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# Multi-criteria material selection for buildings in challenging environments

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**Abstract**. Climate change and future weather conditions are likely to challenge the way buildings are designed because there will be an increase in extreme climatic conditions. What should architects change in their design process to produce human habitats able to withstand those extreme conditions to ensure adequate comfort conditions? This paper presents preliminary results within the scope of an on-going research that addresses one single key issue: what materials will be most suitable in extreme temperature conditions. A set of 52 materials is analysed through a multi-criteria decision process that includes thermal conductivity, thermal diffusivity, thermal effusivity, linear thermal expansion, service temperature, fracture toughness, recycle potential and embodied carbon as criteria. The goals are to find the best-fit materials for each climate scenario within the scope of contradictory objectives and to develop a methodology for the selection of construction materials for buildings in challenging environments. Results show that the best possible material for extreme temperatures, whether it would be a very cold or a very hot environment, is one that could combine the properties of polymers with a very low environmental impact (at the level of the impact from materials such as natural fibres, wood or wood derivatives). The results thus suggest that further research may be directed at biomaterials development.

## 1. Introduction

Climate change and future weather conditions are likely to challenge the way buildings are designed because there will be an increase in extreme climatic conditions. What should architects change in their design process to produce human habitats able to withstand those extreme conditions assuring adequate comfort conditions? The answer to this question requires comprehensive interdisciplinary research. This paper presents preliminary results within the scope of an on-going research that addresses one single key issue: what materials will be most suitable in extreme temperature conditions.

### *1.1. Challenging Environments*

The Astrobiology Institute of NASA (NAI) defines an extreme environment as one characterized by extreme physical conditions, that are outside the boundaries in which humans habit and dwell comfortably [1]. These are conditions such as temperature, desiccation, air quality, pressure, salinity, radiation, and acidity (or alkalinity, pH). An extreme environment is nowadays defined mostly by its location, but due to global warming and environmental disasters, researchers now understand that it is possible for these environments to develop in different and unexpected areas. Examples of extreme environments include the geographical poles of Earth, deserts, very high mountains, the interior of volcanoes, deep oceans, upper atmosphere, and other planets or outer space [1].

Although extreme environments have always existed on Earth, now, thanks to climate change, it is highly likely that other places will face extreme climate scenarios. So, the real question is how will we be able to provide people with the tools to adapt to these new situations? How can architecture help people habit comfortably while facing the possibilities of lack of water and high temperatures, or even the opposite, floods, blizzards or polar deserts? Organizations such as NASA and ESA have been studying self-sufficient human habitats for decades to colonize other planets, and deal with challenges like these. To better understand this topic, it is possible to look at the work of architects such as Neil Leach [2], who guest-edited the edition of Architectural Digest magazine, Space Architecture: The New Frontier for Design Research, or even Lydia Kallipoliti [3], more specifically, her exhibition "Closed Worlds", which deals with the various concepts of closed systems, experiences that have been conducted since the 20th century, with the purpose of experimenting autonomous living. Manuel Kretzer's research in his platform "Materiability" [4] also offers new insight in terms of materials and architectural dynamics. He approached these environments in 2015, on his workshop "Dynamics in Extreme Environments". He states that architecture will have to respond to extreme weather conditions, and that materials will play a critical role in the architectural process of facing these new challenges, on a global scale.

