# Performance-Driven Design Methodology For Habitation Shell Design In Extreme Conditions On Mars

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## Abstract

The research project illustrates how performance-driven design tools can be conducted as an architectural design methodology that suggests an innovative approach to design a habitation shell in extreme environmental conditions without human assistance. This research study attempts to use environmental data revealed from NASA and its habitat design requirements to develop a conceptual design of innovative habitation form and then simulate it with Mars conditions to analyze habitation shell's structural behavior according to the finite element analysis. In this regard, research phases, including layout configuration, form-finding, and structural analysis, have been conducted to explore a habitation concept implemented with generative design tools as a decision-maker in extreme conditions. In conclusion, two generated typologies of proposed habitation forms will be compared in their structural performances under extreme loads of the martian environment. Within this research project, due to the numerous extreme challenges of design and construction of habitation in extreme conditions using conventional approaches, a performance-driven design methodology will provide a rational and sustainable design methodology to tackle extreme barriers to Mars's environment.

**Keywords:** Performance-driven shell design, Finite Element Model, In-situ Material, Extreme Conditions, Mars Habitation

## 1. Introduction

Since the 1950s, hot extremes have almost undoubtedly been more regular and extreme in most geographic regions, whereas cold extremes have become less frequent and less severe (Masson-Delmotte et al., 2021). The growing Earth's evapotranspiration has contributed to the agricultural and ecological droughts in some locations because of human activities. This is also important to realize that global climate change is causing specific extreme ecosystems to become common, with the danger that the biodiversity of these life forms will be threatened.

Extreme environments will emerge in unexpected places due to global warming and environmental problems. The main concern is how professions will support people with the resources they need to respond to these different environments. Since the 1960s, space organizations have been attempting to discover other planets to teach about planetary science and comprehend the nature of climate change. Although data derived from NASA's missions proved the existence of water as ice and underground water, Mars also has geological features that make us think that liquid water flowed on Mars once. Some researchers support that Mars has experienced periods of drastic climate change like Earth during its evolutionary history (Forget, 2009; Milliken et al., 2010; Wordsworth, 2016). A world that was once somewhat Earth-like became the dusty, dry husk we see today forward.

In January 2020, The Human Exploration and Operations Mission Directorate of NASA had commissioned a program status assessment (PSA) of operations aimed at landing humans on the Moon by 2024 (NASA, 2021). Artemis project of NASA will send humanity back to the Moon and prepare humans for a mission to Mars. A multiplicity of factors is driving space settlement. These include improving the standard of living on Earth and significantly improving humanity's long-term survival prospects; developing and deploying space resources to reduce humanity's reliance on Earth-based resources and industry; and protecting the Earth and its environment from climate change. Researching the extreme environment, in comparison to the barriers of the Moon and Mars environments, provides chances to prepare humanity for future environmental problems.

Design methodology to a habitation shell definition to provide an inhabitable space is required for future human developments to adapt to the most extreme conditions, such as the Moon, Mars, and existing and future extreme locations on Earth. This research study explores a methodological approach for designing a habitat that does not need human assistance to be designed under extreme conditions. Responsible and adaptive design strategies are valuable tools to create inhabitable conditions while optimizing design strategy.

### 1.1. Problem statement

Organizations such as NASA and ESA have been studying self-sufficient human habitats for decades to colonize the most extreme environments and deal with challenges to live in extreme conditions of the extraterrestrial environments like Moon and Mars (Bassingthwaighte, 2017). Institutions and space agencies have researched to become milestones to design a habitation concept to live under extreme conditions. Extreme conditions in every unique environment or habitation's functional requirements may differ according to needed functionality for specific purposes. Therefore, the research process's subproblem identifies habitation requirements in terms of functionality, structure, and environment at the early design stage and transforming them into design input of the required habitation to design a performance-based habitation concept to live under extreme conditions.

In the context of architecture, contemporary habitation design approaches rely on material limitations, construction methodology, or the most straightforward pressed shape design to tackle atmospheric challenges; hence, they do not follow standard design criteria. They present different design approaches based on limited perspectives despite using self-generated design methodologies to implement performance analysis. The main problems with designing a habitable construction in extreme conditions like other planets are that humans cannot survive against environmental conditions, and material supply as construction materials is impossible for a sustainable solution because of conditions and cost. This research aims to develop a performance-driven design methodology integrating in-situ material usage to develop an autonomous-designed habitation shell for Mars environments.

## 1.2. Research Questions and Objectives

The research project's main objective is to demonstrate a scientific shell design process that takes design requirements as input data to find the optimum output as a design decision to make progress autonomous for uncrewed missions in extreme environments. The second objective is to provide an autonomous design methodology integrated with advanced construction methods like robotic and additive construction. More specific objectives are:

- to present a simulation-based decision making progress by increasing functionality and rationality of design proposal to make it practical for every habitation design project;
- to propose a habitation shell design methodology that will be implemented to tackle communication problems for long-distance;
- to use space syntax methodology to increase the functionality of habitation layout;
- to create an autonomous architectural form as a shell of optimized layouts;
- to analyze generated habitable form as shell structure to optimize for extreme structural loads.

Due to the numerous challenges of habitation shell design 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.

## 1.3. Framework and proposed methodology

The execution of an operation, or how a system executes, can be defined as performance. It might also be viewed simply as the capacity to perform. In this context, performance is synonymous with efficiency. Performance is frequently used as a hook phrase in architectural design to represent many building difficulties (Shi, 2010). Almost any term may be included in front of performance to create a sentence that architects can understand, such as thermal performance, structural performance, fire-resistant performance, etc. Studying what performance concerns we need to address while constructing a building is a more effective method to grasp what performance means to architectural design.

