A NOVEL HABITATION DESIGN METHODOLOGY FOR EXTREME ENVIRONMENTS OF EARTH

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Abstract

The research paper explores a methodological approach for designing a habitation concept that does not need human assistance to be designed and built under extreme conditions when people cannot protect comfort conditions and cannot send project resources to the construction site.

The methodological approach considers climate change on a global or local scale environment because some environments are 'extreme' for the survival of their natural ecosystems; instances include enormously common unfavorable climatic events such as extreme colds, severe droughts, or storms. Another point is also important to realize that global climate change is causing particular, extreme ecosystems to become common.

Note. For more information on climate change and its consequences with future projections, see Intergovernmental Panel on Climate Change (IPCC, 2018)[1].

The work develops on contemporary research about comprehensive design approaches related to Earth's future and the current uninhabitable ecological locations. This research study uses annual weather data of extreme locations for human survival to develop a conceptual design of innovative habitation form and then simulate it with possible in-situ materials from literature review to analyze habitation's structural and environmental behavior under extreme temperature differences between interior and exterior atmosphere. Using in-situ material is essential to construct autonomously designed habitation by using additive construction technologies. In this regard, research phases including layout configuration, form-finding, a structural and environmental analysis aim to explore a habitation concept implemented with generative design tools as a decision-maker in extreme conditions.

Within this research project, due to the numerous extreme challenges of the design of habitation in extreme conditions by using conventional approaches, a performance-driven design methodology is done to provide a rational and sustainable design methodology to tackle extreme environmental barriers of the future.

Keywords

Extreme conditions; Habitation; Performance-driven design; Autonomous methodology

1 Introduction: The Need for A Novel Design Methodology

Researchers indicated in the IPCC report [1] that extreme conditions will appear in unexpected places due to global warming and environmental challenges. While extreme environments have already occurred on Earth, extreme climate scenarios will arise in other locations due to climate change.

Since the 1960s, space organizations have been attempting to discover other planets to teach about planetary science, comprehend the nature of climate change, and predict Earth's evolution. As a result of these researches, Wordsworth [2], [3], and Forget [4] state that Mars underwent a significant alteration at some point during its history. The dusty, dried husk we see today became a planet that once was something like the Earth.

For decades, organizations such as NASA [5] have been researching self-sufficient human dwellings to colonize the most extreme environments and deal with the obstacles of living in extreme terrestrial environments such as the Moon and Mars. These research projects conducted by institutes and space organizations can serve as a starting point for developing a habitation concept for any extreme environment to develop a design methodology.

The research project explores a methodological approach for designing a habitation that does not need human assistance to be designed and built under extreme conditions when people cannot protect comfort conditions and send project resources to the construction site. Exploring a design and construction methodology to develop an inhabitable space with a habitation definition is necessary for further developments of humanity to adapt to the most extreme environments like current and future extreme locations on Earth.

Extreme conditions that vary in every location or habitation's functional needs may alter depending on desired functionality for specific objectives. As a result, the research framework's subproblem identifies habitation requirements in terms of functionality, structure, and environment at the early design stage. It transforms them into design input of the required habitation to design a performance-based habitation concept to provide sustainability of design methodology under different extreme conditions.

The primary goal of the research project is to show a scientific design process that uses design criteria as input data to identify the most suitable output as an optimized design choice to enable autonomous advancement in extreme environments. The second goal is to enable the use of construction techniques such as robotic and additive construction.

Due to the numerous extreme challenges of design and construction of habitation in extreme conditions by utilizing traditional techniques, a performance-driven design methodology will be developed to conclude the research project to illustrate a systematic and controlled design methodology to overcome extreme environments.