### *1.2. Climate and Architecture*

Bioclimatic Architecture is a concept that encompasses design strategies and the use of materials with sustainable criteria, aiming at assuring comfortable and healthy internal environments respecting the limits of the natural systems [5]. It represents the optimal energy management for buildings, through collection and distribution of renewable energies, in an active or in a passive way [6]. This should be done using proper (and preferably native) materials, with ecological and eco-construction criteria. This turns up as an inseparable concept when researching for construction materials for challenging environments, the relationship between climate and architecture being therefore essential [7]. This research aims to understand how professionals can use and design with materials that fulfil the demands environments put on them, while being at the same time as effective as possible, and how can the impact they have on the environment be minimized. The climate of a region, however, is defined by a variety of factors, being the group of meteorological phenomena that defines the state of the atmosphere, and it varies according to various climate factors. Regardless of these, however, buildings must adapt and change, according to necessity [7]. For example, if one studies the traditional architecture of Aït-Ben-Haddou, in Marroco, which has a desertic climate and hot steppe, it will be drastically different from the architecture of an Igloo, which can be located on the icy tundras of northern Canada (fig. 1). On the first case, the city consists of fortresses and of a defensive architecture, created due to tribal and monarchic wars. The extreme climate conditions these constructions must handle conditions their structure, therefore they form compact group buildings, with narrow interior roads, which offers less exposure to the external climate factors, managing the thermal leaps and offering wind protection. They are build using two wooden barriers, which they fill up with stone first, to avoid rising humidity, and then with rammed earth, which is later coated with a mixture of native clay, sand, lime and sometimes plaster, so that the walls would be water-resistant. When it comes to the igloo, these are subjected to temperatures close to -50º and very strong winds, and they are used by Inuits, which base their economic activities in hunting, and therefore are consistent of nomadic groups, who use the igloo as temporary housing. The base material for its construction is snow which has been compacted by the wind, which is cut into 90cm wide blocks and placed in a spiral to form the igloo's domes; it is always built from the inside. The hemispherical shape of the igloo ensures minimal surface exposed to the winds, and a large interior, which is warmed with an oil lamp. The interior insulation is ensured thanks to animal fur that lines the interior, creating small pockets of air between the fur and the ice. The igloo gains solidity with time, making it a monolithic and very solid structure. With these examples in mind one can begin to understand how buildings differ depending of the environment they exist in; however, most of the examples of bioclimatic architecture are of vernacular origin, and with the existence of air-conditioned units and generally used materials, a sort of generalization of building assemblies happened, where wherever the place, the construction technologies do not vary significantly. What this research aims to achieve is to offer a way of selecting materials for nowadays buildings, that will face new climate-based challenges, that haven't been faced before. As vernacular and ancient architecture responds to the demands of populations from ancient times, so must contemporary architecture do so [7].

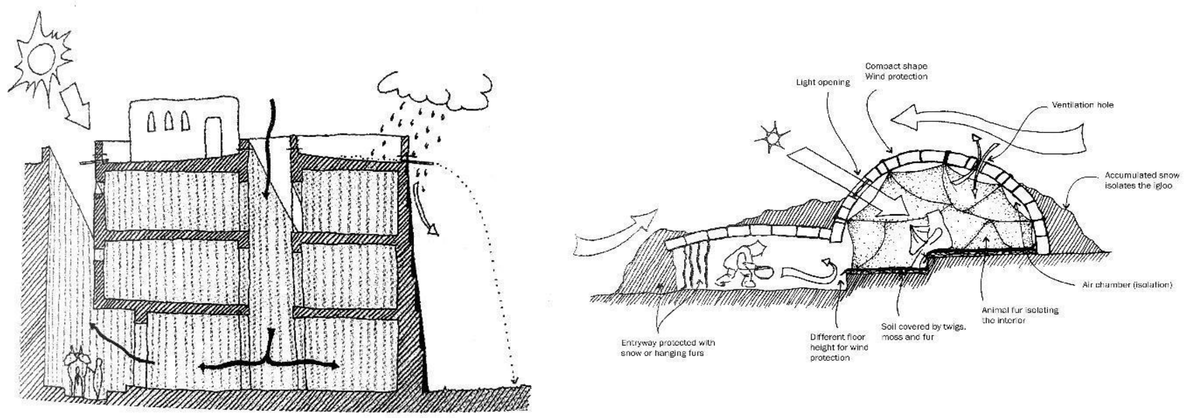


**Figure 1.** Drawn sections of the traditional architecture of the city of Aït-Ben-Haddou in Marroco and a typical Igloo from the Canadian Tundra (Adapted Illustration [7])

