951	-	-
No. 4	-	-	1106	27404
No.4.1	-	-	809	27108
No.4.2	-	-	387	26659

The possibility to use just one construction assembly for both environments is a positive aspect as it would save resources to produce, and could present itself as a proper solution for various types of environments, without the need to make alterations. Construction assembly 2 is then the chosen assembly and is the assembly used in all the next stages of the research. In the following chapter, the final simulations for consolidated results will be presented and it's results posteriorly analysed.

It is important to note that OSB was used as a proxy for wooden-based materials. A water-proofing layer needs to be considered in all cases. Other material options that could be used are carbon fibre-reinforced polymer layers, later simulations could be performed in this sense, to understand its effectiveness while also considering the environment's humidity.

CHAPTER 6

Integrated Analysis of an Architecture for Extreme Climates

With all the information gathered in the scope of this research, presented in the previous chapters, the final stage focuses essentially on the main objective of this study: validating an evaluation methodology to address architectural proposals for extreme environments, in terms of interior spatial configuration/design, building morphology, and construction materials. The first step is to devise and propose architecture projects to be evaluated, which are presented previously in Chapter 3 and 4. Afterwards, the final set of evaluation criteria is determined, taking into account all of the changes this criteria list has already gone through throughout the scope of the research. Subsequently, the final MCDA models are created, with the new final set of criteria, giving origin to new evaluation scenarios. Finally, the simulation results are presented, and the MCDA analysis is tested in order to assess the models' robustness and reliability. These results are presented in this chapter.

To further improve the quality of the energy performance simulations outputs, it is necessary to adapt certain elements and requirements of the simulation process. These are questions such as the ventilations settings, schedules, occupation and interior energy requirements for lighting and equipment and appliances, which influence the final energy requirements. It is also necessary to adjust the analysis periods at which the simulations run. While previously the simulations were focused on what was considered the three hottest and the three coldest months, now the analysis period is defined through a threshold value for the daily average external temperature, defined at 15 ºC, thus being able to define a "heating" annual period. As the climates vary so much, the previous approach used for the energy performance simulations, (which consisted of utilizing the traditional notion of "winter" and "summer" months), seemed insufficient as the objective of the research is to evaluate architecture proposals in these climates, and not the climates in themselves. Due to this, it is possible to use analysis periods which are tailored specifically to which climate, with different durations, which allow for more accurate results in terms of building behaviour in those climates. With these essential bases, it is possible to advance into a final set of simulations, where it becomes possible to adequately analyse the proposed architectural design solutions, presented in chapters 3 and 4, regarding "Morphology" and "Spatial Configuration Design

Principles". The simulations are also performed using the self-proposed material construction assembly and the selected glass materials for the windows, presented in chapter 5, regarding "Material Selection".

6.1. Energy Performance Simulations

6.1.1. Defining a Control Climate and Analysis Periods

Throughout the research, it became evident that the two chosen extreme environments had, as indicated, extremely high and low temperatures, where buildings seem to present a couple of thermal behaviours that didn't occur the way it was expected when compared to regular and temperate climates. Due to this, the necessity to have a specified "control climate" came along. For this, the climate of Lisbon is chosen as it is a temperate Mediterranean climate, with mild winter temperatures and although warm summers, not extreme. It is defined that for the final set of simulations, besides the climates of Needles and Yakutsk, the climate conditions for winter and summer in Lisbon would also be simulated, in order to comprehend better the behaviour of the proposed buildings in a temperate climate, as opposed to an extreme one, and be able to see and analyse those differences.

Regarding analysis periods, in the beginning of the research and on the simulations presented previously, two different analysis periods were used for Needles and Yakutsk, corresponding to the summer and the winter months, respectively. For Needles, simulations were ran between June and August, and for Yakutsk between December and February. However, as explained previously, as the climates vary so much, using the traditionally defined "winter" and "summer" months seemed insufficient, as in Yakutsk, for instance, most of the year has very cold temperatures, not just from December to February. Also, there doesn't seem to exist a specific international definition for what a "heating" and a "cooling" yearly period is, instead, this is defined individually by each country. As the purpose of the research is to evaluate different architecture projects and morphologies, new analysis periods are defined, which are tailored to each climate, which produces more accurate energy performance simulations.

In order to obtain these analysis periods, the criteria used in the Portuguese regulation is used as a reference. The heating season initial day is the first day of the 15 day-period which daily average external temperature is below 15 ºC. This season ends at the last day of the period matching the same condition, i.e., which daily average external temperature is below 15 ºC. Regarding the cooling season, in Portugal, it is considered as the months where there is a risk of over-heating, which is a combined effect of solar gains and temperature (Stavropoulos, 2013). This period extends from June to September.

With this information, an excel spreadsheet is created, including all the hourly temperatures of a whole year, for the environments of Needles, Yakutsk, and Lisbon. Then, the average daily temperature is calculated, and the analysis periods are defined by the same criteria explained above. For Needles and Lisbon (summertime), the same process is used for the "cooling" season, except instead of an average daily temperature below 15º C, it was considered an average daily temperature above 28º C. This resulted in the following analysis periods: For Yakutsk, the analysis period of July 20th to June 26th, for Needles, the analysis period of April 29th to October 16th, for Lisbon from October 21st to April 21st (heating season), and from June 1st to September 30th (cooling season).

6.1.2. Simulations Schedules and Loads

To conduct simulations, it is necessary to define building loads and schedules. The plug-in Honeybee for Grasshopper is used to define a constant occupation of six people for the full 24 hours, as in such an extreme environment, it is most likely that people remain within the building, during the whole day.

Regarding the zone loads, the desired equipment load intensity (per unit floor area) is of 7 W/m^2, as values typically range between 2 W/m^2 (for just a laptop or two) to 15 W/m^2 for an office filled with appliances (Tedeschi, 2011). As the habitats have a kitchen area as well as a workspace, considering half of the load seemed an adequate value. The rate of outside air infiltration is then defined. To obtain the value for this parameter, the values suggested by ASHRAE are used, specifically the one used in Passive House (ASHRAE, 2020), as it requires a fewer amount of outside air infiltration. The used value is 0.000071 m^3/s per m^2 of facade at 4 Pa pressure difference. The next load is regarding the desired lightning load per unit floor area, and the values usually range between 3 W/m^2 for efficient LED bulbs to 15 W/m^2 to incandescent heat lamps. The considered value is 3 W/m^2, considering light appliances are as efficient as possible. Ventilation is the next parameter to be defined. It relates to the minimum rate of outdoor air ventilation per unit floor area that is brought in for assuring internal air quality. Typical values range between 0.0001 $m^3/s.m^2$ for houses, and 0.0025 $m^3/s.m^2$ for places like laboratories and clean rooms where dust contamination is a major concern. The defined value for the simulations is 0.0001 $m^3/s.m^2$, as the values are dependent on the floor area of the building and the required ventilation per person, addressed next. This value is necessary by the software as it ensures the necessary ventilation for when the spaces are unoccupied. The following load is the ventilation per person, which relates to the desired minimum rate of outdoor air ventilation, brough in by the mechanical system into the zone per person in the zone. Most standards suggest that a minimal of 0.001 m^3/s for each person in the zone is necessary. The defined value for this load is 0.0083 m^3/s, as defined in the previous chapter of this research.

Another input required for the simulation is an annual schedule, this remained the same throughout the whole research. The habitats are to have people within them 24 hours a day, should it be required.

The next step of the simulation is to defined interior comfortable temperatures for the uses of the habitat, these values also remain the same throughout the research, 26 to 28 degrees Celsius for Needles, and 16 to 18 degrees Celsius for Yakutsk.

The type of simulation, since simulations now consider windows, is also chosen. The third type of solar distribution simulation type is defined, the simulation will perform the solar calculation in a manner that accounts for both direct sun and the light bouncing off outdoor surrounding context. For the inside of the building, all beam solar radiation entering the zone is assumed to fall on the floor. A simple window view factor calculation is used to distribute incoming diffuse solar energy between interior surfaces." (Ladybug Tools LLC, 2021). The fourth type of simulation is considered the most complete one, as it accounts for light bounces outside and inside the zones. However, this does not work in shapes which are concave, as the EnergyPlus engine cannot calculate interior light bouncing of such shapes and is thus advised by Grasshopper that such simulation method not be used, as it will crash the program.

Lastly, the final parameter to input into the simulation are the analysis periods, which have varied and altered since the beginning of the research and were defined previously. For Needles, the defined period was between the 29th of April and the 16th of October, for Yakutsk, between the 20th of July and the 24th of June, and for Lisbon, the 1st of June to the 1st of September for the cooling period, and the 21st of October to the 21st of April for the heating period.

A general scheme of the final Grasshopper simulations script (with all the nodes) can be seen below in image 6.1. In general, all presented information regarding simulation standards, materials, and analysis periods, has been thoroughly studied and experimented, thus allowing for the next stage of the research to start, where the exploratory design proposals can be evaluated, through the means of digital energy performance simulations, which provide results to be input into various MCDA models. This allows for architecture projects to be compared with one another, in order to figure out which are the best to endure the challenging physical conditions of very hot, and very cold, extreme environments.

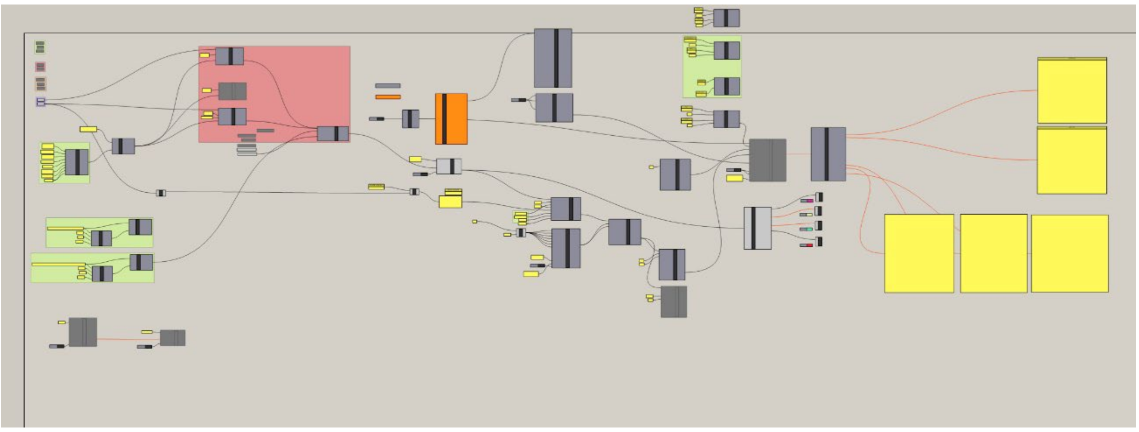


Image 6.1 – Grasshopper script with all the nodes required to import the 3D models, insert self-defined materials into the models, insert zone loads and comfort requirements, climate data, and the final yellow windows are for simulations result presentation in data.

6.1.3. Energy Performance Simulations Results

For the energy performance simulations ran in Grasshopper, all the projects are designed in Rhinoceros 3D and then imported into Grasshopper. Both the surface of the walls of the buildings and the surface of the windows have to be modelled, as in order for Grasshopper to consider window surfaces there must be a “host” surface (the wall) and a “window” surface, overlapping. The software then subtracts the window surface from the “host” wall, and creates both the wall surface and the window surface, with the defined materials. In previous tasks of the research simulating the semi-ellipsoid volume was an issue, as the simulation program didn’t seem to run, due to the curved surfaces. This happens due to the fact that the EnergyPlus engine, which Grasshopper uses to do the energy simulations, cannot run curved surfaces. This ended up being a handicap of the software. In order to solve this question, it is necessary to transform the building 3D surface into a geometrical mesh, which is then reformed into a surface built out of very small planar surfaces. This allowed the 3D volume to keep its initial curved shape, but being now divided into small planar surfaces with which the EnergyPlus engine can work with and thus is able to perform the required energy simulations.

As the more complex a shape is, the longer it takes for the simulation to perform, it is asked of Grasshopper to divide the surfaces into the smallest possible amount of them. The difference between the 3D surfaces in terms of digital representation, before and after this process, are seen in image 6.2.

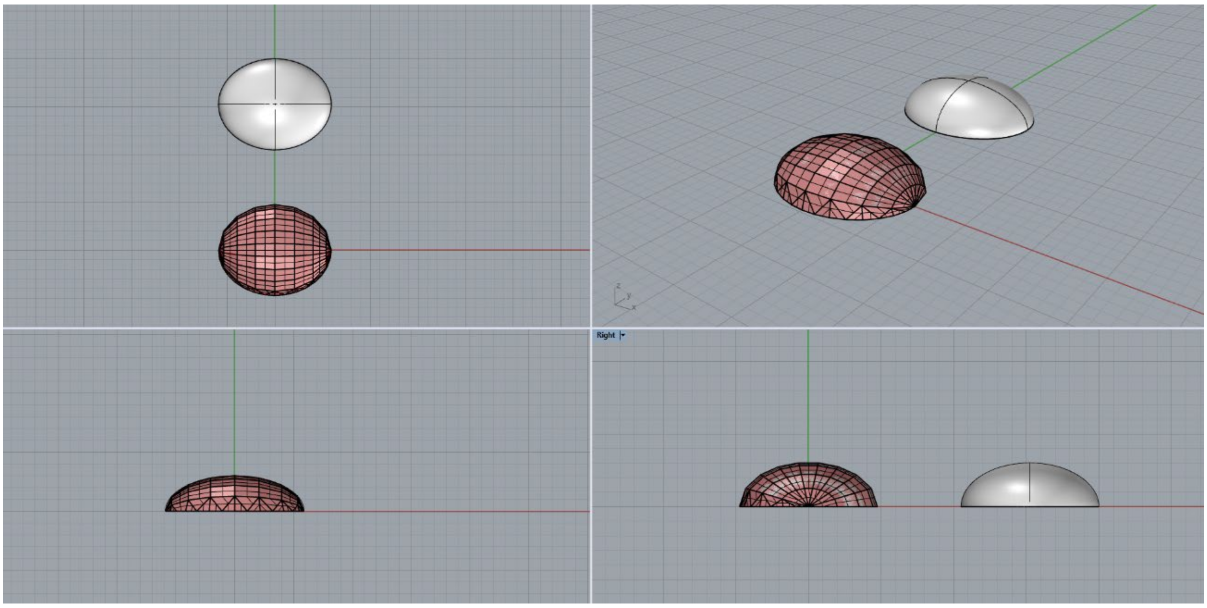


Image 6.2 – Differences in the semi-ellipsoid project shape between the curved surface created by Rhino (in silver), and the imported Grasshopper shape (in red), divided into planar surfaces to be simulated and analysed.

After creating and importing the projects 3D models into Grasshopper, it is necessary to provide them materials. The construction materials that are the input to the models are the ones of wood-based construction assembly 2, as previously presented, and the glass materials are either the Tripe Suncool Optifloat Clear or the Triple Glazing Iplus Advanced, whether the simulation was being performed for Needles or Yakutsk, respectively. It is important to note that the floor surfaces of all models are considered to be adiabatic. Therefore, energy transfer through the floor is not considered, as it could provide less accurate results, because this energy transfer (typically a heat loss) is dependable on the type of material that the building is set on, and one of the purposes of this study was to comprehend the impact of the buildings morphology and built material. Turning the floors into adiabatic allows for the research to be more focused on the two questions mentioned earlier.

The first results obtained are regarding energy consumption. In this case, the building that rates the best on the energy performance criteria varies from climate to climate.