2 Performance-driven Habitation Design In Extreme Environments

Shi and Yang [6] show that the performance-driven design theory effectively increases design rationality and efficiency, which stimulates its architectural design application. They highlight that performance-driven architectural design focuses on optimizing the design proposal's performance, taking into account the context, climate conditions, and functional needs, ensuring comfort, and putting in place the appropriate design strategies for the digital design platform. Before showing a performance-driven design process, each design need should be specified to be used as input for parametric CAD (Computer-aided Design) tools. To build a habitation for extreme environments, three fields of knowledge must begin and end the computer simulation cycle. Architectural design requirements, structural design requirements, and environmental conditions to create a proposal are covered.

After specification of design criteria from the literature review, a performance-driven methodology will be implemented to provide a reasonable and sustainable design cycle to define a generative habitation concept by following five phases which are;

- a literature review of habitation design requirements for the extreme environment;
- generation of diagrammatic configurations of design requirements with space syntax methodology and layout generation process;
- form-finding simulations for diagrammatic space syntax layout;
- structural analysis for habitation shell performance;
- the environmental performance evaluation of the proposed habitation concept.

2.1 Design parameters as input of the digital workflow: phase 1

Analyzing past space habitat missions and their design concepts is the starting point for establishing design criteria. Space habitats illustrate an optimal habitation concept where it has enough volume and surface internal size, which ensures that the crew can carry out mission work in a secure, productive, and effective way, including work, sleeping, feeding, servicing, housing, and other activities necessary for safe and successful missions.

In 2009, the Paragon Space Development Corporation's team of space engineers [7] carried out expert analysis of historical data and existing requirements for estimating crew volumes for the general nominal, contingency, and emergency operating scenarios using the 95th percentile male crew member of the American crew. The results of this study displayed in Table 1 will be specified as architectural needs for the design and analysis phases.

Table 1: Summary of volume allowances for functional areas per crew member [7].

Functions	**m^3 per crew**	**m^2 per crew**
Command / Control Area	1.06	0.7
Paylaod / Science Area	2.36	1.16
Kitchen/ Galley / Wardroom	1.06	0.7
Private Hygiene	2..36	1.16
Sleeping Quarters	0.85	0.56

The system's material choices, mechanical load, and thermal loads will determine the structural design requirements. Furthermore, using reference studies, particular structural requirements for the most extreme environments, such as the surface of Mars, are examined to execute design suggestions for specific extreme conditions.

Structural analysis of generated habitation in extraterrestrial circumstances must consider the significant loading variables impacting the structural framework of the habitat zone. The gravity, air pressure, internal air pressure, and temperature fluctuation are as indicated in Table 2 and Table 3. For three examples of thermal conditions, higher, lowest, and average outdoor habitat temperatures due to the changes in daylight, the thermal load calculations have been performed. Data in tables are taken from the study of Park et al. [8] on the design of structural Martian habitat analysis.

Table 2: Environmental loads at the Mars surface and the inside of the habitation [8].

Loading Case	**Mars Surface**	**Inside of the habitat**
Gravity Acceleration	3.721 m/s^2 (146.496 in/s^2)	
Air Pressure	0.6 kPa (6.0 mbar; 0.087 psi)	52.67 kPa (526 mbar; 7.639 psi)

Table 3: Temperature differences between Mars surface and the interior of habitat [8].

Loading Case	**Mars Surface**	**Interior Temperature**	**Temperature Difference (Δ)**
High Temperature (Viking 1 lander site)	-31°C (242K; -24°F)		56°C (56K; 101°F)
Low Temperature (Viking 1 lander site)	-89°C (184K; -128°F)		114°C (114K; 205°F)
Highest Temperature (Equator)	20°C (293K; 68°F)	25°C (298K; 77°F)	5°C (5K; 9°F)
Lowest Temperature (South pole)	-153°C (120K; -243°F)		178°C (178K; 320°F)
Average Temperature	-63°C (210K; -82°F)		88°C (88K; 158°F)

Table 4: Properties of Martian Concrete.