### 1.3. *Spatial Configuration and Materials*

When it comes to buildings needing to adapt to new challenges and surroundings, Robert Kronenburg studies lead him [8] to believe that human beings and buildings can and will be flexible and that the latter should adapt to changing situations, depending on place, culture or use. He gives examples of spatially flexible buildings, such as Toyo Ito's Matsumoto Performing Arts Centre, in Japan, which has transformable elements and movable parts in its architecture, such as the ceiling, stage and seating, that can move and adapt according to necessity. It also features fluid spaces, with no determined used, and encourages visitors to interact with each other. He believes this sort of scheme allows buildings to be more responsive, instead of remaining standardized and static [9]. On the other hand, psychologist Sally Augustin studied the attributes of well-designed spaces and their comforting qualities [10], which she states are often under looked in challenging environments, both because of budget limitations and lack of designer involvement. When it comes to feeling well in these sort of spaces, researchers Yan and England, who focused on artic environments [11], concluded that the physical built environment becomes one of the few resources available to help inhabitants cope and adapt to their extreme climate surrounding conditions. When a building is so isolated from other stimuli, the smallest detail can make a difference in one's perception of it. More than adapting to exterior climate factors, spatial configuration and materials in buildings influence greatly those who experience it, and this becomes even more important when we deal with environments that are not ideal, and even may be aggressive, to the human condition; within this context, the best choice of materials and good interior spatial configuration can make the experience as comfortable and ecologically responsible as possible, for both humans and the environment. Having an efficient tool to uncover the best materials for each environment will certainly make the task of designing and building much simpler.

## 2. Methodology

### *2.1. Choosing Climate Conditions*

To select what would be the temperature conditions that could be defined as 'extreme', a simple criterion was used: to refer to the most extreme temperature values ever recorded on permanently inhabited places on Earth. These values are -62 ºC and +57 ºC, corresponding, respectively, to Oymyakon (Siberia, Russia, registered in 2018) [12] and to Furnace Creek (Death Valley, USA, registered in 1913) [13].

### *2.2. Material Library and Selection Criteria*

Next step in this research methodology was to identify the set of materials that would build the library for multicriteria selection based on different climate scenarios. The complete set has a total of 52 materials organized in twelve categories: metals, glass, ceramics, stone, concrete, elastomers, polymers, polymer foams, biopolymers, wood, wood derivatives and natural fibres. Besides materials commonly used in construction (e.g. aluminium, steel, soda glass, bricks, stone, concrete, PVC, PS and PU foams, wood), other materials were included to further extend the base of comparison and find if any of the non-common materials would have suitable properties for extreme climates. The information regarding material properties was retrieved from two main sources, both from the same author, to ensure coherence among the set of data [14] [15].

As previously mentioned, extreme low and extreme high temperatures were chosen as climate scenarios for this analysis (section 2.1.). Eight material properties were used as criteria for analysing the suitability of each material for the two climate scenarios, categorized as thermal, mechanical and eco properties. Thermal category includes thermal conductivity, thermal diffusivity, thermal effusivity, linear thermal expansion and service temperature. Therefore, heat transfer, thermal inertia and thermal stability were considered. The mechanical behaviour was characterized by the fracture toughness because this property was considered as an effective way of dealing with different types of materials having quite dissimilar mechanical performance (e.g. fibres and concrete). Eco properties include recycle potential and embodied carbon (accounting for climate change potential), thus considering the environmental impact of each material.

Service temperature was used to assign to each material a qualitative characterization about its resistance to extreme low, and high, temperatures. By comparing the minimum and maximum service temperature values with the temperature threshold considered for climate conditions (section 2.1.), materials were classified as having high, medium or low resistance to extreme temperatures. It was found that maximum service temperature is higher than +57 ºC for every material. Therefore, this is not a critical property for very hot climates and therefore it was excluded from the models. In what concerns extreme low temperatures, materials having minimum service temperature below -62 ºC were classified as high resistant, the ones having minimum service temperature between -62 ºC and -30 ºC were considered as medium resistant, and those having minimum service temperatures above -30 ºC were classified as having low resistance to extreme low temperatures.

The set of 52 materials, characterized by the above-mentioned eight criteria were the base to build the multi-criteria decision model.

### *2.3. Multi-criteria decision analysis (MCDA)*

To select the best suitable material, or group of materials, for a given climate condition, considering, simultaneously, the eight properties mentioned above (used as criteria), requires that these criteria are prioritized and put together in a single analysis tool. Together with the complexity of simultaneously analysing eight criteria, the fact that some of these are contradictory (e.g. thermal inertia and environmental impact) [16] is the reason why MCDA is an adequate option in this case. MCDA is a general term for systematic approaches that are used to support the analysis of various alternatives in complex problems involving multiple criteria. Various multi-criteria methods have been developed, usually supported by software tools built to help create the evaluation and analysis model [17]. The method used in this research is MACBETH (Measuring Attractiveness by a Categorical Based