Various energy simulations are run in Grasshopper, using the defined final criteria presented previously. Although buildings without windows shouldn't be considered, as this proved to be an essential element of the habitat for the psychological well-being of the inhabitants, simulations are still run in that sense to understand the effectiveness of just the shape of the project. Almost all buildings which have better energy consumption results this way, have the best results when windows were considered as well. This proves to be an exception only in Yakutsk, which will be analysed and justified posteriorly in the discussion of the results. Other than the values for energy consumption, Form Factor is also analysed, to understand if there is a possible relation with it, to also be discussed in the next chapter. The results of all energy simulations and their results can be seen in tables 6.1 to 6.4.

Table 6.1 - Representation of the energy consumption simulation results, ran in Grasshopper, for the four proposed exploratory architecture projects for the environment of Yakutsk, with the best values marked in blue.

Projects (Yakutsk)	Form Factor (S/A)	Form Factor (S/V)	Total Heating Load (no windows) kWh	Total Heating Load (South windows) kWh	kWh/day (with windows)	kWh/day /m^2 (with windows)
Base Prism	2.41	1.00	18957.63	18135.44	53.18	0.94
High Prism	2.91	1.15	21190.68	20358.62	59.70	0.70
Ellipsoid	1.47	0.70	18625.28	18246.98	53.51	0.62
High Ellipsoid	1.48	0.72	19487.90	18103.21	53.09	0.53

Table 6.2 - Representation of the energy consumption simulation results, ran in Grasshopper, for the four proposed exploratory architecture projects for the environment of Lisbon in Winter, with the best values marked in blue.

Projects (Lisbon - Winter)	Form Factor (S/A)	Form Factor (S/V)	Total Heating Load (no windows) kWh	Total Heating Load (South windows) kWh	kWh/day (with windows)	kWh/day /m^2 (with windows)
Base Prism	2.41	1.00	804.82	453.66	2.49	0.04
High Prism	2.91	1.15	1189.67	732.08	4.02	0.05
Ellipsoid	1.47	0.70	579.39	283.24	1.56	0.02
High Ellipsoid	1.48	0.72	941.77	418.86	2.31	0.02

Table 6.3 - Representation of the energy consumption simulation results, ran in Grasshopper, for the four proposed exploratory architecture projects for the environment of Needles, with the best values marked in orange.

Projects (Needles)	Form Factor (S/A)	Form Factor (S/V)	Total Cooling Load (no windows) kWh	Total Cooling Load (North windows) kWh	kWh/day (with windows)	kWh/day /m^2 (with windows)
Base Prism	2.41	1.00	3127.19	3445.53	20.27	0.36
High Prism	2.91	1.15	3154.46	3456.45	20.33	0.24
Ellipsoid	1.47	0.70	4277.92	7022.94	41.31	0.48
High Ellipsoid	1.48	0.72	3257.89	4750.99	29.95	0.28

Table 6.4 - Representation of the energy consumption simulation results, ran in Grasshopper, for the four proposed exploratory architecture projects for the environment of Lisbon - Summer, with the best values marked in orange.

Projects (Lisbon - Summer)	Form Factor (S/A)	Form Factor (S/V)	Total Cooling Load (no windows) kWh	Total Cooling Load (North windows) kWh	kWh/day (with windows)	kWh/day /m^2 (with windows)
Base Prism	2.41	1.00	177.72	271.2	2.95	0.05
High Prism	2.91	1.15	38.51	77.38	0.84	0.01
Ellipsoid	1.47	0.70	398.14	1495.12	16.25	0.19
High Ellipsoid	1.48	0.72	98.92	479.69	5.21	0.05

The presented results represent what is the first stage of the assessment process, which is done in Grasshopper, in order to have the necessary energy data to fill in the final MCDA models.

6.2. Final MCDA Models for Architectural Evaluation

After all the simulation parameters are defined, it is also necessary to determine the final set of criteria to input into the MCDA models, in order to validate and evaluate the proposed architecture projects. A couple of changes are made regarding the previous MCDA models, which were presented at PLEA2020. The PLEA model considered four main groups, which were Energy Efficiency, (containing both Free-floating Temperature and Energy

Consumption), Material Performance (with Service Temperature, Material Fracture Thoughness, Construction Weight, Carbon Foot-print and End-of-Life), Architecture Performance (which consisted of Area, Height and Space Organization), and lastly Circularity (which contained all "environmental impact" criteria, Carbon Footprint, Energy Consumption, Free-floating Interior Temperature and End of Life). The research done for PLEA allowed to reach certain conclusions, such as the redundancy of the "Circularity" criteria group, which was already eliminated in the last two proposed MCDA models presented in the conference, and the average free-floating interior temperature was also retrieved from these models as it also became redundant, especially when it is impossible for humans to inhabit within these extreme temperatures, so the buildings always require climatization.

These changes are maintained in the final set of models. Other changes that are made for the final models are: the criterion of Service Temperature, removed from the Yakutsk (or cold climate) models as using construction assembly no.2 is a guarantee that the material can withstand extremely cold temperatures; Material Fracture Toughness is also ensured by the construction assembly, thus becoming an unnecessary criterion which is removed; and Recycle Potential, being a construction assembly essentially built using wood and wood derivatives, it's recycle potential is also guaranteed, which also made the criterion unnecessary.

The final set of criteria is then defined into three groups, similarly to those presented at PLEA. "Energy Consumption" remained as a criteria group, but it no longer considers free-floating temperature. Instead, it considers energy load per day (KWh/day, in a normalization process which objective is to allow for comparisons along the three climates), which remains named "Energy Consumption"; and energy load per day per unit floor area (KWh/m^2), which for the purpose of this research is named "Energy Intensity"; this allows for a more accurate measure of energy consumption depending on each of the different architecture project proposals. For the "Material Performance" theme, the Carbon Footprint criterion remains, the proposed construction assembly has negative embodied carbon values, which makes it extremely environmentally friendly (the material stores 1.5 kgCO$_{2e}$/kg, and the Lightness criterion is added. This criterion relates to the full weight of the construction (in Kg) in terms of required construction material, including both the wood-based materials and the necessary glass surfaces. This is important as the lighter a construction is, the least costly it will be to transport and build, making it a better option. Finally, the third group, "Architectural Performance" is divided into the same three criterions as the previous model: Floor Area, Height and Space Organization. The minimal value for floor area is the one proposed in the

NASA research (NASA Human Research Program, 2015), however, by having buildings with an ellipse as a base, it allows for more floor area, which is a positive in terms of habitat comfort. For Height, a minimum of 2.40 meters was defined in order for the space to be comfortable (Ministério Público, 1951). However, the semi-ellipsoid allows for a central habitat zone with more height, which can be kept that way or used for storage. As this criterion is defined as qualitative, a minimum height is always ensured (considered "min"), and in case there's extra height (on the semi-ellipsoids), it rates slightly higher (considered "ext"). Lastly, Spatial Organization is also defined as a qualitative criterion, as the minimum conditions are always guaranteed as by the NASA research, and using the first simple prism as a reference for design guidelines. The case of the prism's design always rates "min", as it is the minimal are that guarantees good spatial organization. Nonetheless, all the other projects allow for more area (which can be used for storage, for example) so, due to this, the semi-ellipsoids rate extra (defined as "ext"), as they also present more possibilities of flexibility in terms of space usage. Regarding the high prism and the high semi-ellipsoid, these rate super extra, as they have areas that can be used for various purposes (defined as "extS").

Table 6.5 - Inserted values of each proposed architecture project on each criterion for the MCDA model, quantitative and qualitative, for the environment of Yakutsk.

Projects (Yakutsk)	Energy (kWh/day)	Energy In (kWh/day/m^2)	Lightness (Kg)	Carbon (kgCO$_2$e)	Floor Area (m^2)	Height (m)	Spatial Organization
Base Prism	53.18	0.939	8220	-14	56.64	min	min
High Prism	59.70	0.703	14167	-16	84.96	min	ext
Ellipsoid	53.51	0.623	9030	-13	85.83	ext	extS
High Ellipsoid	53.09	0.526	10637	-13	100.84	min	extS

Table 6.6 - Inserted values of each proposed architecture project on each criterion for the MCDA model, quantitative and qualitative, for the environment of Needles.

Projects (Needles)	Energy (kWh/day)	Energy In (kWh/day/m^2)	Lightness (Kg)	Carbon (kgCO$_2$e)	Floor Area (m^2)	Height (m)	Spatial Organization
Base Prism	20.27	0.358	8143	-15	56.64	min	min
High Prism	20.33	0.239	14067	-16	84.96	min	ext
Ellipsoid	41.31	0.481	8924	-14	85.83	ext	extS
High Ellipsoid	27.95	0.277	10512	-14	100.84	min	extS

All the criteria and values for each exploratory architecture project, in the different climates can be seen in tables 6.5 to 6.8.

Table 6.7 - Inserted values of each proposed architecture project on each criterion for the MCDA model, quantitative and qualitative, for the environment of Lisbon, during heating season ("winter").

Projects (Lisbon W)	Energy (kWh/day)	Energy In (kWh/day/m^2)	Lightness (Kg)	Carbon (kgCO$_2$e)	Floor Area (m^2)	Height (m)	Spatial Organization
Base Prism	2.49	0.044	8220	-14	56.64	min	min
High Prism	4.02	0.047	14167	-16	84.96	min	ext
Ellipsoid	1.56	0.018	9030	-13	85.83	ext	extS
High Ellipsoid	2.30	0.023	10637	-13	100.84	min	extS

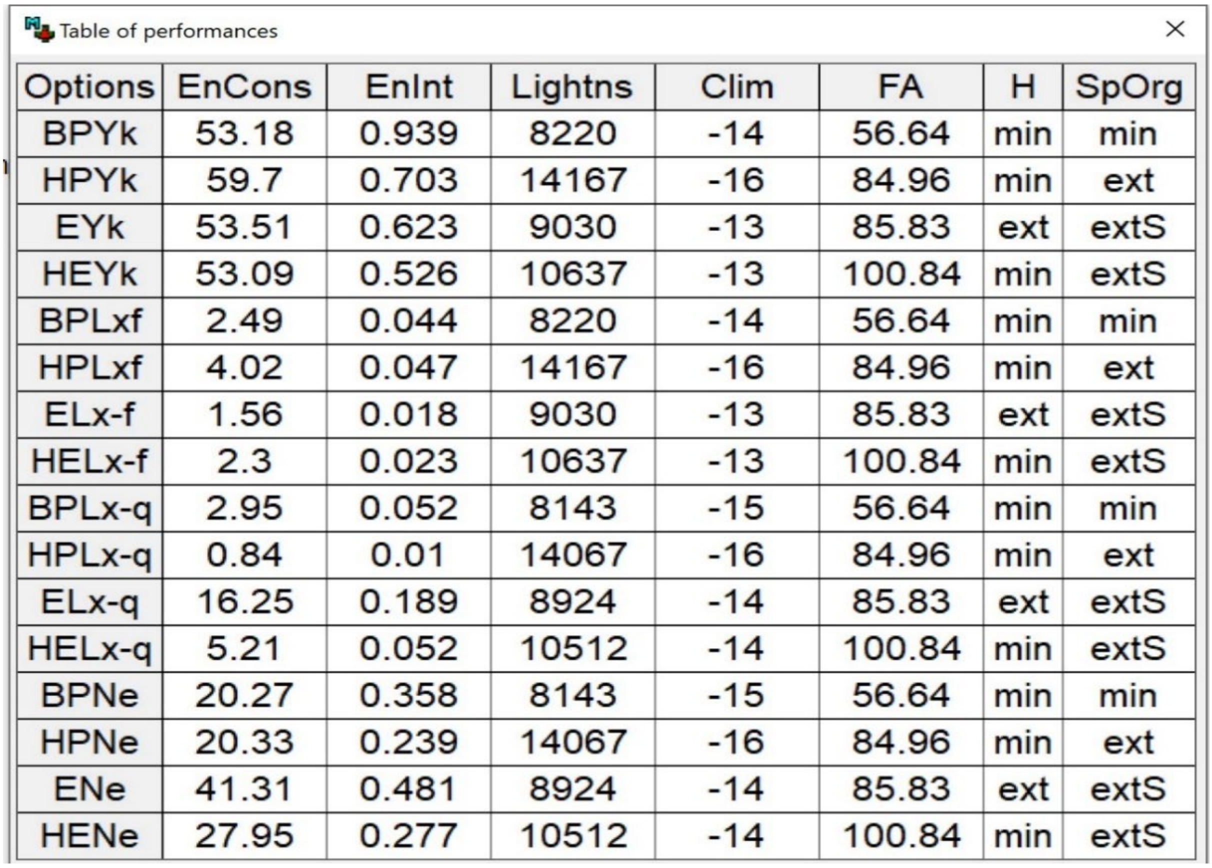
Table 6.8 - Inserted values of each proposed architecture project on each criterion for the MCDA model, quantitative and qualitative, for the environment of Lisbon, during cooling season ("summer").

Projects (Lisbon S)	Energy (kWh/day)	Energy (kWh/day/m^2)	Lightness (Kg)	Carbon (kgCO$_2$e)	Floor Area (m^2)	Height (m)	Spatial Organization
Base Prism	2.95	0.052	8143	-15	56.64	min	min
High Prism	0.84	0.010	14067	-16	84.96	min	ext
Ellipsoid	16.25	0.189	8924	-14	85.83	ext	extS
High Ellipsoid	5.21	0.052	10512	-14	100.84	min	extS

The values and criteria presented in the previous tables represent the criteria that is input into the MCDA models, as well as the performance values for each of the proposed architecture projects. The projects are the "options" of the model, and so this allows the creation of MCDA models with 4 options and 7 criteria. Similarly, to the ones presented in PLEA, 4 final MCDA models are also created. The values and criteria presented in the previous tables represent the criteria that are input into the MCDA models, as well as the performance values for each of the proposed architecture projects. The projects are the "options" of the model, so all MCDA models have four possible options, the "Base Prism", the "High Prism", the "Ellipsoid" and the "High Ellipsoid", for each of the four climates, Yakutsk, Needles, Lisbon – Winter and Lisbon – Summer. In fact, this amounted to a total of 16 options, which are input into the final basic MCDA model. So, all the information presented in the previous 4 tables is input into the software M-MACBETH. The decision to input all the options in the model is taken because that way it would be possible not only to understand how each option rates according to climate, but also how the options relate to one another. By having input all the options it is possible to digitally visualize which rated higher than others, in all possible climates.

The M-MACBETH table of performances can be seen in table 27; this is the table used for all the final MCDA models, as what is altered in the variation models is only the weighting between criteria, to create additional scenarios, to represent alternative realities. “BP” stands for “Base Prism”, “HP” stands for “High Prism”, “E” stands for “Ellipsoid” and “HE” stands for “High Ellipsoid”. The letters that follow these accronyms are “Yk” which stands for “Yakutsk”, “Ne”, which stands for “Needles”, “Lxf/Lx-f” which stands for “Lisbon – Winter” and “Lxq/Lx-q” which stands for “Lisbon – Summer”.