Normal modulus [GPa]	10
Densification ratio [–]	1
Tensile strength [–] [MPa]	3.7
Yielding compressive Stress [MPa]	300
Shear Strength Ratio [–]	4
Tensile characteristic length [mm]	55
Softening exponent [–]	0.2
Initial hardening modulus ratio [–]	0.12
Transitional strain ratio [–]	4
Initial friction [–]	0.1

The last structural load factor that influences the simulation is the construction materials selected for the solution. This research project does not involve developing new material for extreme conditions, but it is a crucial step to develop an approach that can be adopted rapidly to understand the behavior of any material under extreme conditions. The fundamental difficulty with the material is that the main research topic is based on extreme environments, and the existing opportunities to offer material from construction sites are seen as the only choice to use for building material. From this point of view, the mechanical characteristics of a newly produced in-situ material will be determined to perform the simulation, although the simulation procedure can be implemented in any local material. In the case of Mars, because the planet has previously been characterized as a "sulfur-rich planet," Wan, Wendner, and Cusatis [9] created Martian concrete, a novel material for on-site construction made primarily of synthetic Martian soil and molten sulfur. Table 4 displays its mechanical properties.

2.2 Generative layout design with the space syntax: phase 2

In this study phase, the architectural criteria of space habitation specified in the previous research phase are applied to develop the best-integrated plan configuration using Syntactic, a generative space-syntax tool created by Pirouz Nourian and Samaneh Rezvani at TU Delft [10]. This plugin integrates Space Syntax theory into parametric design processes with diagrammed input data configurations defined by Paragon Space Development Corporation for this research study [7]. Four syntactic steps can be computed, which are integration, connectivity, depth, and control value. The interior layout follows the functional needs for habitation, such as working, hygiene, exercise, preparing, and eating food.

The previously established architectural requirements are entered into the generative design interface via .csv (comma-separated values) files in the initial stage of generating a connection diagram. After inserting input data, points for each functional area are randomly determined, and connecting lines between the areas are drawn that must be linked to other specified areas following functional requirements. The result disc graph drawing and its analyses are shown in Figure 1. In addition, the space-syntax analysis of layout configuration is shown in the tables of analyses in Figure 1. Integration analysis defines the integration value of space as a result of the input data to indicate the degree to which space is public or private. According to this measurement, the higher the value, the more private space, and the lower the value, the more communal space. The degree to which a vertex in a network is superior to other points is calculated using control analysis. The choice analysis evaluates the degree of choice, determining how frequently space is on the shortest path between other spaces. Lastly, entropy analysis illustrates how space in a system is related. The greater the value, the more difficult it is to move from one location to another.