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Evaluation Technique), supported by the software tool M-MACBETH. It is a measurement approach from the early 90's that uses non-numerical judgments and weights for criteria in MCDA [17]. The non-numerical judgments implemented by the user are based on a qualitative difference of attractiveness attributed to each pair of criteria. A numerical scale is then generated according to the decision maker's judgments [18]. The MACBETH method was chosen for this research because its efficacy has been proved in various fields, such as urban strategies, environmental planning and eco-system managing. Moreover, the method can include a large number of options and criteria and has a high degree of flexibility in the way options are characterized and judgments are performed. This flexibility allows for a straightforward way of representing different scenarios by changing the difference of attractiveness between criteria and/or between levels of a given criteria to further fine tune the analysis. Furthermore, the decision maker may adjust the relative weights of the criteria within a certain range keeping the consistency of the overall set of judgements.

To represent the two climate scenarios – extreme low and extreme high temperatures, two base models were used. For the extreme cold climate scenario, thermal conductivity and resistance to extreme low temperatures were the first priority properties to consider, having the same relative weight. Environmental impact was considered as the second priority and thus recycle potential and embodied carbon were equally weighted with a weak difference of attractiveness in relation to thermal conductivity and resistance to extreme low temperatures. The third level of priority was given to fracture toughness and linear thermal expansion to which a moderate difference of attractiveness was attributed in relation to the top priority properties. Finally, thermal diffusivity and thermal effusivity were considered as not significant for extreme cold climates because thermal inertia is not a determinant requirement for comfort in these conditions; therefore, these two properties were judged in the model as having an extreme difference of attractiveness to all the others. For the extreme hot climate scenario, thermal conductivity, thermal diffusivity and thermal effusivity were considered as the top priorities because, besides the need to reduce heat transfer, thermal inertia generally plays a crucial role in obtaining comfort in hot climates. The second and third levels of priority are the same as for the previous model, with the same differences of attractiveness. Finally, resistance to extreme low temperatures is not a priority in this case.

In both models, as for the resistance to extreme low temperatures, recycle potential was also characterized by qualitative levels: high, moderate and low. All the other properties were quantified for each material option. In all these quantified properties but thermal conductivity, the levels used for judging and weighting correspond to the full interval of the set of individual values for each material. In the case of thermal conductivity, and considering the scope of this specific research, a limit was established for a material to be considered as suitable in this particular property. In this case, a lower reference of 0.51 W/m.K was considered so that materials with higher thermal conductivity would have a negative rate for heat transfer.

The research further evolved to consider a second set of analysis scenarios in which climate conditions are the same as previously described but where a higher importance was given to the materials environmental impact. In the MACBETH models, this new priority was considered by changing the difference of attractiveness between the levels of recycle potential and of embodied carbon. In the former, levels 'medium' and 'low' were considered as having an extreme difference of attractiveness to 'high', whereas in the base models' variation amongst criterion levels is linear. In the latter, an upper threshold was introduced at 1.30 kg$CO_2$/kg together with a lower reference of 1.95 kg$CO_2$/kg judged as having an extreme difference of attractiveness to the upper threshold value. This procedure was the way to model an analysis where materials having a value for embodied carbon up to that threshold would be highly rated while above that threshold the rate would rapidly decrease to zero and, above the lower reference value, have a negative rate. The threshold of 1.30 kg$CO_2$/kg corresponds to the upper value of a set of materials including stone, simple concrete, ceramics, glass, wood, wood derivatives and some natural fibres.

The four models are designated as 'cold', 'hot', 'cold-eco' and 'hot-eco'.

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## 3. Results and Discussion

As previously mentioned, this paper reports a preliminary phase of an on-going research about selecting materials for buildings in extreme environments. A set of conclusions may be drawn that gives valuable information to direct next steps.

In the base scenario for extreme low temperatures (‘cold’), best ranked materials are polymers, polymer foams, glass, biopolymers, wood and wood derivatives. Ceramics, concrete, stone and metals are very poorly ranked, with negative scores for the cases of stone and metals. The highest ranked material is Polytetrafluoroethylene (PTFE) with a weighted score of 66.48 (out of 100); this modest score shows that there is no material that performs very well in all the criteria within the model structure that was adopted for this research. This means that the ranking of each material is a compromise between the several types of performance considered. For instance, soda-lime glass is the fifth best ranked material in the ‘cold’ scenario although its thermal conductivity is high within the purpose of this study (1.0 W/m.K). However, thermal stability, resistance to extreme low temperatures and recycle potential are strong properties for glass; on the other hand, fracture toughness for glass is very low. These first observations show that the overall ranking is useful for a general analysis, but a more detailed consideration of each individual property is necessary to assure a good match to specific performance requirements of each design case.