Table 6.9 - – Table of performances inserted into the basic final MCDA model, in the software M-MACBETH



Options	EnCons	EnInt	Lightns	Clim	FA	H	SpOrg
BPYk	53.18	0.939	8220	-14	56.64	min	min
HPYk	59.7	0.703	14167	-16	84.96	min	ext
EYk	53.51	0.623	9030	-13	85.83	ext	extS
HEYk	53.09	0.526	10637	-13	100.84	min	extS
BPLxf	2.49	0.044	8220	-14	56.64	min	min
HPLxf	4.02	0.047	14167	-16	84.96	min	ext
ELx-f	1.56	0.018	9030	-13	85.83	ext	extS
HELx-f	2.3	0.023	10637	-13	100.84	min	extS
BPLx-q	2.95	0.052	8143	-15	56.64	min	min
HPLx-q	0.84	0.01	14067	-16	84.96	min	ext
ELx-q	16.25	0.189	8924	-14	85.83	ext	extS
HELx-q	5.21	0.052	10512	-14	100.84	min	extS
BPNe	20.27	0.358	8143	-15	56.64	min	min
HPNe	20.33	0.239	14067	-16	84.96	min	ext
ENe	41.31	0.481	8924	-14	85.83	ext	extS
HENe	27.95	0.277	10512	-14	100.84	min	extS

Regarding the scales of the criteria, these are dependent of each criterion by itself. For Energy Consumption per day, the lowest value of consumed energy of the sample is considered the best (0.84), and thus rates the 100%, the highest value of consumed energy of the sample is considered the worst (62.75), and thus rates 0%. Variation between these two limits is set to be linear in order to have an even distribution in the scale. The following criterion, Energy Consumption per day per unit floor area (here named Energy Intensity), follows the same pattern. As the lowest value for this criterion is 0.01, the value of 0 is considered as the 100%, while the maximum value, 1.005 is considered the worst at 0%. Again, a linear variation between these limits is determined. This allows for a distributed scale, as it's presented on the M-MACBETH graph, presented on Image 6.3.

For the criterion of lightness, a different approach is used. For the value of 100% (which rates the best), the lowest weight value of all the options is considered, the 8143, while for the value of 0% (that rates the worst), the highest weight value of all options is considered, 14167. This way, the lightest options always rates next to 100%, while the heaviest one's rates as 100%. Regarding the criterion climate change potential (or embodied carbon for the scope of this research), value 44 is defined as the 0%. This value is defined as it is the embodied carbon value

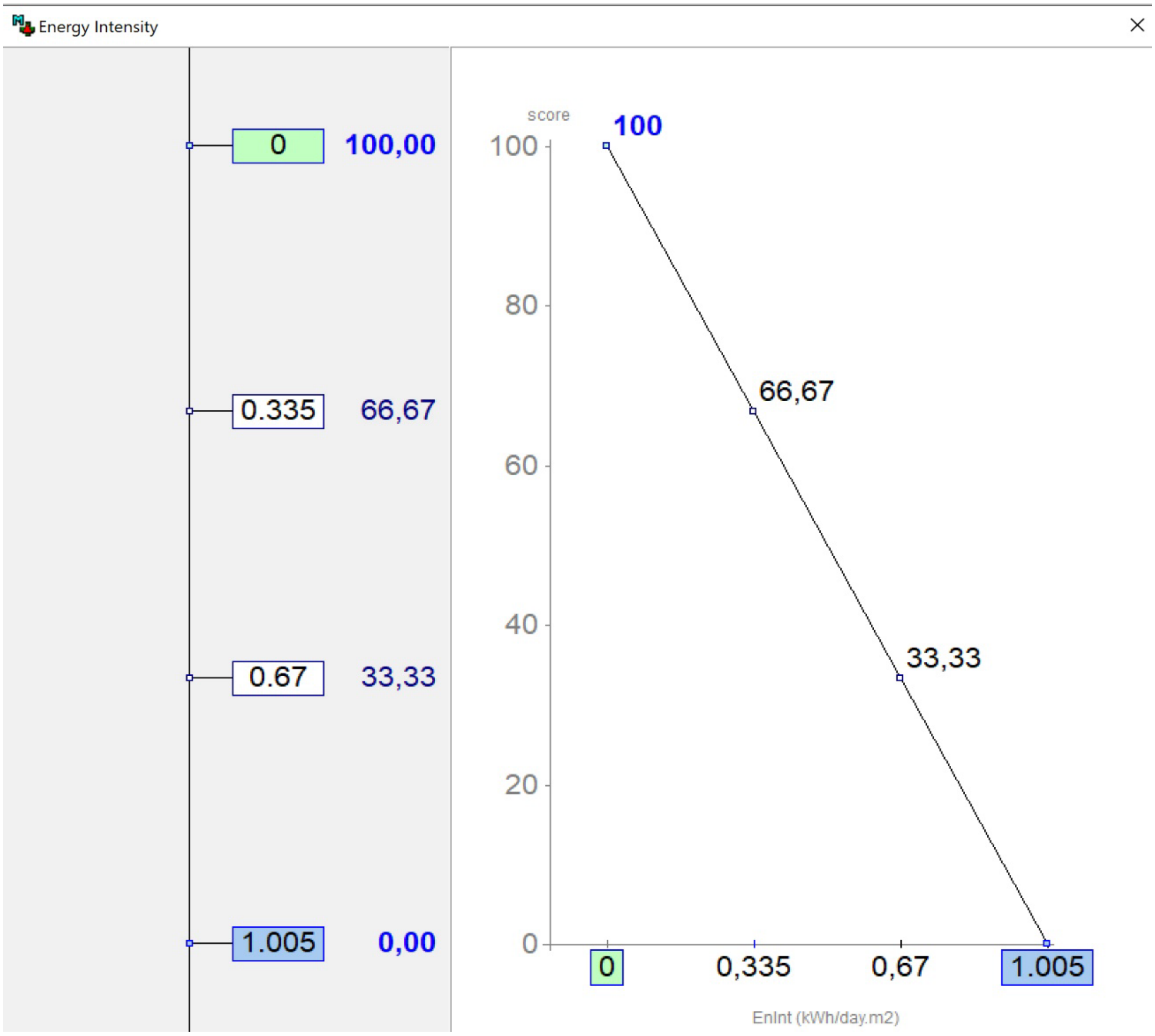


Image 6.3 – Weight scale for the values of the criterion Energy Intensity, as presented in the software M-MACBETH.

of a 20 centimetres thick brick wall with plaster (University of Bath, 2011). For the 100%, the value of 0 is defined, this way, all the values of incorporated carbon which rate below 0, will always be superior to 100%, which serves to prove they're even better than what's ideal, as the ideal option would be one which has as little embodied carbon as possible. For the criterion of Floor Area, the minimal amount of possible area (which is 56 m^2), rates 100%, as it is the value that is necessary, it can't be less, and the maximum area of all the options, which is 112 rates 200%, as it's higher than the minimum value, it's more positive. This way, since all the areas are between the 56 and the 112 square meters, they will always rate over 100% as they are, at least, ideal. In order to construct the scale, values for 0% and less are necessary to balance the scale out, so 55 m^2 is defined as the 0%, as it can't be done being that it's lower than the minimal possible area, and 54 m^2 is defined as the -100%. The weighting of this criterion can be seen in image 82. Images 81 and 82, representing the weighting of those two criterion are only

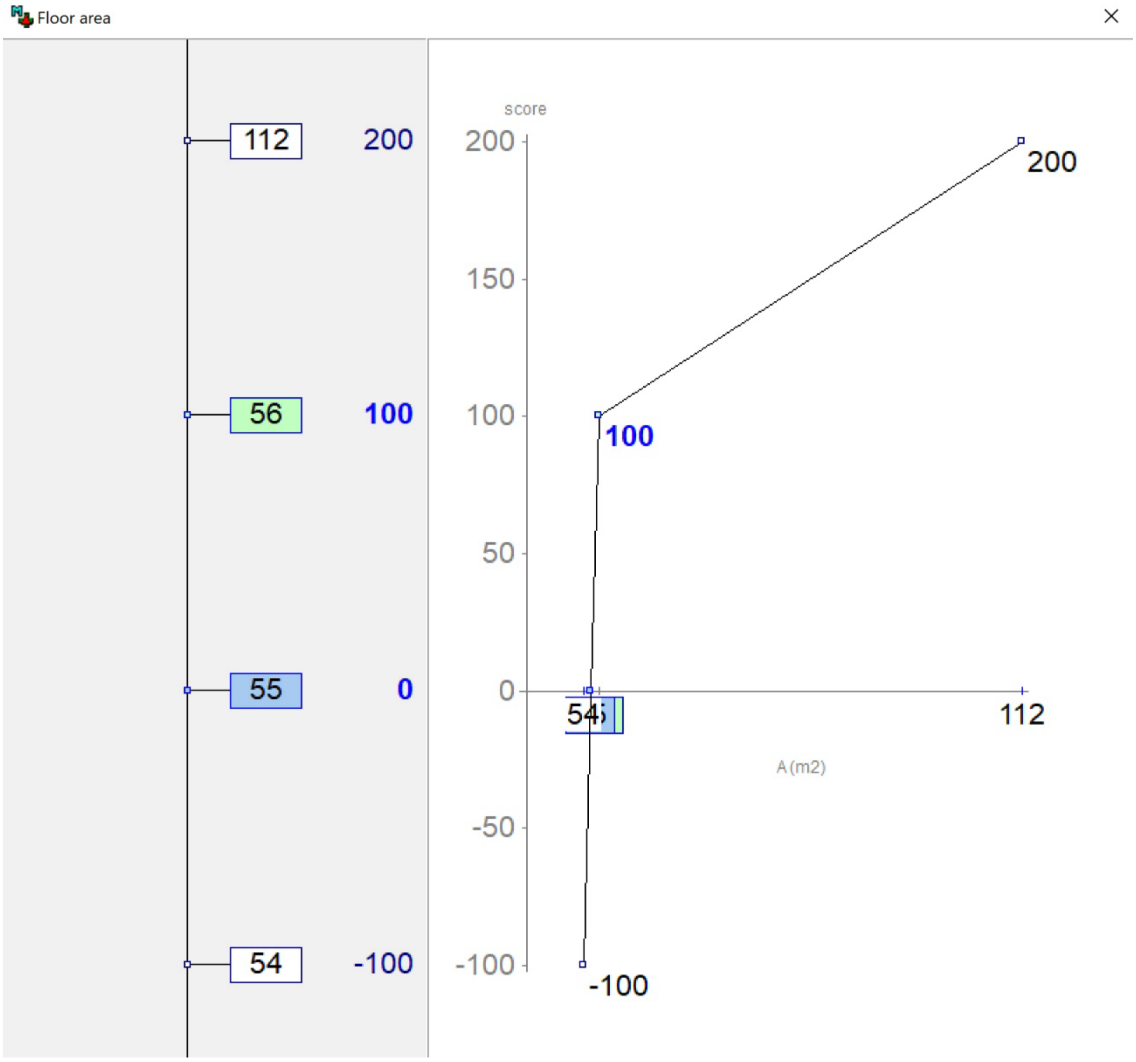
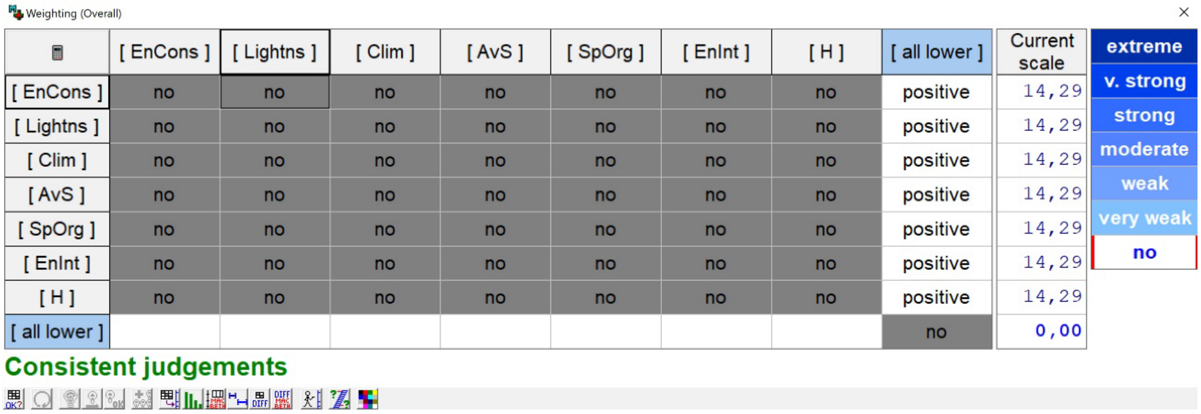


Image 6.4 - Weight scale for the values of the criterion Floor Area, as presented in the software M-MACBETH.

indicative examples. The weighting for the criterion of Height is done in a slightly different way, as it is the first of the seven to be a qualitative criterion. As all option rate at least “min” (minimum), which stands at 2.40 meters, this is the value for the 100%. The height of the ellipsoid, which is slightly higher, 3.05 meters, is defined as “ext” (extra height), rating 115%. As all options ensure at least the minimum height, so 0% is not considered. For the criterion of Spatial Organization, which is also a qualitative criterion, “min” (minimum) stands at 100%, as all options rate the minimum value, “ext” (extra) rates at 115%, and “extS” (extra super) rates 130%. This happens as the other options rather than the Base Prism allow for more area and therefore more spatial options. Once again, as all options ensure the essential guidelines for the interior configuration of spaces, the 0% is not considered.

For the first MCDA model, which is named “V0”, no weighting between criteria is given, meaning no criterion is superior in importance to another, and they all share the same percentage in the overall model scale. Seven criteria means that each criterion is worth 14.29% in the model scale. This is a generic model and allows to understand which of the four architecture proposals is better, for each climate, if all these questions have the same importance. The overall M-MACBETH table representing the difference of attractiveness for this model can be seen in the image 6.5.



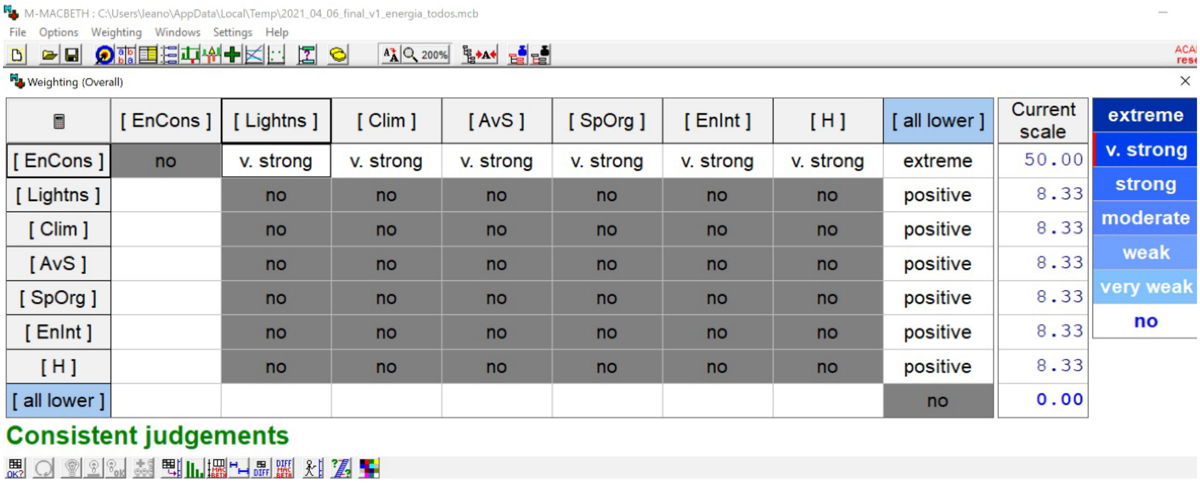
	[EnCons]	[Lightns]	[Clim]	[AvS]	[SpOrg]	[EnInt]	[H]	[all lower]	Current scale
[EnCons]	no	no	no	no	no	no	no	positive	14,29
[Lightns]	no	no	no	no	no	no	no	positive	14,29
[Clim]	no	no	no	no	no	no	no	positive	14,29
[AvS]	no	no	no	no	no	no	no	positive	14,29
[SpOrg]	no	no	no	no	no	no	no	positive	14,29
[EnInt]	no	no	no	no	no	no	no	positive	14,29
[H]	no	no	no	no	no	no	no	positive	14,29
[all lower]								no	0,00

Consistent judgements

Image 6.5 - Overall Weighting table of the software M-MACBETH of the MCDA model “V0”, with all the criteria, their values and judgments.