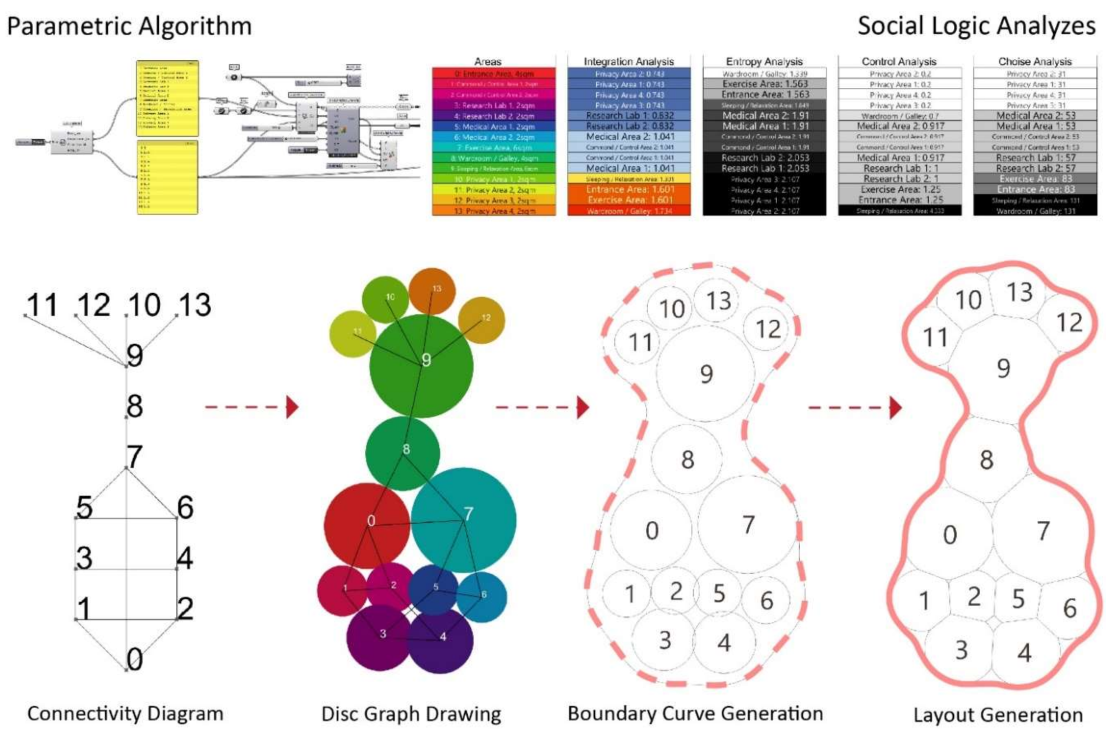


Figure 1. Bubble diagrams for generation and analyses of habitation layout

For generated diagrams, the next step is to mimic a boundary curve. The boundary curve must be automatically computed when the configuration of a conceptual diagram is renewed with a revised requirement input. The bubble diagram algorithm in Figure 1 generates center points for each circle, and radius values for each circle are calculated in Grasshopper using math equations derived from each region's areal data. The center points and radius values are then used as input data for Grasshopper's Metaball tool, which generates a metaball geometry from merged circle definitions. The radius settings have been tuned to produce the bubble diagram-like boundary curves. An isocurve with index zero was chosen to establish a boundary, and then the bubble diagram's circles were calculated angular geometries using a method to fit bubble diagrams within the produced boundary.

2.3 Shell Form generation with volumetric design tools: phase 3

The design of a floor-plan is an essential element in architectural form design that takes place between the design phase and the development phase to produce architectural form morphology as an input parameter, according to Sumini and Mueller [11]. The formula for the development of the inflatable habitat for exploration was provided by Sumini and Müller [11], as seen in Figure 2. The methodology created uses a 3-dimensional optimum layout diagram with areas that reflect the corresponding volume of each functional space. According to this process, the optimized diagram defines an external metabal envelope around the spheres by packaging them. The proposed form-finding simulation approach does not necessitate manual iteration, and the resultant geometry was used for structural calculations utilizing a structural simulation program called Karamba2.

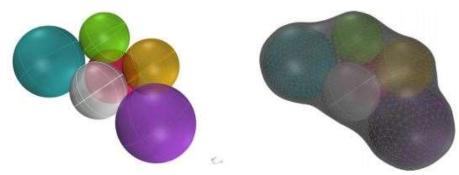


Figure 2. Form generation illustration [11].

This research study follows Sumini and Mueller's methodology, but instead of employing spherical volumes to build a metaball envelope, it considers using the resulting space-syntax diagram. When the space-syntax diagram is changed, the resulting envelope will be updated and will wrap the floor plan diagrams.

Figure 3 illustrates the space-syntax-based volumetric shape generating process. The center points of the functional regions are utilized as input data to characterize the volumes that correspond to them, and the overall volume is determined. The isocurves surrounding this volume are then approximated at regular intervals to construct a cocoon-like envelope that can be used as a shell against extreme conditions. The resulting isocurves are used to build the volumetric envelope.