In the case of the base scenario for extreme high temperatures (‘hot’), best ranked materials are polymers, biopolymers, polymer foams and glass. The above conclusion for the ‘cold’ scenario about a compromise between the different criteria is again relevant although some nuances may be observed. The best ranked material for this ‘hot’ scenario is polythylene terephthalate (PET) with a very modest score of 48.04. On the other hand, there is now more consistency in the ranking of each individual criterion. The materials that are on the top of the ranking list have a relatively low thermal conductivity and a relatively low environmental impact if assessed by recycle potential and embodied carbon. Wood is an interesting case in this scenario analysis: its rank ($24^{th}$) is a result of a relatively higher thermal conductivity and a low recycle potential. This observation makes the case for the need of further developing and detailing the way of analysing the environmental impact of materials. Another critical observation in the ‘hot’ scenario is related to thermal inertia. The two material properties to assess this type of performance – thermal diffusivity and thermal effusivity – were given priority for extreme high temperatures. In the MCDA model, these two properties have the same weighting judgements as thermal conductivity. However, the materials that have a good thermal inertia performance (concrete, stone and metals) have a very poor thermal insulation performance as assessed by the thermal conductivity. The weighted balance between these three properties privileges thermal conductivity to the detriment of thermal inertia due to the relative differences between the values of these properties in each material. Therefore, there is in this preliminary phase a clear indication that the way to consider thermal inertia for very hot climates needs further development and research.

When a higher importance is given to the materials environmental impact (scenarios ‘cold-eco’ and ‘hot-eco’), generally the overall tendencies observed in the previous models are maintained, with two significant changes. The first is related to the consistency of the ranking of each individual criterion (above mentioned for the ‘hot’ scenario); the higher relative importance attributed to recycle potential and embodied carbon in the ‘hot-eco’ scenario reduces the weight of thermal conductivity and there are good ranking materials that have a poor thermal insulation performance. The second significant change is that the best ranking materials, both for extreme high and low temperatures, are now natural fibres, wood and wood derivatives.

Two additional overall features may be observed from the results, related to contradictory objectives between criteria. There is a conflict between thermal insulation and mechanical strength because the materials with a lower thermal conductivity are the ones with a lower fracture toughness. Another conflict exists between thermal storage and thermal insulation; this observation is not at all surprising because materials that effectively share heat with the surrounding environment must have a moderate to high thermal conductivity. Finally, it is worthwhile to note that almost all the materials have a good thermal stability as assessed by the linear thermal expansion; therefore, this property does not represent

a challenge in material selection for the purpose of extreme temperatures and may thus be removed from the analysis.
The results seem to show that the best material for extreme climate conditions would be one combining the properties of polymers with a very low environmental impact. Specifically, for very hot climates, the ability of storing heat (thermal inertia) would be crucial. It may be said that biopolymers and natural materials as mycelium [19] seem to be good opportunities for further research.

## 4. Conclusion and future directions
The selection of building materials for buildings in the context of extreme temperatures and challenging climates is an issue that requires special attention and constant research, not only due to the effects of climate change but also due to an increasing global environmental concern. Because of this, designers and builders need to be able to ensure that buildings respond to the needs of their users, but also ensure that this can be done without further damaging the environment and thus contributing to the aggravation of the fragile environmental conditions of our world. This process can be made faster and more effective with the use of multi-criteria decision models, for a selection process that has into account various options and criteria in a flexible way. This process allowed to perform a series of analysis within the set of chosen materials considering two base scenarios of extreme temperatures, a very cold and a very hot scenario. With these as references, two other scenarios were introduced, through preference levels, which offered more environmentally positive alternative results to the base ones. Preliminary results show that the best possible material for extreme temperatures, whether it would be a very cold or a very hot environment, is one that could combine the properties of polymers with a very low environmental impact (at the level of the impact from materials such as natural fibres, wood or wood derivatives). The results thus suggest that further research may be directed at biomaterials development to combine high thermal insulation, high mechanical strength and very low environmental impact; for hot climates, thermal storage is an additional requirement. Material performance has a critical role in the search of the best possible ways to design and build in ever-changing and ever-challenging environments.

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