The second MCDA model is focused on energy consumption. This is to understand which of the architectural proposals would be better if the major concern was energy, and for this case specifically, the energy criterion that greater weight is given, is to Energy Consumption, meaning how much energy is spent daily. For this model, a 50% scale value of importance is given to Energy Consumption, meaning that the rest of the criteria are given only 8.33% of importance, all having the same value. When it comes to judgements, Energy Consumption is deemed very strong when in comparison to other criteria, the overall weighting table of this model can be seen in image 6.6. This model is named “Energy”.

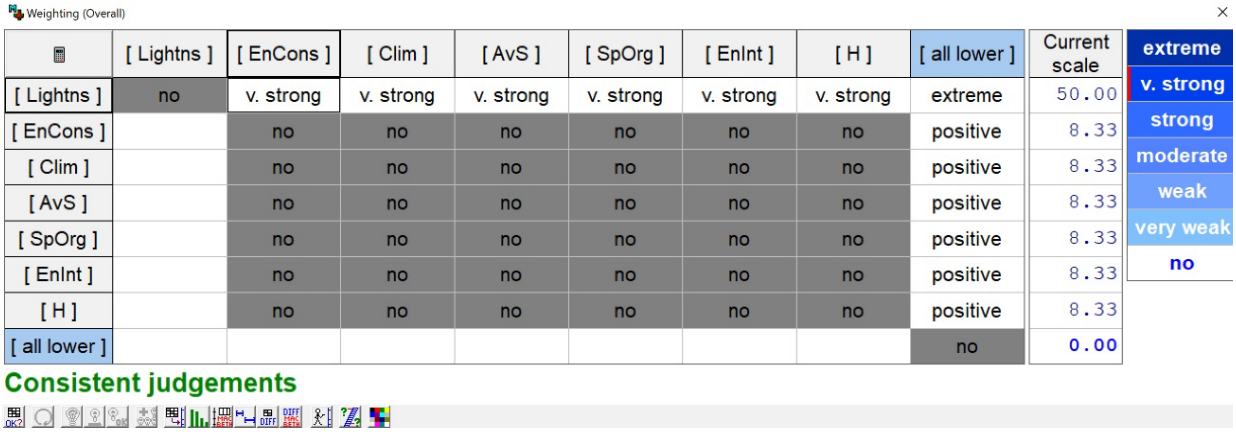
The third MCDA model is focused on the proposal’s weight, thus on the criterion “Lightness”. An identical approach to the previous model was used, in this case, 50% of the scale value of importance is given to “Lightness”, while the rest of the criteria weight 8.33%. This model allows to conclude which of the architectural proposals would be better if the main essential concern is how much the building weights. The judgements are defined in the same way they were in the previous model, the difference between “Lightness” and the rest of the criteria is “Very Strong”, to indicate its importance. This model is named “Lightness” and its overall table of weighting its presented in Image 6.7.



	[EnCons]	[Lightns]	[Clim]	[AvS]	[SpOrg]	[EnInt]	[H]	[all lower]	Current scale
[EnCons]	no	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	extreme	50.00
[Lightns]		no	no	no	no	no	no	positive	8.33
[Clim]		no	no	no	no	no	no	positive	8.33
[AvS]		no	no	no	no	no	no	positive	8.33
[SpOrg]		no	no	no	no	no	no	positive	8.33
[EnInt]		no	no	no	no	no	no	positive	8.33
[H]		no	no	no	no	no	no	positive	8.33
[all lower]								no	0.00

Consistent judgements

Image 6.6 - Overall Weighting table of the software M-MACBETH of the MCDA model “Energy”, with all the criteria, their values, and judgments.

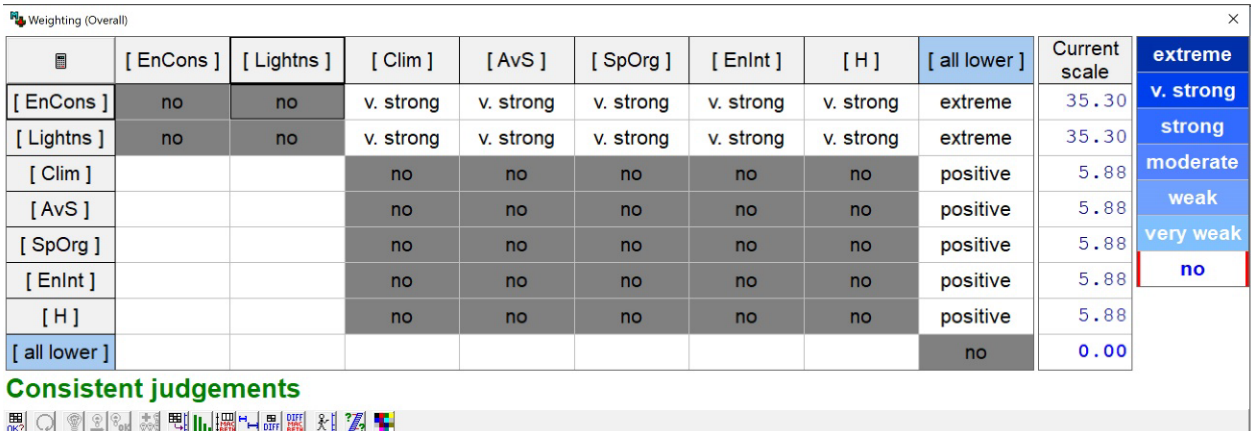


	[Lightns]	[EnCons]	[Clim]	[AvS]	[SpOrg]	[EnInt]	[H]	[all lower]	Current scale
[Lightns]	no	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	extreme	50.00
[EnCons]		no	no	no	no	no	no	positive	8.33
[Clim]		no	no	no	no	no	no	positive	8.33
[AvS]		no	no	no	no	no	no	positive	8.33
[SpOrg]		no	no	no	no	no	no	positive	8.33
[EnInt]		no	no	no	no	no	no	positive	8.33
[H]		no	no	no	no	no	no	positive	8.33
[all lower]								no	0.00

Consistent judgements

Image 6.7 - Overall Weighting table of the software M-MACBETH of the MCDA model “Lightness”, with all the criteria, their values, and judgments.

Lastly, the fourth MCDA model is a conjunction of the two previous ones, it is named "Energy+Lightness", and it is meant to give equal importance to both energy waste and construction weight, as these would probably be the most critical questions when building in extreme environments. This is due to the fact that it should be as easy as possible to transport and assemble on site, less weight and construction time would also make it cheaper, and less energy loads would make it more environmentally friendly, and more sustainable the longer it's used. As long as the other criteria, which are also important are granted, this seems to be an adequate weighting scale to evaluate these building proposals. In this model, more importance is given to the criteria "Energy Consumption" and "Lightness", which were both given 35.30% of importance in the MCDA model's scale. The rest of the criteria are given 5.88% of importance. Regarding Judgments, both main criteria are considered "Very Strong" regarding all the other criteria, as done above, but this time to two criteria instead of just one.The overall table of weighting for this model can also be seen in image 6.8.



	[EnCons]	[Lightns]	[Clim]	[AvS]	[SpOrg]	[EnInt]	[H]	[all lower]	Current scale
[EnCons]	no	no	v. strong	v. strong	v. strong	v. strong	v. strong	extreme	35.30
[Lightns]	no	no	v. strong	v. strong	v. strong	v. strong	v. strong	extreme	35.30
[Clim]			no	no	no	no	no	positive	5.88
[AvS]			no	no	no	no	no	positive	5.88
[SpOrg]			no	no	no	no	no	positive	5.88
[EnInt]			no	no	no	no	no	positive	5.88
[H]			no	no	no	no	no	positive	5.88
[all lower]								no	0.00

Consistent judgements

Image 6.8 - Overall Weighting table of the software M-MACBETH of the MCDA model "Energy+Lightness", with all the criteria, their values, and judgments.

6.2.1. Final MCDA Models Results

Overall, four MCDA final models are created, in order to access what would be the best architecture project proposal, for both extreme environments and the "control" environments of Lisbon (summer and winter). For the first MCDA model (V0), where all the criteria have the same importance, meaning the same weight in the scale (14%) and there is no attribution of difference of attractiveness between the criteria (making it the first final generic model), the results depending on climate were as follows. Due to the fact that there are options that rate higher than 100%, as explained above, there are overall ratings higher than this value. For Yakutsk, the ellipsoid rates higher (95.86%), followed by the high ellipsoid (94.97%), and the base prism (79.10%), with the high prism rating the worst (77.10%). For the environment of Lisbon, in winter, the ellipsoid rates the best of all values (116.44%), followed by the high ellipsoid (113.83%), the base prism (103.51%) and lastly the high prism (99.27%). Regarding the very hot climate of Needles, the best rated is the high ellipsoid (104.93%), followed by the ellipsoid (101.27%), next to the base prism (95.46%), ending on the high prism (93.02%). Finally, for the environment of Lisbon in summertime, the best rated project is the high ellipsoid (113.37%), closely next to the ellipsoid (111.20%), followed by the base prism (103.80%) and lastly by the high prism (100.76%). A collection of this data of each rated project by climate can be seen in table 6.10 and image 6.9.

Table 6.10 - Overall MCDA model score for the model "V0" of the four architecture projects considering the 7 final criteria, depending on the climate. The best values are indicated in green.

Projects (Overall MCDA score)	Yakutsk	Lisbon – Winter	Needles	Lisbon - Summer
Base Prism	79.10%	103.51%	95.46%	103.80%
High Prism	77.10%	99.27%	93.02%	100.76%
Ellipsoid	95.86%	116.44%	101.27%	111.20%
High Ellipsoid	94.97%	113.83%	104.93%	113.37%

The second MCDA model, (named "Energy"), is where the energy consumption criteria are given the greatest importance (50%), while the rest of the criteria share the same importance (8.33%). This criterion for energy also has the "very strong" difference of attractiveness in comparison to all the other criteria. As energy requirements have a much bigger weight in the overall scale, the results are slightly different, with the overall ratings values being much lower than previously. For Yakutsk, the project which rates the highest is the ellipsoid (62.13%), followed by the high ellipsoid (61.90%), the base prism (52.58%) and lastly the high prism (47.03%). For the climate of Lisbon during wintertime, the project with the higher score is the ellipsoid (109.08%), next to the high ellipsoid (107.06%), then the base prism (100.91%) and the last one is the high prism (97.41%). Regarding the climate of Needles, the best rated proposal is the high ellipsoid (84.62%), followed by the base prism (84.26%), next to the high prism (82.79%) and lastly the ellipsoid (73.49%). For the last climate, Lisbon during summer, the best rated is the high ellipsoid (104.83%), then the base prism (100.77%), followed by the high prism (100.42%) and the ellipsoid (96.14%).

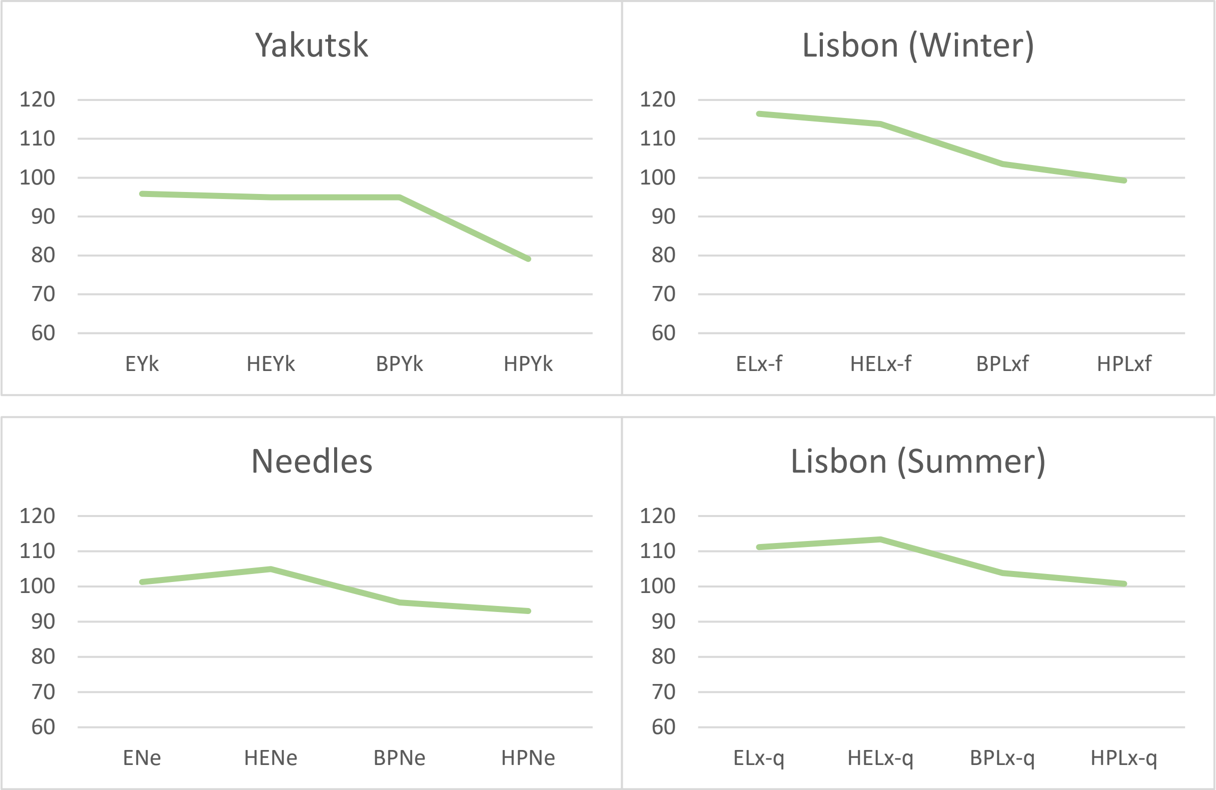


Image 6.9 – Graphical representation of the Overall MCDA model "V0" score data of the four architecture projects (organized in the following way: Ellipsoid, High Ellipsoid, Base Prism and High Prism), for the four proposed climates.

Table 6.11 - Overall MCDA model score for the model "Energy" of the four architecture projects considering the 7 final criteria, depending on the climate. The best values are indicated in green.