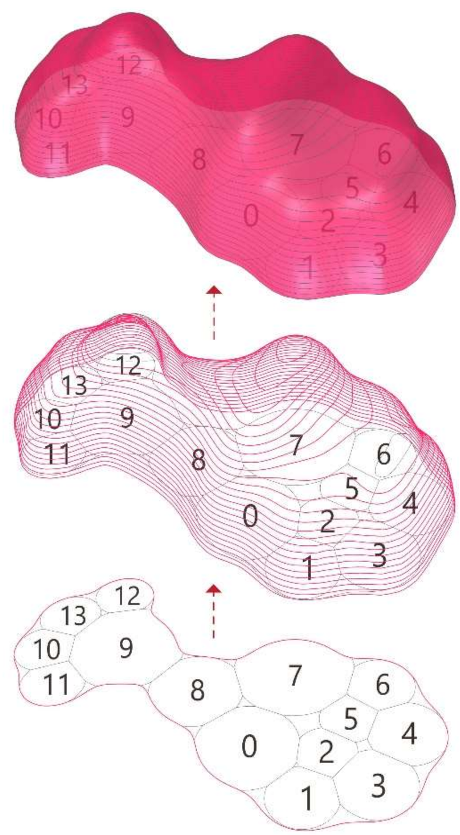


Figure 3. The illustration of habitation form generation process.

2.4 Structural simulations for Extreme conditions: phase 4

During this phase, numerical finite element modeling (FEM) was used to synchronize structural requirements with habitation design as a shell structure using a Karamba Structural Analysis Tool in the Grasshopper interface. The developed habitation form was analyzed as a shell structure since the system must be built with solid in-situ material, and the behavior of the structure must demonstrate stiffness like a shell under extreme environmental conditions.

The Support (Karamba) component defines the support conditions with six degrees of freedom (dofs), three rotational, and three translational. Because all supports are considered fixed, six dofs are indicated as fixed. The vertices as support points, a series of points on the edges of the form on the XY plane, are achieved with the MeshToShell component (Karamba).

The shell structure's self-weight is integrated with an algorithm of gravity, atmospheric pressure, internal air pressure, and the temperature load to model the structural behavior of the habitation shell under specified extreme conditions. The load of gravity is 3,721 m/s^2 and 0.6 kN/m^2. The air pressure inside is 52.67 kN/m^{2,} and the load of the temperature at the lowest, average, and greatest temperature on the Martian surface is computed independently. It is estimated that the internal temperature of the house was 25°C. For the analysis of habitat proposals, the defined data have been used: main forces, moments, shifting forces, maximum movement, and material use.

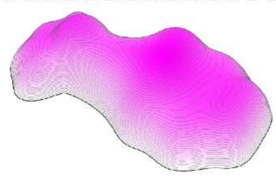
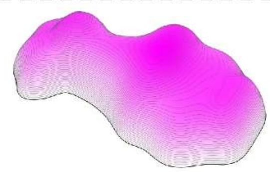
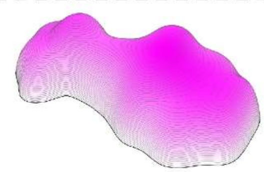
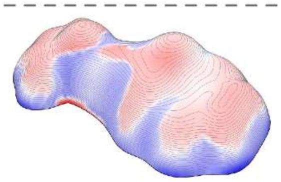
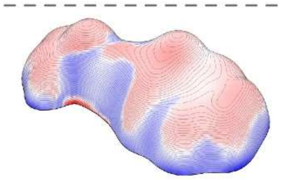
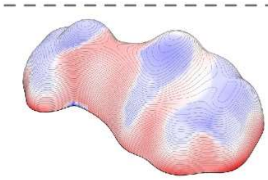
Interior Temperature: +25 °C	Exterior Temperature: -153 °C	Exterior Temperature: -63 °C	Exterior Temperature: +20 °C
Displacement Simulation (cm) +			
Utilization Simulation (%) − +			
Min & Max Principal Forces (kN)	-53.26 to +7696.70 (kN)	-53.26 to +3171.28 (kN)	-447.79 to +292.94 (kN)
Min & Max Principal Moment (kNm)	-300.39 to +1121.86 (kNm)	-125.88 to +453.55 (kNm)	-50.32 to +110.74 (kNm)
Min & Max Shear Force in X (kN/m)	-16681.86 to +25309.53 (kN/m)	-6869.52 to +10455.28 (kN/m)	-3243.62 to +2179.62 (kN/m)
Min & Max Shear Force in Y (kN/m)	-104579.09 to +102916.47 (kN/m)	-42993.33 to +42363.42 (kN/m)	-13479.94 to +13802.41 (kN/m)
Maximum Displacement (cm)	0.988558 (cm)	0.406 (cm)	0.129 (cm)
Material Utilization (%)	-12.4% to +14.3%	-5.2% to +5.7%	-2.2% to +1.9%