Projects (Overall MCDA score)	Yakutsk	Lisbon – Winter	Needles	Lisbon - Summer
Base Prism	52.58%	100.91%	84.26%	100.77%
High Prism	47.03%	97.41%	82.79%	100.42%
Ellipsoid	62.13%	109.08%	73.49%	96.14%
High Ellipsoid	61.90%	107.06%	84.62%	104.83%

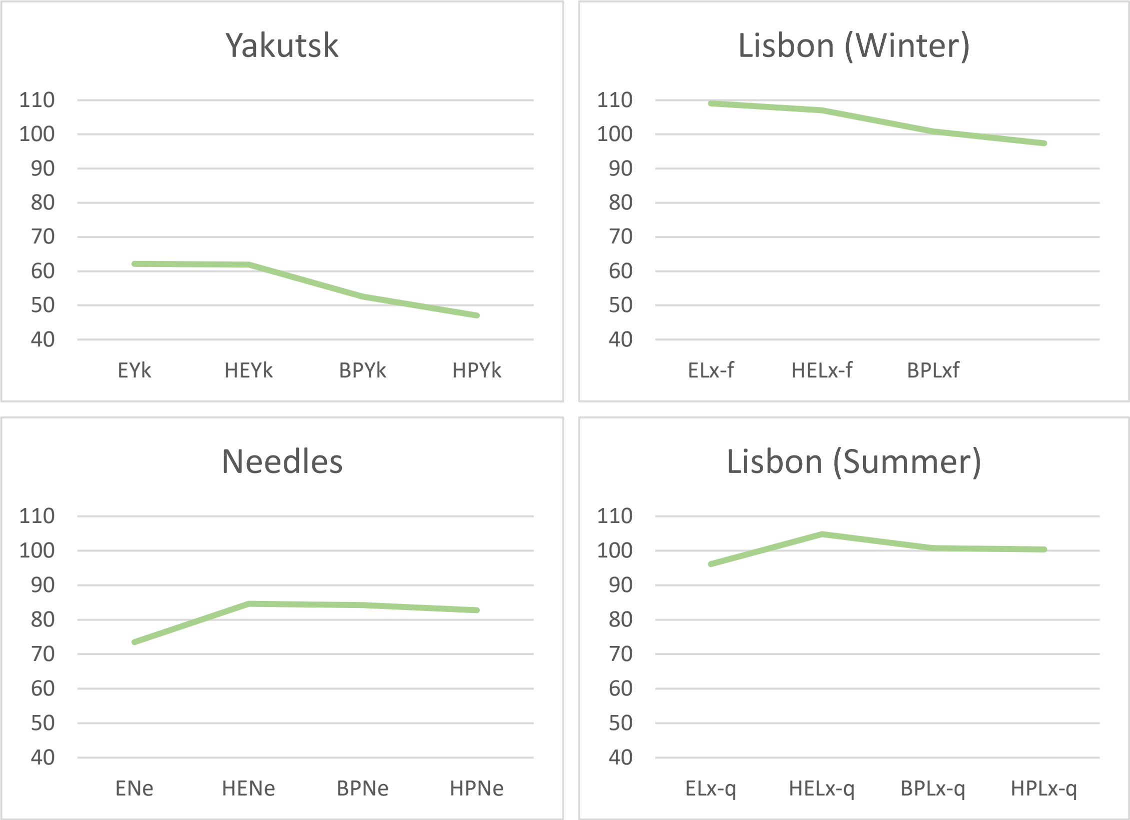


Image 6.10 - Graphical representation of the Overall MCDA model "Energy" score data of the four architecture projects (organized in the following way: Ellipsoid, High Ellipsoid, Base Prism and High Prism), for the four proposed climates.

Regarding the third MCDA model, which is named "Lightness" due to the criteria of more importance being the weight of the construction, the ratings are in terms of values similar to the ones in the previous model. While the criterion for Lightness is given 50% importance in the scale, the rest of the criteria are given the same 8.33%, as the "Energy" model, in order to access what would be the best project proposal if weight was the major concern. Just as in the previous model, the criterion of "Lightess" is considered to be "very strong" in terms of difference of attractiveness when compared to all the other criteria. In the climate of Yakutsk, the best rated proposal is the Ellipsoid (at 91.45%), followed by the base prism (87.28%), next to the high ellipsoid (79.82%) and finishing in the high prism (44.98%). For Lisbon in the wintertime, the best project is the ellipsoid, topping the overall scale (103.45%), followed by the base prism (101.52%), next is the high ellipsoid (90.82%) and lastly the high prism (57.91%). Regarding Needles, the best rated proposal is the base prism (97.35%), next to the ellipsoid (95.34%), the high ellipsoid following next (86.49%) and finally the high prism (54.95%). For the last environment, Lisbon during summer, the best rated project is the base prism (102.22%), next to the ellipsoid (101.13%), followed by the high ellipsoid (91.41%), and the high prism

(59.47%). On this model, the base prism rates higher in both Needles and Lisbon – Summer, instead of the ellipsoid, as previously. These results can be seen in table 6.12 and image 6.11.

Table 6.12 - Overall MCDA model score for the model "Lightness" of the four architecture projects considering the 7 final criteria, depending on the climate. The best values are indicated in green.

Projects (Overall MCDA score)	Yakutsk	Lisbon – Winter	Needles	Lisbon - Summer
Base Prism	87.28%	57.91%	97.35%	102.22%
High Prism	44.97%	97.41%	54.95%	59.47%
Ellipsoid	91.45%	103.45%	73.49%	101.13%
High Ellipsoid	79.82%	90.82%	86.49%	91.41%

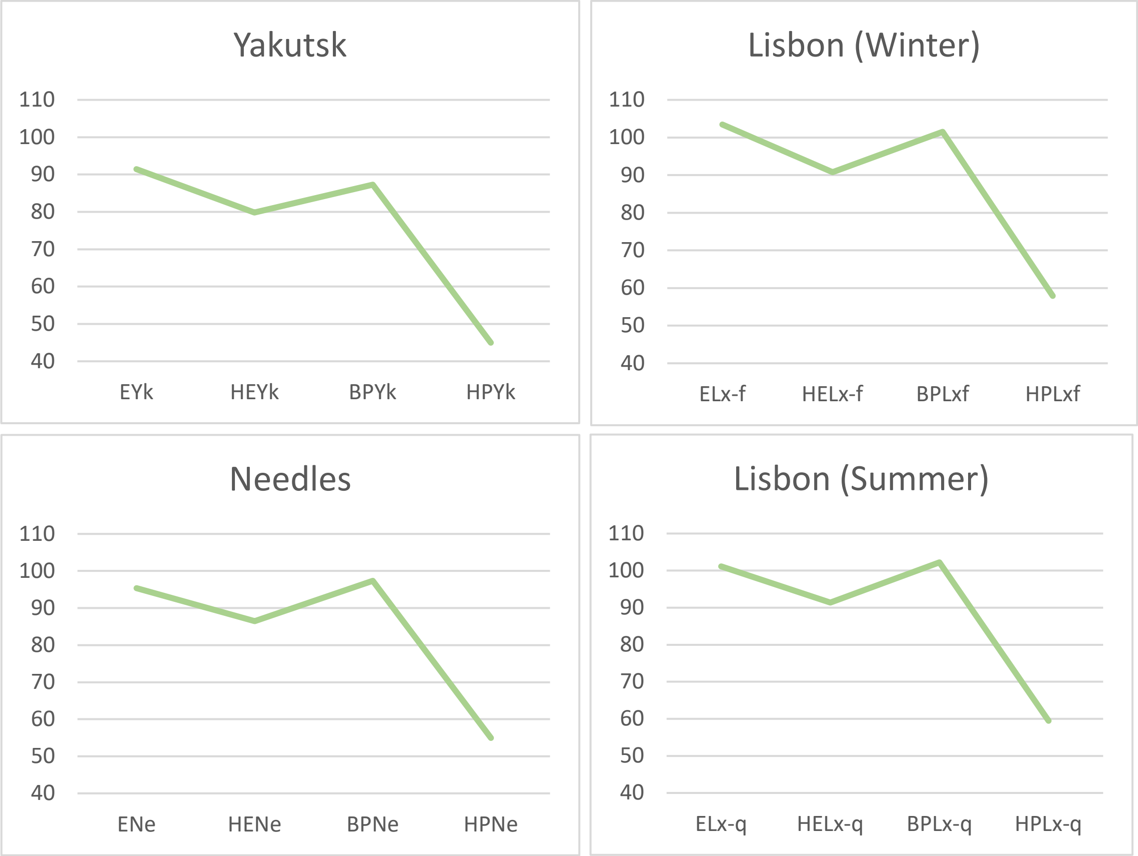


Image 6.11 - Graphical representation of the Overall MCDA model "Lightness" score data of the four architecture projects (organized in the following way: Ellipsoid, High Ellipsoid, Base Prism and High Prism), for the four proposed climates.

The fourth and last MCDA model, is named "Energy+Lightness", and divides the major scale importance between the criteria of Energy Consumption and Lightness. On this model, these two criteria occupy 35.3% of the overall MCDA scale each, while the other five criteria have 5.88% of importance. In terms of judgements, both these criteria are considered to be "very strong" in comparion to all the other criteria, to enlight its importance in the model. This way both the energy loads and the weight of the construction are considered the main concerns, allowing for a set of results that define which of the four proposed projects would be the best, in terms of being light as well as being more energetically sustainable. For the climate of Yakutsk, the project proposal that rates the highest is the ellipsoid (68.93%), followed by the base prism (66.15%), next to the high ellipsoid (60.92%) and the high prism rating last (33.18%). Regarding Lisbon during the wintertime, the best rated proposal is the ellipsoid, topping the overall scale (102.07%), followed by the base prism (100.27%), rating third is the high ellipsoid (92.80%), and finally the high prism (68.75%). For Needles, the project with the best rating is the base prism (88.88%), followed by the high ellipsoid (77.57%), close to the ellipsoid (77.47%) and lastly the high prism (58.92%). For the last clime, Lisbon in the Summer, the best proposal is the base prism (100.54%), next to the ellipsoid (93.46%), followed by the high ellipsoid (91.84%), and with the high prism rating last (71.36%). As the largest importance is given to two criteria instead of just one, the overall results rate lower than the other sets of results, the higher rating staying at 102.07%, very close to the 100%. These results can be seen in table 6.13 and image 6.12.

The results of both the energy simulations, required to input into the MCDA models, and the MCDA models are presented and will be discussed in the next chapter. However, in order to ensure the validation of this data, a robustness analysis is conducted on each of the MCDA models *(Bana e Costa, et al., 2017)*, in order to be sure that the presented results are robust and accurate.

Table 6.13 - Overall MCDA model score for the model “Energy+Lightness” of the four architecture projects considering the 7 final criteria, depending on the climate. The best values are indicated in green

Projects (Overall MCDA score)	Yakutsk	Lisbon – Winter	Needles	Lisbon - Summer
Base Prism	66.15%	100.27%	88.88%	100.54%
High Prism	33.18%	68.75%	58.92%	71.36%
Ellipsoid	68.93%	102.07%	77.47%	93.46%
High Ellipsoid	60.92%	92.80%	77.57%	91.84%

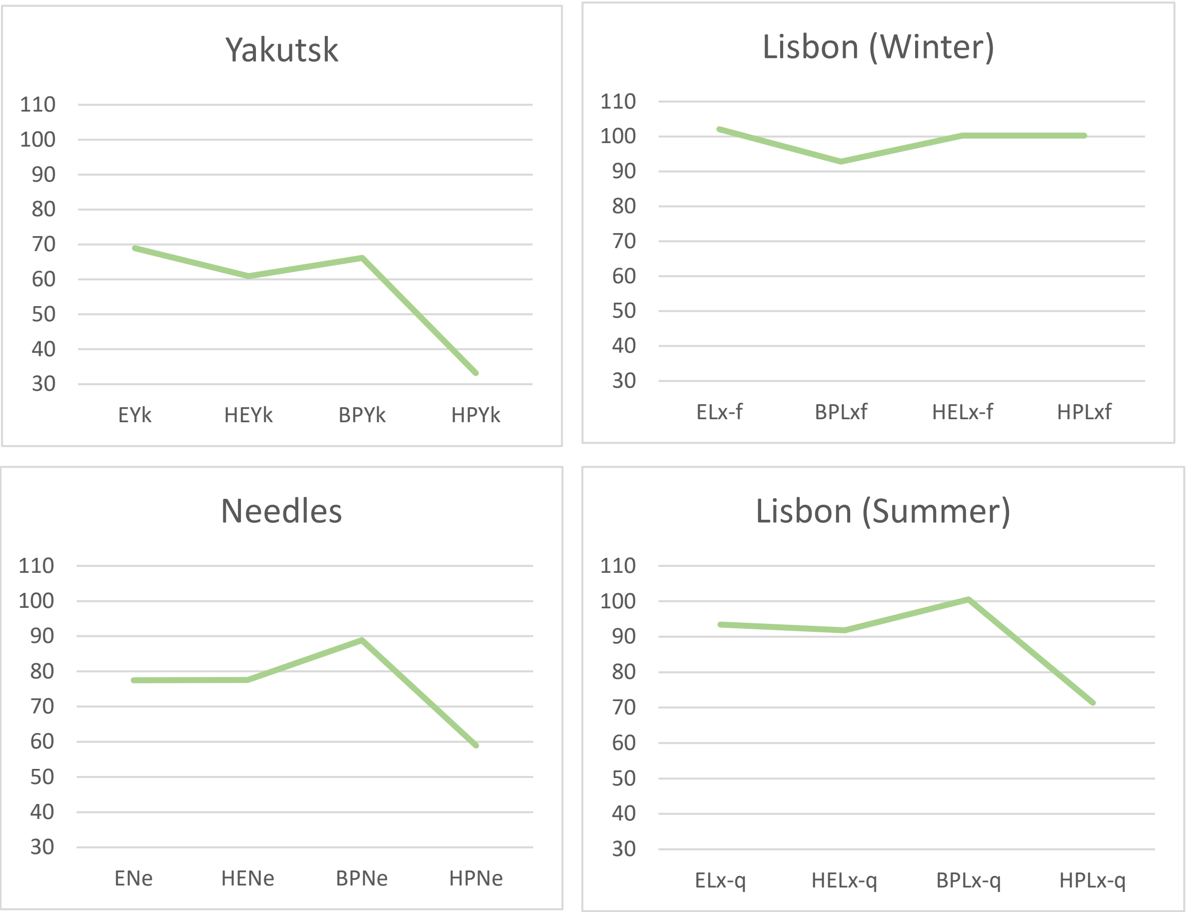


Image 6.12 - Graphical representation of the Overall MCDA model "Energy+Lightness" score data of the four architecture projects (organized in the following way: Ellipsoid, High Ellipsoid, Base Prism and High Prism), for the four proposed climates.

For the first model, "V0", which is considered the generic one, the analysis is considered robust and the model and results are validated as the percentage of cardinal values (goes up over than 20%), doesn't affect the overall rating of the model options. This means that an error margin of over 20% is necessary in order to obtain different results than the ones presented, which is a very large margin of error, ensuring that the analysis is accurate and effective. Regarding the second MCDA model, "Energy", a very large margin of error is still necessary to affect all values except those related to the climate of Lisbon in summer. There is a margin of between 5% to 11% that make the priority of options different, and makes the distinction between the base prism and the high prism not so clear, in terms of which would be better for that specific environment. This is solely from the point of the criterion of Energy Consumption, on that specific climate. For the third MCDA model, of "Lightness", the alteration of other parameters imediatelly changes the analysis and offer different results. Consequently, this is an effect similar to thay which happens in the fourth MCDA model, “Energy+Lightness”, and occurs due to the fact that all environments are input into the same model, at the same time. This doesn’t allow to properly define the robustness of the model as there are minimal differences within criteria which are not important for the whole of the analysis. However, it is not necessary to create individual MCDA models for each climate as the same conclusions could be taken from models which include all data, as they are defined.