Figure 4. Structural simulation result comparison for habitation design

The maximum displacement values for the generated habitation typology shown in Figure 4 for a horizontal circulation orientation are 0.99 cm, 0.40 cm, and 0.13 cm at -153°C, -63°C, and

+20°C, respectively. Maximum principal forces increase by 143 percent, maximum principal moments increase by 147 percent, and maximum shear force values in the x and y directions rise by 142 percent and 143 percent when the temperature is reduced from -63°C to -153°C, but the model behaves differently when the temperature is increased to +20°C. As the exterior temperature parameter is raised from -63°C to +20°C, the maximum principal forces decrease by 91 percent, the maximum principal moment values decrease by 76 percent, and the maximum shear force values x and y directions decrease by 79 percent and 67 percent, respectively. The material utilization value for horizontal habitat design is between -12.4% and +14.3% at -153°C, between -5.2% and +5.7% at -63°C and between -2.2% and +1.9% at +20°C.

The resulting habitation shell design proved stable under dead and environmental loads. On the other hand, material utilization will vary depending on the material standards in place, and its attributes can be adjusted to fit specific requirements. Integrating structural outputs into future research stages will result in a complete procedure for autonomously designing advancement and optimizing it for varied functional purposes and environmental settings.

2.5 The Environmental Evaluations As A Decision-Maker On-Site: Phase 5

As stated, in extreme environmental conditions, a decision-making process is required for design and construction. The study will use weather data for one specific area to examine the level of radiation on the habitation surface to optimize site orientation for the annual maximum level of radiation.

NASA has been conducting research investigations in the most extreme corners of the Earth to understand better the environmental effects on specialized vehicles, technologies, and human comfort requirements. Devon Island, the Atacama Desert, and Death Valley are three of NASA's most extraordinary study locations. Except for January, Devon Island is the largest island with no human habitation and has a similar sunlight duration and radiation intensity to Mars. NASA conducted extensive tests on the island before deploying Mars exploratory vehicles. The island is located on Canada's northwestern coast, near Cornwallis Island.

Before running an environmental simulation, a particular meteorological data file called .epw must be retrieved from the EnergyPlus database. This file format contains a specific location, daily and annual meteorological data such as temperature, radiation, humidity, and wind. However, this information is only available in the database for the specific site having human settlements. As a result, the .epw file is missing from the weather data files for Devon Island, the Atacama Desert, and Death Valley. The meteorological characteristics and geography of the Atacama Desert and Death Valley may change if a different location is chosen, even if it is adjacent to them. On the other side, Cornwallis is separated by a river and has similar weather characteristics from Devon Island. Cornwallis Island has a file of weather data that can be utilized to simulate the environment as it is neighboring Devon Island.

In order to demonstrate the radiation orienting process shown in Figure 5, radiation analyzes have been performed on generated habitation design. The gathered annual temperature data showed that the maximum temperature of Cornwallis Island is +12.8°C, and the lowest temperature is –43.10°C. From February to December, the overall radiation level is 841,53 kWh/m^2, a low level compared with the average radiation on Earth.