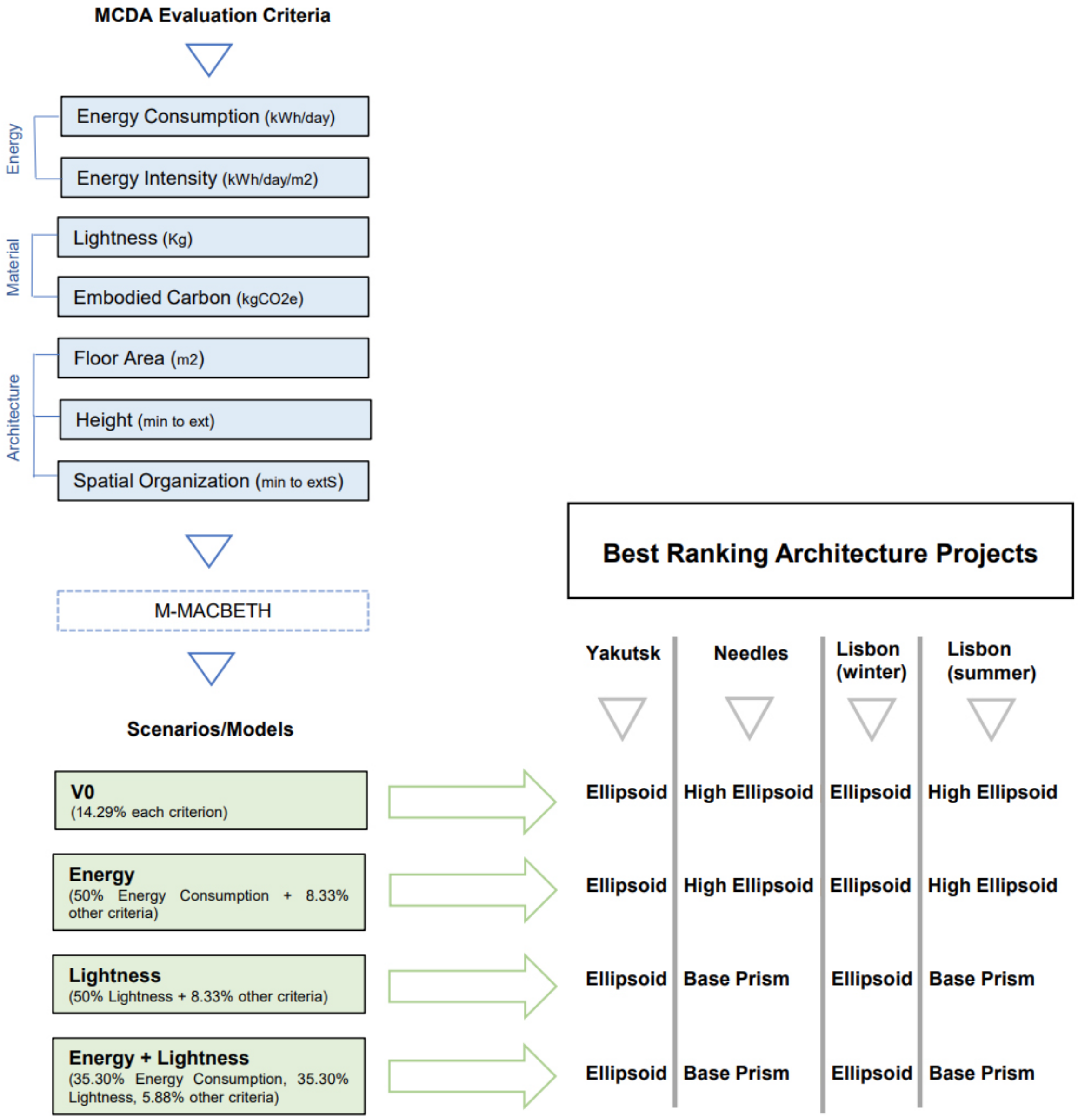


Image 6.13 – Representation of the evaluation criteria used in the MCDA Evaluation Model, the four proposed Scenarios/Models, and the best ranking architecture projects for each proposed climate.

Taking into account that the main, generic model (“V0”) is extremelly robust, it is possible to conclude that the model is robust, the analysis is accurate, and that the differences observed in the next models are related to the great difference in criteria depending on if the climates are very extreme, or temperate (such as the ones from Lisbon, for comparison).

CHAPTER 7

Discussion

The results presented on the previous chapter allowed for a set of conclusions to be taken, regarding what would be the best type of architectural projects for both environments that are very extreme in terms of external temperature (Yakutsk and Needles). As a reference for comparative analysis, a temperate climate was used (Lisbon).

The first set of results was related solely to the energy consumption required in order to keep these buildings comfortable for humans to inhabit them. Taking only energy loads into consideration, the project that allowed for less energy needs in extreme cold climate (Yakutsk) was the ellipsoid (if no windows were considered) and the high ellipsoid (if windows facing South were considered). The high prism rated the worst. The differences in the daily quantity of energy (kWh/day) didn't vary a lot among the four projects (between 53.09 to 59.70). This observation is probably since it is an extremely aggressive environment, with temperatures going to as low as -62 ºC, and thus large quantities of energy will always be necessary to warm a building up, at least to a comfortable temperature of 16-18 ºC. In the winter period of Lisbon's climate, the project which needed the least amount of energy was the ellipsoid and, in this case, there is already a very significant difference between the four projects in terms of the daily quantity of energy needed for comfort: from 1.56 to 4.02 kWh/day. The high prism also rates the worst in Lisbon. If an extremely hot environment is considered (Needles), the project which requires the least amount of daily energy to be kept comfortable is the base prism, although very close to the high prism. The differences in values here are also quite significant (from 20.27 to 41.31 kWh/day), and the ellipsoid rates worst by far, requiring double the energy from either the base prism or the high prism to keep the volume comfortable. If the daily energy per unit floor area is considered (kWh/day/m^2), the high prism has the best performance since it has more area. For comparison, in Lisbon during summertime, the high prism performs the best in terms of daily energy, instead of the base prism, requiring only 0.84 kWh/day, being the lowest value by a significant difference. The ellipsoid again rates the worst, with 16.25 kWh/day, nineteen times more than the high prism.

With these results in mind, it's possible to conclude that higher volumes are worst in winter (the high prism rated the worst in both cold climates, Yakutsk and Lisbon). This is most likely due to the fact that they have much larger surfaces and so the quantity of heat transfer is greater.

This should also be, in general terms, the reason why they are better in warmer climates (such as Needles and Lisbon during Summer): the larger amount of heat loss during the night period seems to play an important role in the internal temperature. Besides the area of the external envelope, there seems to be however some influence related to the total internal air volume to be kept comfortable when extreme climates are considered. In the Needles climate, the base prism has slightly lower energy loads in comparison to the high prism. This seems to be justified by the fact that a smaller volume of air is to be cooled down, what would have some significance when external temperatures that may rise up to 54 ºC are considered; in this case, the heat loss at night does not seem to be enough to compensate for the larger temperature difference during the day (when comparing to the summer Lisbon climate).

On the other hand, the ellipsoid morphology seems to be better in cold climates since energy loads are smaller, although worse in hot climates. In Yakutsk, the high ellipsoid is the best option, while in Lisbon during winter the ellipsoid has the best results. This is likely due to the fact that the curved surface of the ellipsoid leads to higher heat gains because the number of hours when there is a more favourable angle between solar radiation and the building surface is greater. This very same advantage in cold climates is an unfavourable aspect in hot climates. When it comes to Yakutsk, where the sun is very low during winter, it is key that the habitat can absorb as much heat as possible, and the high ellipsoid has a windowed facade that spreads over all floors. In Needles, the sun is very high during summer, same as in Lisbon, and a facade that is perpendicular to the floor surface (as in the prismatic morphology) actually offers more shade to the windows, as they are located in the interior side of the wall, so the glass surface actually remains at least partially shaded during the whole day. With the ellipsoids, it would be exactly the opposite, the windows would be exposed to the sun for longer during the day. These results allow to state that ellipsoid shapes are better for cold climates, including extreme climates such as Yakutsk, and more traditional prismatic shapes are better for hot climates; the hottest the climate, smaller internal air volumes lead to better results.

The second set of results presented in the previous chapter, relates to which would be the best architecture project for these four environments, if all evaluation criteria were considered, through the use of a multi-criteria decision analysis (MCDA) approach. These criteria were “Energy Consumption”, “Energy Intensity”, “Lightness”, “Climate Potencial”, “Floor Area”, “Height” and “Spatial Organization”. The first two criteria were inputs from the energy performance simulations results previously analysed.

For the results of the first MCDA model, “V0”, where all criteria had the same importance, the ellipsoid morphology rated the best for the cold climates, 95.86% in Yakutsk and 116.44% in Lisbon, being clearly a better choice for Lisbon than Yakutsk. This can be justified by the difference in energy consumption, discussed previously. In this model, taking into consideration all criteria, the high ellipsoid does not rate higher than the ellipsoid for Yakutsk, but remains very close at 94.97%, what is coherent with the previous set of results. When it comes to the warm climates, in both Needles and Lisbon in Summer, the high ellipsoid rates better, at 104.93% and 113.37% respectively. Although the energy simulations showed that either the high prism or the base prism would be better options for the warmer climates, this doesn’t seem to be the case when all criteria are considered (with the same weight of importance), as the energy that is required to cool the volume down is not the only aspect to take into consideration. However, the tendency of having a higher volume is maintained, just as previously observed. Curiously, in both warm climates, the project that rates the worst is the base prism, at 93.02% and 100.76%, in Needles and Lisbon in Summer, respectively. However, it is worth mentioning that all projects rate very closely to 100% or even higher, which means that independently of which is the best, they all response effectively to the needs of these climates, and would all be valid options, at least when compared through the use of this base model.

The second MCDA model, “Energy”, takes the criterion of “Energy Consumption” as the most important of criteria in the whole scale (50%). Interestingly, this doesn’t change the results from the previous base model. The projects are not so effective right now, and rate in general much worse than before, but the tendencies are the same. The ellipsoid still rates better in both Yakutsk and Lisbon in Winter, but right now, it rates 62.13% in Yakutsk, which is close to the middle point of the scale, and 109.08% in Lisbon. This can be explained of course by the amount of energy that is required to warm a volume that is in an extreme environment. While this isn’t a problem for Lisbon where the temperatures are temperate, it is the greatest challenge to overcome in Yakutsk, great enough for a 50% difference in terms of model rating. When it comes to Needles and Lisbon in summertime, the high ellipsoid remains the project with the higher rating, as before, at 84.62% and 104.83% respectively, and while the difference isn’t as large as in the cold climates, the same tendency can be observed. There is a 30% difference in terms of model rating, exactly due to the fact that much more energy in Needles is required to keep the volume comfortable than what would be needed in Lisbon. These results therefore show that while the ellipsoid and the high prism would be good options for the climate of

Lisbon, both rating higher than 100% if the energy consumption criterion is the main concern, these projects don't rate as well when it comes to extreme environments, especially in the cold environment.

Regarding the third MCDA model, "Lightness", where the major relative importance was given to the criterion of "Lightness", which relates to the weight of the construction, different results can be seen, specifically in the warmer climates. For Yakutsk and Lisbon in wintertime, the ellipsoid still rates the best, with rather high ratings (91.45% and 103.45% respectively), followed by the base prism (87.28% and 97.41%), then the high ellipsoid and lastly the high prism. The tendency is exactly the same in both climates, what makes sense as "Lightness" relates to the weight of the construction, and both the ellipsoid and the base prism are the lightest options between the four project proposals. The high ellipsoid rates better than the high prism as it still rates better in all the other criteria, and the high prism is the heaviest proposal of all. For Needles and Lisbon in the summertime, the base prism rates the best (97.35% and 102.22% respectively) between all the proposals, and the tendency is also the same between the two climates: the ellipsoid is the second best rated, than the high ellipsoid and finally the high prism (54.95% and 59.47% respectively). These results are also coherent as the ellipsoids rate very bad in the hot environments, and the base prism is the lightest of all other options. The high prism once again rates the worst because it is the heaviest proposed project.

Lastly, the fourth MCDA model, "Energy+Lightness", gives equal importance to both energy consumption and the construction weight, and it gives in a way similar results as the previous model. For Yakutsk and Lisbon during Winter the ellipsoid still rates the best; however, as more importance is once again given to energy consumption it has a much lower rating for Yakutsk (68.93%) when compared to Lisbon (102.07%), and all the other projects rate much lower for Yakutsk as well. The worst rated project for both climates is the high prism, rating only 33.18% for Yakutsk and 68.75% for Lisbon, which, comparing to all the other projects, ends up not even being a good choice for Lisbon, as all others rate over 90%. In the case of Yakutsk, no project rates higher than 70%. When it comes to Needles and Lisbon in Summer, the base prism rates higher once again (88.88% and 100.54% respectively), and the same tendency as the model "Energy" can be seen: the volumes are much less effective in Needles as much more energy is necessary to keep them comfortable, due to the extreme temperatures of that environment. Similarly to the cold climates, the high prism is also the worst rated project, with 58.92% for Needles and 71.36% for Lisbon, while all the other projects for Lisbon rate over 90%.

These results allow for a set of major conclusions. Whenever energy is considered as a criterion of utmost importance, compared to the others, all architectural proposals will rate much lower in extreme environments when compared to temperate climates, due to the energy demands of such climates. However, even taking that into consideration, the lowest a proposal has rated for an extreme environment was always over 60%, in Yakutsk. While not a good rating, it was never bellow the middle point of the scale. Curved surfaces as ellipsoids always seem to be the better option when considering cold climates, as they allow for a better utilization of solar radiation in terms of heat gains. The ellipsoid is the volume with the lowest form factor of all others, followed by the high ellipsoid, and while this doesn't seem to be a guarantee of less energy needs in hot climates, it does seem to be for cold environments. This conclusion may find a sense as in a hotter environment heat loss during the night contributes to lower the internal temperature, while in cold climates the greater area of the external envelope means that additional energy needs to be supplied to the internal environment. In hot climates, if only energy consumption is considered, it seems that a higher building morphology is better when comparing to the lower buildings. Besides the above-mentioned explanation related to the heat loss during the night period, one other factor may explain this observation: the relationship between the roof area and the façade area is lower in the higher buildings; therefore, the heat gains through the roof are less significant. Previous studies have shown that heat gains through the roof surface represent an important part of the cooling energy loads (Mahmoodzadeh & Fatehi, 2018). As in Needles and in Lisbon in the summertime, the solar altitude is very high, the roof surface has a significant impact. This is a question that was also discussed previously in chapter 3, section 3.2. regarding the influence of morphology in interior temperatures, which shows that the results are coherent. On the other hand, higher buildings also have a greater internal air volume, what may play an important role in the internal air temperature due to thermal inertia effects. If other criteria are also considered as having major importance, the tendency of the results in the hot climates changes for the base prism. This is due to two reasons: first, the weight of the construction is also considered and the base prism is lighter than the high ellipsoid; second, in terms of energy it was the second best when compared to the high ellipsoid.

This allows to conclude that for cold and extreme cold environments, the project proposal of the ellipsoid is the best, and seems to perform the best in all models and simulations. Regarding hot and very hot climates, the base prism seems to be the best, and although it doesn't perform the best in all of the models, it does rate the best in the model that considers both the main criteria of energy consumption and construction weight, making it energetically effective, and more manageable, it terms of construction. The high prism seems to be the worst in all models, as it has the worst energy efficiency and it is also the construction with more weight, making it less manageable.

CHAPTER 8

Conclusion

The purpose of this research was to find an evaluation methodology that would allow to assess architecture proposals, in the context of extreme environments, and to validate the proposed approach.

The first task to achieve this goal was to do extensive research on extreme environments, what they are, where they are located, how other environments would become similar to them due to climate change; moreover, how that would affect architects and designers in adapting constructions for these new challenges was a critical step. Afterwards, interior spatial configuration for extreme environments was researched, what would be the required minimal areas and what would be psychologically important to have in an habitat for the people that inhabit it, as well as the design principles for this type of construction. For this, much information was retrieved from the research of NASA for space-travel and potential life on other planets. Next, a material research was conducted, and material libraries were created, in order to understand what the best materials for these types of environments would be, and if traditional materials could answer these questions, or new and innovative materials would be necessary to tackle and respond to the demands of very challenging climates. Then, architecture case studies were gathered, to comprehend how these design principles and materials were being used in actual built projects, or concept projects to be built in extreme environments. The last part of the initial research was dedicated to 3D parametric modelling software, which allowed for digital simulations to be performed to assess a building's efficiency concerning energy needs with factual information from existing climates, as explained in Chapter 1, "State of Art".

The second task of the research was to develop a research methodology, presented on the "Methodological Note", on Chapter 2. Work was being developed at the same time the methodology was being devised, to create strategies and do preliminary work (which would then be the basis for the later development of simulation models). Due to this, the research was presented following a clear line of development, while in reality, the process was often based on revisiting various parts of the research at the same time. Chapter 2 then helps to the comprehension of the research, organizing themes in a way that is clear and offers a well defined work path. It first starts by tackling the question of what would be extreme environments? As the choice was dependant on whether there would be the necessary climate files available (to use in the simulation software), the climates of Yakutsk in Russia, and Needles, in the USA were chosen, as both are located closely to both the coldest city on Earth, and the hottest point on Earth, and present extremely challenging temperatures.

The following chapter, Chapter 3, presented research that had been made according to what would be the preferred architectural morphology shape for these types of environments. First, calculations were made in order to better comprehend the possible thermal performance of the shapes included in the study, which were then simulated in a 3D environment (Rhinoceros with the aid of plug-in Grasshopper) to verify outputs, resulting in a final total of four morphologies, which would be explored further on the research, as possible ideal buildings for climates with extreme temperatures. All ensured the required minimal areas and spatial configuration principles; some ended up having more area due to their shape, which was a plus, and different window solar orientation which, depending on the climate, could be either good or bad.

Next, Chapter 4 assessed the question of interior spatial organization and minimal areas, which had been previously referred but only in the sense of habitats for outer space, or other planets, in the first chapter of the research, “State of Art”. In that sense, changes were made in order to create a habitat that would be fit for the environments of Earth (without the need to use strategies defined for outer space, that take the lack of gravity into account, for instance), and using the morphologies devised and presented on the previous chapter, four proposals of interior spatial configurations were presented. With this information, the research contained already four proposed architecture projects, to be evaluated in the following research tasks.

Finally, material selection was studied, presented in Chapter 5, and the first material library was devised. A lot of information from a very different array of materials was reunited, which allowed for the first contact with materials which could possibly be most adequate for very challenging environments. A second material library was created, containing only glass materials, as these would be essential to devise windows for these climates. Four glasses ended up being tested on the plug-in Grasshopper for energy simulations, and two ended up being chosen, one for each extreme environment. Both triple glasses, one more specific for hot climates, and another one for cold environments. Using the information gathered during this stage of the research, a first multicriteria decision analysis (MCDA) model was created, with a preliminary list of criteria, in order to comprehend which would be the best materials for environments with extreme temperatures. Another MCDA model was created, and although it was used to assess only the first of the proposed architecture habitats (the low-rise prism), various types of construction assemblies (that existed as standard options within the software) were tested, which allowed to obtain important preliminary results, in terms of which type of construction was the best for these environments, but also served as a guarantee that the model could work, with that first set of evaluation criteria. With this model as a base, three more variations were created, one taking into consideration European energy-efficiency standards, another which assessed essentially environmental impact, and a third one that would consider essentially material performance. These steps were the first in creating a preliminary basis of what would become the final set of evaluation criteria and the final models. Both models offered important preliminary results, that contributed to the creation of the first self-proposed material assembly, which consisted essentially of wood-derived materials (OSB panels and wood fibre insulation boards), as previous research had suggested these were the materials with the best relation between energy efficiency and sustainability. Various possibilities for this assembly were studied and eventually a single one was chosen for the two environments, as it could sustain both very hot and very cold temperatures, serving as an adequate construction assembly.

Chapter 6 presents the final digital simulations to achieve consolidated results, on the four proposed habitats, as well as the final MCDA model, to evaluate these architecture proposals. First, the adaptations performed to the simulations were presented, such as adapting the analysis period of the simulations, and also defining a temperate climate as a “control climate”. This would serve as a comparison term between a moderate climate in terms of temperatures, and two very extreme environments. This way it would be possible to determine if the evaluation of a determined proposed project would change depending on the climate, and what would those differences be. The environment of Lisbon was chosen for this role. It was also necessary to adapt the ventilation rates for the volumes, to improve energy efficiency, while keeping the habitats comfortable. The schedules and loads required to perform the simulations were also explained and adapted accordingly, and the final Grasshopper script was devised. So, final energy consumption simulations were ran for the four architecture projects, all with the self-proposed construction assembly and the respective glass materials. This information was then input into the final MCDA models, in the energy consumption part, where data for daily energy and for daily energy per unit floor area were used. Regarding the final MCDA models, a final set of criteria was defined, after making the necessary alterations to the first ones, and seven final criteria were maintained. Daily energy consumption (kWh/day), energy intensity (kWh/day/m^2), climate change potential (which was the carbon footprint of the material, from cradle-to-gate, in kgCO$_{2e}$), lightness (in kg, for the weight of the construction materials), minimal areas, height and spatial organization. The information for all these criteria were input into the MCDA model, as well as the four options (four architectural project proposals), the base prism, the high prism, the ellipsoid and the high ellipsoid, for all four climates, Yakutsk, Lisbon in Winter, Needles and Lisbon in Summer. The first MCDA model, named “V0”, ensured all criteria had the same weight, and was the base model. Three other models were created, one which focused essentially on energy consumption (“Energy”), one which focused essentially on the construction weight (“Lightness”), and a third one which focused on both these criteria equally (“Energy+Lightness”). The models proved to be robust, stable, and deliver coherent and accurate results.

The results from the MCDA analysis showed that the semi-ellipsoidal architecture project was the best option for cold environments, while either taller buildings, or the base prism (this was the best choice considering energy consumption and weight as main criteria) were the best options for hot environments. This was also coherent with previous findings within the work that was developed throughout the research. In this sense, and with the objective of the research being to develop an evaluation methodology that assesses architecture proposals for extreme environments, it is considered that the goal has been fulfilled, as an evaluation methodology was studied, devised, created and experimented on, and delivered coherent results. These results ensure an adequate mediation between the interior habitat of the architectural object, and the outside, which in this case is comprised of an extremely challenging environment. This is obtained through the use of adequate materials, specific spatial configuration principals, and also of a suitable exterior morphology.

This research began as an attempt to answer climate challenges which have surfaced in recent years, taking extreme environments as an example of how some climates on Earth will become, due to climate change, with increasing problematic temperatures. In that sense, a change of paradigm is necessary in the way architects, designers and builders plan and build buildings. The results of this research aim to be of aid to those questions and offer possible solutions to evaluate whether a building is a good fit to a specific environment, or not, as the MCDA models can also be changed to better match certain necessities of certain environments. With these models, various types of projects can be tested, with various types of construction assemblies and morphologies.

This research aims to contribute to the existing knowledge of architecture for extreme environments, to bring attention to the possibilities of using digital tools to formulate and evaluate architecture projects before they are built, and to help create more effective buildings, which can withstand extreme climatic conditions, with less costs.

Many challenges were encountered throughout this research. The first was the lack of information that is disclosed to the public regarding building for very extreme environments, such as outer space or other planets. Usually, the information provided is vague and very generic, offering little content that can be used adequately when it comes to building for these environments. This is, for instance, information regarding the type of materials that are used and their physical characteristics and mechanical/thermal behaviour. Some information is provided by NASA or ESA, and more specific information can't be accessed easily. The main challenge, however, was related to the user's interaction with the softwares used for energy comfort simulations. Although the use of these softwares is justified in literature, and they are adequate for the analysis performed, Grasshopper, LadyBug, HoneyBee and EnergyPlus are not intuitive plug-ins/softwares to work with. Learning to work with them is a very time-consuming process, as these softwares do not have a designer-like approach, in order to be user-friendly. Although visual programming allows for users which are not versed in programming languages, such as python, to create working scripts, they still require a lot of learning and research to be able to use them. Users in the official McNeel forum state that it takes about one year for a regular user to feel comfortable working with Grasshopper, without the need to use tutorials. The users also state that while the software works with visual programming, in the long-run many users feel the need to learn how to write code so that they can be more effective in Grasshopper. Another challenge found throughout the research were the limitations of the softwares themselves. Grasshopper uses the engine from EnergyPlus to perform energy simulations; however, this engine cannot analyse curved surfaces, which makes it impossible to analyse a sphere-like building, or an ellipsoidal one. The only way to solve this situation was by dividing the curved surfaces into small orthogonal ones, which then would make the outer shape of the building. It appears curved in the digital model, but it is not a perfect curved surface. This is a handicap of the software, as it is impossible for a user to analyse a true digitally modelled curved surface, which Rhino is capable of rendering. Another challenge was the lack of interaction that the softwares have, although Grasshopper can export its data into Excel and communicate with it, these do not communicate with the MCDA software, M-MACBETH. Due to this, all data had to be manually inserted into the MCDA software, which makes it, also, a very time-consuming process. If there were specific tools to facilitate the relationships between the softwares, it would allow for a much more effective workflow, making the process faster and more intuitive. This would make these digital processes more accessible to the regular professional or student.

On the other hand, using visual-programming tools is to experiment a different side of technology and a new design-process, as it has a very different approach than regular CAD. While the learning process was challenging, many new skills were achieved through this research, which hopefully will be of use to the academic community and to architecture/design professionals. As climate change effects are being felt throughout the world, the knowledge of how to build for very cold and very hot environments will be essential, as temperatures become more extreme. Creating a methodology which relates outer building shape, materials and architecture design, was extremely rewarding, and although it was planned for extreme environments, this methodology can be adapted to regular or even heritage buildings, to access their behaviour and resilience as a whole in extreme temperatures. Also, being able to devise a process to evaluate a determined building as a whole, including both architectural questions and mechanical and construction elements, like materials, commonly associated with engineering disciplines, seemed essential. Although architecture considers many processes and factors, whether they are social, environmental, aesthetic, technological or economic-related, it cannot ignore how its limits are ensured. A building, designed by an architect, as a built existence and art-form, exists because it was built in a determined material, and with a structure that was calculated by an engineer. The resilience of a building is also determined by which materials are used in its construction, which is studied by the scientific field of material engineering. In that sense, it made no sense to evaluate the effectiveness of a building, without considering these three questions: ensuring the interior design was effective to the needs of the inhabitants, designing a building's outer shape for maximum effectiveness, and what would be the consequences in terms of performance of the materials that were chosen for the building. Chris Wilkinson, winner of the Architecture Stirling Prize, states in its monograph the following: "Is it architecture or engineering? The answer is "Yes"." (Wilkinson, 2001). In that sense, this research also spawned a set of questions regarding the limits of architecture and engineering, and how dependant they are of one another. To create the most effective building possible, that responds both to a better living/spatial experience, and building effectiveness, both disciplines are required, and are deeply intertwined and dependant from one another.

When it comes to further research development, there are some questions that remain unanswered. There doesn't seem to be a direct connection between the form factor values and the results given by the energy performance simulations. This can be due to the fact that the environments have very extreme climate conditions and temperatures, or there can be some other yet unknown reason which requires further investigation. During the course of the research, it seemed the building's volume had more impact than the form factor, as the results could be related to it, and not specifically to the form factor values. Also, the fact that higher volumes show better energy performance results in the hotter climates is also a theme for further research, whether it is due to having larger facades and smaller roof surfaces, which allow for less heat gains during the day through the roof, or greater heat losses in the night period through the larger facades, it remains yet to be answered. It is also possible that the reason is due to thermal inertia, as the higher buildings have more volume, and thus the heat is distributed by the larger interior air volume. A more detailed analysis is required of these issues to better explain why the higher morphologies rate better, in hotter climates.

The questions presented in this research, related to climate change, building resilience and adaptability, environmental impact, architecture design and effective construction assemblies, are all actual themes that are being debated nowadays throughout various institutions worldwide. In the primary stages of this research, it was defined that one of the objectives was to ensure that it would be useful, in a practical way. This way, other students and professionals could benefit from it, use it in their academic or professional work, and improve the cities they live and work in, by making them more adapted and adaptable to an ever-changing climate, which will become increasingly more challenging as time goes by. In that sense, with the obtained results that allowed to validate the proposed methodology, that objective is nearly fulfilled.

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ANEX A

Auxiliary Calculations & Simulation Assumptions

The following calculations are related to Images 3.4 and 3.5, presented in Chapter 3.2.

Square Area Prisms characterization, to access Form Factor Variations.

Prisms	Side 1 (m)	Side 2 (m)	Floor Area (m^2)	Height (m)	Volume (m^3)	Surface Area (m^2)	Form Factor (S/A)	Form Factor (S/V)
1	4.50	4.50	20.27	2.20	44.60	80.17	3.95	1.80
2	4.95	4.95	24.53	2.20	53.97	92.65	3.78	1.72
3	5.45	5.45	29.68	2.20	65.30	107.31	3.62	1.64
4	5.99	5.99	35.92	2.20	79.02	124.57	3.47	1.58
5	6.59	6.59	43.46	2.20	95.61	144.93	3.33	1.52
6	7.25	7.25	52.58	2.20	115.69	168.98	3.21	1.46
7	7.98	7.98	63.63	2.20	139.98	197.45	3.10	1.41
8	8.77	8.77	76.99	2.20	169.38	231.19	3.00	1.36
9	9.65	9.65	93.16	2.20	204.95	271.25	2.91	1.32
10	10.62	10.62	112.72	2.20	247.98	318.87	2.83	1.29
11	11.68	11.68	136.39	2.20	300.06	375.56	2.75	1.25
12	12.85	12.85	165.03	2.20	363.32	443.12	2.69	1.22
13	14.13	14.13	199.69	2.20	439.32	523.74	2.62	1.19
14	15.54	15.54	241.63	2.20	531.58	620.04	2.57	1.17
15	17.10	17.10	292.37	2.20	643.21	735.20	2.51	1.14
16	18.81	18.81	353.76	2.20	778.28	873.05	2.47	1.12
17	20.69	20.69	428.06	2.20	941.72	1038.18	2.43	1.10
18	22.76	22.76	517.95	2.20	1139.48	1236.17	2.39	1.08
19	25.03	25.03	626.72	2.20	1378.77	1473.73	2.35	1.07
20	27.54	27.54	758.33	2.20	1668.32	1758.98	2.32	1.05

Rectangular Area Prisms characterization, to access Form Factor Variations.