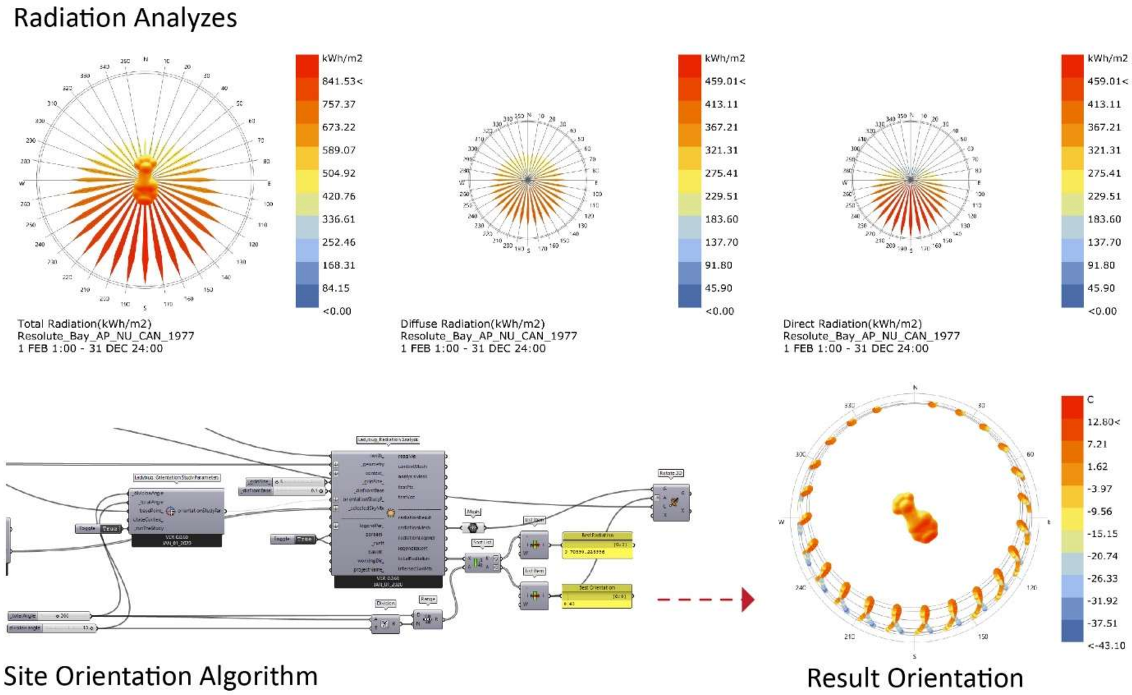


Figure 5. Structural simulation result comparison for habitation design

Following the completion of the radiation study, one of Ladybug's component tools, an optimization tool for orientation, is used to identify the optimal orientation degree. The overall orientation angle is defined as 360 degrees to include radiation from all directions, and a target angle of 10 degrees is defined to rotate the habitation according to this value to repeat its radiation level in each sequence of defined target angles. According to the output data, the habitation has been rotated 40 degrees to get the highest overall radiation. The use of radiation analysis-based site orientation parameters enables a decision-maker process in terms of site orientation without human assistance.

3 Conclusion and Future Work

This study explains the different phases of designing habitation solutions for the most extreme conditions to develop an autonomous process utilizing performance-driven design methodologies. Internal layout creation, form-finding investigations, and structural simulations with Mars load conditions have recently been done to establish an autonomous technique that does not require human assistance in extreme environments.

Layout configurations are formulated utilizing bubble diagrams generated by space-syntax generating tools to determine the best defined spatial relationships. When the layout configuration changes due to a change in connectivity definitions, a self-generated habitation envelope method is created using parametric design tools to reconstruct itself. As a result of this method, habitation forms for various design options could be developed. Because in-situ materials must be used, habitation envelopes are converted into a Finite Element Model as a shell structure for analysis and tested under unique load circumstances. A decision-making system, which allows the structure to be optimized based on its surroundings after showing that the proposed shell designs can resist extreme load situations, should be described as environmental analysis. In order to define the environmental positioning technique, the radiation study was performed, and site orientation in terms of sunlight was fully automated.

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