Prisms	Side 1 (m)	Side 2 (m)	Floor Area (m^2)	Height (m)	Volume (m^3)	Surface Area (m^2)	Form Factor (S/A)	Form Factor (S/V)
1	3.18	6.37	20.27	2.20	44.60	82.57	4.07	1.85
2	3.50	7.00	24.53	2.20	53.97	95.29	3.88	1.77
3	3.85	7.70	29.68	2.20	65.30	110.22	3.71	1.69
4	4.24	8.48	35.92	2.20	79.02	127.77	3.59	1.62
5	4.66	9.32	43.46	2.20	95.61	148.45	3.42	1.55
6	5.13	10.26	52.58	2.20	115.69	172.85	3.29	1.49
7	5.64	11.28	63.63	2.20	139.98	201.71	3.17	1.44
8	6.20	12.41	76.99	2.20	169.38	235.88	3.06	1.39
9	6.82	13.65	93.16	2.20	204.95	276.40	2.97	1.35
10	7.51	15.01	112.72	2.20	247.98	324.54	2.88	1.31
11	8.26	16.52	136.39	2.20	300.06	381.79	2.80	1.27
12	9.08	18.17	165.03	2.20	363.32	449.97	2.73	1.24
13	9.99	19.98	199.69	2.20	439.32	531.28	2.66	1.21
14	10.99	21.98	241.63	2.20	531.58	628.34	2.60	1.18
15	12.09	24.18	292.37	2.20	643.21	744.33	2.55	1.16
16	13.30	26.60	353.76	2.20	778.28	883.09	2.50	1.13

17	14.63	29.26	428.06	2.20	941.72	1049.22	2.45	1.11
18	16.09	32.19	517.95	2.20	1139.48	1248.32	2.41	1.10
19	17.70	25.40	626.72	2.20	1378.77	1487.10	2.37	1.08
20	19.47	38.94	758.33	2.20	1668.32	1773.68	2.34	1.06

Semi-Spheres volumes characterization, to access Form Factor Variations.

Prisms	Axis 1 (m)	Axis 2 (m)	Floor Area (m^2)	Axis 3 (m)	Volume (m^3)	Surface Area (m^2)	Form Factor (S/A)	Form Factor (S/V)
1	5.08	5.08	20.27	5.08	34.33	40.55	2.00	1.18
2	5.59	5.59	24.53	5.59	45.70	49.06	2.00	1.07
3	6.15	6.15	29.68	6.15	60.83	59.37	2.00	0.98
4	6.76	6.76	35.92	6.76	80.96	71.83	2.00	0.89
5	7.44	7.44	43.46	7.44	107.76	86.92	2.00	0.81
6	8.18	8.18	52.58	8.18	143.43	105.17	2.00	0.73
7	9.00	9.00	63.63	9.00	190.90	127.26	2.00	0.67
8	9.90	9.90	76.99	9.90	254.09	153.98	2.00	0.61
9	10.89	10.89	93.16	10.89	338.19	186.31	2.00	0.55
10	11.98	11.98	112.72	11.98	450.13	225.44	2.00	0.50
11	13.18	13.18	136.39	13.18	599.12	272.78	2.00	0.46
12	14.50	14.50	165.03	14.50	797.43	330.07	2.00	0.41
13	15.95	15.95	199.69	15.95	1061.38	399.38	2.00	0.38
14	17.54	17.54	241.63	17.54	1412.70	483.25	2.00	0.34
15	19.29	19.29	292.37	19.29	1880.30	584.74	2.00	0.31
16	21.22	21.22	353.76	21.22	2502.68	707.53	2.00	0.28
17	23.35	23.35	428.06	23.35	3331.07	856.11	2.00	0.26
18	25.68	25.68	517.95	25.68	4433.65	1035.89	2.00	0.23
19	28.25	28.25	626.72	28.25	5907.19	1253.43	2.00	0.21
20	31.07	31.07	758.33	31.07	7854.49	1516.65	2.00	0.19

Semi-Ellipsoidal volumes characterization, to access Form Factor Variations.

Prisms	Axis 1 (m)	Axis 2 (m)	Floor Area (m^2)	Axis 3 (m)	Volume (m^3)	Surface Area (m^2)	Form Factor (S/A)	Form Factor (S/V)
1	7.19	3.59	20.27	5.08	34.33	43.16	2.13	1.26
2	7.90	3.95	24.53	5.08	41.55	48.94	1.99	1.18
3	8.69	4.35	29.68	5.08	50.27	55.67	1.88	1.11
4	9.56	4.78	35.92	5.08	60.83	63.54	1.77	1.04
5	10.52	5.26	43.46	5.08	73.60	72.78	1.67	0.99
6	11.57	5.79	52.58	5.08	89.06	83.66	1.59	0.94
7	12.73	6.36	63.63	5.08	107.76	96.51	1.52	0.90
8	14.00	7.00	76.99	5.08	130.39	111.75	1.45	0.86
9	15.40	7.70	93.16	5.08	157.77	129.85	1.39	0.82
10	16.94	8.47	112.72	5.08	190.90	151.42	1.34	0.79
11	18.64	9.32	136.39	5.08	230.99	177.17	1.30	0.77
12	20.50	10.25	165.03	5.08	279.49	207.96	1.26	0.74
13	22.55	11.28	199.69	5.08	338.19	244.86	1.23	0.72
14	24.81	12.40	241.63	5.08	409.21	289.14	1.20	0.71
15	27.29	13.64	292.37	5.08	495.14	342.33	1.17	0.69
16	30.01	15.01	353.76	5.08	599.12	406.31	1.15	0.68
17	33.02	16.51	428.06	5.08	724.94	483.32	1.13	0.67
18	36.32	18.16	517.95	5.08	877.17	576.09	1.11	0.66
19	39.95	19.97	626.72	5.08	1061.38	687.93	1.10	0.65
20	43.94	21.97	758.33	5.08	1284.27	822.84	1.09	0.64

ANEX B

Simulation Temperature & Energy Outputs

The following calculations are related to Images 3.7, 3.8 and 3.9, presented in Chapter 3.3.

Auxiliary Calculations and values for Form Factor for all the 10 prisms.

Prisms	Side 1 (m)	Side 2 (m)	Floor Area (m^2)	Height (m)	Volume (m^3)	Surface Area (m^2)	Form Factor (S/A)	Form Factor (S/V)
1	11.80	4.80	56.64	2.40	135.94	136.32	2.41	1.00
2	12.80	5.80	74.24	3.40	252.42	200.72	2.70	0.80
3	13.80	6.80	93.84	4.40	412.90	275.12	2.93	0.67
4	14.80	7.80	115.44	5.40	623.38	359.52	3.11	0.58
5	11.80	4.80	56.64	3.40	192.58	169.52	2.99	0.88
6	11.80	4.80	56.64	4.40	249.22	202.72	3.58	0.81
7	11.80	4.80	56.64	5.40	305.86	235.92	4.17	0.77
8	12.80	5.80	74.24	2.40	178.18	163.52	2.20	0.92
9	13.80	6.80	93.84	2.40	225.22	192.72	2.05	0.86
10	14.80	7.80	115.44	2.40	277.06	223.92	1.94	0.81

Simulation output values for interior free-floating temperature for the hot climate of Needles.

Prisms	Minimal Air Temperature (ºC)	Maximum Air Temperature (ºC)	Average Air Temperature (ºC)	Minimal Operative Temperature (ºC)	Maximum Operative Temperature (ºC)	Minimal Relative Humidity (%)	Maximum Relative Humidity (%)
1	36.91	49.30	43.10	36.67	43.34	95.58	100
2	36.82	48.86	42.80	36.57	48.00	95.82	100
3	36.80	48.54	42.70	36.53	47.76	92.48	100
4	36.79	48.30	42.50	36.50	47.55	90.39	100
5	36.80	48.56	42.70	36.54	47.79	96.83	100
6	36.78	47.99	42.40	36.49	47.34	94.48	100
7	36.75	47.54	42.10	36.45	46.97	93.66	100
8	36.99	49.55	43.30	36.74	48.52	96.28	100
9	37.10	49.73	43.40	36.85	48.66	96.15	100
10	37.16	49.87	43.50	36.89	48.76	95.97	100

Simulation output values for interior free-floating temperature for the cold climate of Yakustsk.

Prisms	Minimal Air Temperature (ºC)	Maximum Air Temperature (ºC)	Average Air Temperature (ºC)	Minimal Operative Temperature (ºC)	Maximum Operative Temperature (ºC)	Minimal Relative Humidity (%)	Maximum Relative Humidity (%)
1	-46.97	-25.52	-36.20	-47.15	-26.49	100	100
2	-46.85	-25.47	-36.20	-47.03	-26.37	100	100
3	-46.76	-25.44	-36.10	-46.94	-26.29	100	100
4	-46.69	-25.43	-36.10	-46.86	-26.24	100	100
5	-46.87	-25.43	-36.20	-47.04	-26.28	100	100
6	-46.80	-25.36	-36.10	-46.95	-26.11	100	100
7	-46.75	-25.31	-36.00	-46.89	-25.97	100	100

8	-46.95	-25.56	-36.30	-47.15	-26.58	100	100
9	-46.94	-25.58	-36.30	-47.15	-25.64	100	100
10	-46.93	-25.60	-36.30	-47.15	-26.70	100	100

Simulation output values for interior comfort temperature for the hot climate of Needles, including Total Cooling Load.

Prisms	Minimal Air Temperature (ºC)	Maximum Air Temperature (ºC)	Minimal Operative Temperature (ºC)	Maximum Operative Temperature (ºC)	Minimal Relative Humidity (%)	Maximum Relative Humidity (%)	Total Cooling Load (kWh)
1	26	28	26.90	30.79	9.53	33	4003.45
2	26	28	26.89	30.69	9.58	31	5465.93
3	26	28	26.89	30.62	9.63	30	7113.36
4	26	28	26.88	30.56	9.70	29	8997.49
5	26	28	26.88	30.62	9.57	32	4334.5
6	26	28	26.88	30.48	9.61	30	4659.62
7	26	28	26.88	30.38	9.65	30	4983.50
8	26	28	26.91	30.85	9.53	33	5093.93
9	26	28	26.91	30.90	9.54	33	6294.50
10	26	28	26.92	30.95	9.54	33	7606.02

Simulation output values for interior comfort temperature for the cold climate of Yakutsk, including Total Heating Load.

Prisms	Minimal Air Temperature (ºC)	Maximum Air Temperature (ºC)	Minimal Operative Temperature (ºC)	Maximum Operative Temperature (ºC)	Minimal Relative Humidity (%)	Maximum Relative Humidity (%)	Total Heating Load (kWh)
1	16	18	9.91	13.12	0.49	1	11296.48
2	16	18	10.05	13.25	0.49	1	15780.59
3	16	18	10.14	13.34	0.49	1	20894.15
4	16	18	10.22	13.41	0.49	1	26834.82
5	16	18	10.17	13.37	0.49	1	12747.62
6	16	18	10.36	13.55	0.49	1	14192.84
7	16	18	10.50	13.69	0.49	1	15634.30
8	16	18	9.80	13.04	0.49	1	14148.40
9	16	18	9.70	12.97	0.49	1	17275.22
10	16	18	9.63	12.91	0.49	1	20676.99

ANEX C

Grasshopper Script

In order to conduct an energy simulation using Grasshopper, the user first modulates the 3D building in Rhinoceros 3D, the surfaces for the walls, floors and roof must be created. It is important to note that the simulation engine of Energy Plus does not run curved surfaces, for this, a different approach must be taken. However, if a prism is considered, then six surfaces are formed, four walls, a floor and a roof. The surfaces for the windows must also be created, and they must overlap the wall surfaces, in order for the software to consider them as windows.

After modelling the building surfaces, they are imported into grasshopper using the command “brep”, which can be used to set one brep (ex: floor surface) or multiple breps (ex: wall surfaces). After these are defined, the breps are connected to the command “createHDSrfs”, this is a command that creates a HoneyBee surface. In this command, the user defines the surface type, from a pre-defined list, and connects the command to an input from EnergyPlus, which allows to give the surface a construction material. The output of this command is a HoneyBee surface, which can be used to conduct energy simulations.

In order to define a construction material for a HoneyBee surface, an EnergyPlus command is used, called “EPOpaqueMat”, which stands for “EnergyPlus Opaque Material”, and the required inputs to create a material are a name, a defined roughness, the thickness, the thermal conductivity, the density, the specific heath capacity and thermal absorptance of the material, as well as the solar and visible absorptance of the material. To create a glass material, the command “EPWindowMat” is used, which stands for “EnergyPlus Window Material”, and requires as inputs a name, the U-value of the material, the solar heath gain coefficient and the visible transmittance of the glass material.

After materials are assigned to the previously created HoneyBee surfaces, all surfaces are connected to a command called “addHBGlz”, which is a command that connects the window surfaces to the wall surfaces, so that windows can be properly simulated. This command is then connected to another called “createHBZones”, this is used to create an entire zone/building with all the surfaces created previously. It is possible to create a HoneyBee zone without creating the surfaces previously, but in order to define construction materials, defining the surfaces previously is required.

The HoneyBee zones are then connected to another command, called "setEPZoneLoads", which is a command that defines a set of loads for the simulated building. These are the equipment load by area, (W/m^2), the software suggests between 2 (for just a laptop) to 15 (an equipped office); outside air infiltration into the zone per m^2 of exterior façade, the software suggests various values; lightning density per area (W/m^2), the software suggests between 3 (LED bulbs) and 15 (incandescent heat lamps); number of people per area, this value variates depending on the floor area of the building and the amount of people which will use it; ventilation per area (m^3/s per m^2); ventilation per person (m^3/s) and recirculated air per area (only has an effect on OpenStudio models, and therefore was not considered in this study).

This node is connected afterwards to another, called "setEPZoneSchedules", which defines the schedules on which the building will be used, as for this investigation all of the systems would be required to be connected 24-hours, throughout the whole year, that was the input given to the command, through another node called "AnnualSchedule". The output of the HoneyBee zones are then connected to another node called "SetEPZoneThresholds". In this node, it is possible to define maximum and minimum interior temperature, humidity, outdoor air and daylight requirements. For this investigation, only cooling and heating setpoints and setbacks were used as inputs. One node was created for the cold environment, and another one for the hot environment. Finally, these HoneyBee zones are connected to the simulation command, called "runEnergySimulation", which is a node from EnergyPlus.

Among the required inputs for the simulation are the HoneyBee zones, the building, as explained previously, the epw file, which is the weather file, retrieved from the on-line weather files library of the USA Department of Energy. This file is imported to Grasshopper from a command called "Open weather file", which is then connected to the simulation node. Another input for the simulation engine is the Analysis Period, which relates to the yearly period that the analysis in run, this is defined with another command called "analysisPeriod", where the used defines the analysis period from month, day and hour, to month, day and hour. For this investigation, four different analysis periods were considered, for the cold environment, the hot environment, and two for the control environment (one for summer and one for winter). Another input to the simulation node is the command "EnergySimPar", which stand for Energy Plus Shadow Parameters, which sets, among other data, the solar distribution. This value must be set to "3" instead of "4", the most accurate, if the user wants to simulate either concave or L-shaped geometry, as otherwise the simulation will not run. The user can also define the desired outputs of the simulation command, through a node called "EPOutput" which stands for

Generate EnergyPlus Output. This allows for the user to define exactly what outputs it wants, making the simulation time smaller, and having more specific information to analyse after the simulation runs. For this investigation, the defined outputs were “zoneEnergyUse”, “zoneComfortMetrics”, “surfaceTempAnalysis” and “surfaceEnergyAnalysis”.

After the analysis is run, it is necessary to connect the node output of “resultFileAddress” to another command named “readEPResult”, and in order to obtain the data from the simulation, it is necessary to connect the outputs of this command to grasshopper “panels”, to read the results. For this specific research, the results that were retrieved from the simulations were from the outputs of “cooling”, “heating”, “operative temperature” and “relative humidity”. However, since the research was essentially focused on temperature, this last output was not considered as a part of the final criteria. These results were then copied into excel sheets, in order to be analysed.