Shi (2010) suggested a performance classification of architectural design phases based on their objectives. The proposed classification comprises three performance considerations: structural, physical environment, and aesthetic and cultural. The main design limitations in this study are structural performance, which is the most crucial performance challenge that must be successfully studied in habitation design because it is directly related to the safety of inhabitants under the accommodation of the human settlement.

In structural performance optimization, performance-based architectural design refers to a strategy or technique in which the designer focuses on the structure's performance. Once the structural set-up is created, the simulation software is run to assess one or more structural performances of interest to the designer. The simulation results are then examined and evaluated. Based on the assessment, the architect adjusts the design to improve the building's structural performance.

As Figure 1 illustrates, the research study represents a performance-driven design methodology applied in the most extreme conditions, such as Mars and future extreme conditions of Earth. Defining a scientific definition of a performance-driven design set-up with Mars conditions, habitation design requirements, and structural load conditions on Mars surface are specified via a literature review. After clarification of design requirements and load conditions, generative design tools will be used to define an autonomous and iterative design loop with the integration of structural simulations. The research methods and goals mentioned by the author impacted the collection of methodologies listed below.

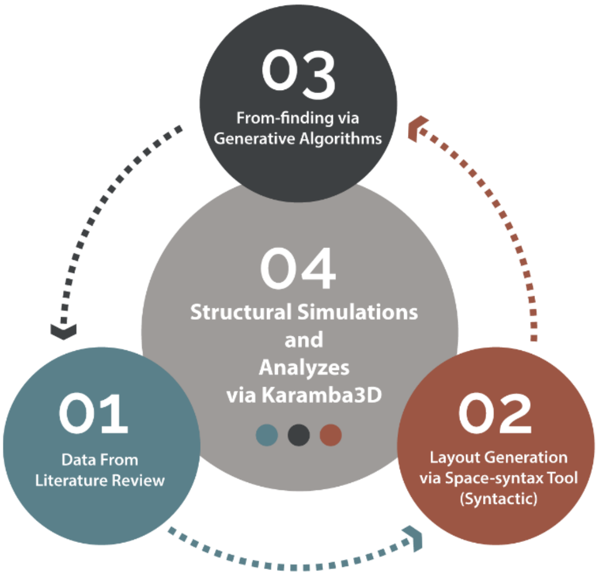



*Figure 1: Diagrammatic illustration of the methodology.*

1) A literature review of habitation design requirements for the extreme environment;

Before demonstrating a performance-driven design methodology, every design requirement should be identified to make them functional input for generative CAD (Computer-aided Design) tools. Three areas of knowledge are required to start and complete the computational simulation cycle to design a habitation shell for extreme environments. These areas are architectural design requirements, structural design requirements, and environmental conditions to build a proposal. A literature review will be implemented to define habitation's design requirements.

2) Layout generation process with diagrammatic configurations of design requirements;

After the literature review, the functional requirements of a habitation design and their corresponding area and volume values will be defined in the conceptual design of habitation. The second phase of defined methodology suggests implementing space syntax via a generative design tool, Syntactic, to provide planning automation with the most integrated layout option.

3) Form finding simulations for layout generations;

The third phase of the methodology aims to create a self-optimized architectural envelope covering floor plans generated in the second phase and defining a self-generated habitation shell form by combining space syntax simulations and volumetric form generation methodologies.

4) Structural analysis for habitation shell performance;

The generated habitation envelope will be analyzed as a shell structure in this phase, using the Karamba3D structural analysis tool in the Grasshopper interface to synchronize habitation structural design requirements not only for load types like internal pressure, reduced gravity, and thermo-mechanical loads but also for possible in-situ construction materials from the literature.

## 2. Research Content

### 2.1. A literature review of habitation design requirements: phase 1

In this research phase, input data of digital design workflow and structural simulation set-up will be defined to use as design requirements. The research project's methodological approach is based on the assessment of specific sections of references and studies, with a focus on the following three knowledge requirements:

- the architectural design requirements contain area and volume specifications which are based on a research study about historical data of habitat design of Nasa for their space missions;
- the structural design requirements will be specified according to material choice, system's structural and mechanical load, internal pressure, and gravity;
- the environmental design requirements contain specifications of temperature loads that happen as conclusions of the temperature difference between interior end exterior of habitation. On Mars's surface, temperature changes during a sol (name of a day for Mars) are the most challenging barrier to provide sustainability for the habitation. The interior of habitation must have a stable temperature value; that is why the temperature difference between interior and exterior during a sol remarkably changes. Extreme temperature differences cause very high thermal loads, which highly affect the rigidity of the structure.

#### Architectural design parameters for the habitation concept

In this research phase, architectural habitation requirements are explained by analyzing previous space habitat missions with their design principles, and area and volume requirements are identified to take as references during the research project.

Habitat designs for space missions are a kind of representation of the optimum habitation concept, where it has a sufficient internal size in terms of volume and surface area, and also ensures that crew members can conduct mission tasks in a secure, productive, and effective manner, including work, sleeping, feeding, maintenance, housekeeping and other tasks necessary for a safe and successful mission.

In 2009, the team of space life science engineers at Paragon Space Development Corporation conducted an expert analysis of historical data and existing requirements to estimate crew volumes for generic nominal, contingency, and emergency operational scenarios based on the 95th percentile American male crewmember (representing the largest specimen at approximately 1.93 meters tall, passively occupying about 0.102 cubic meters of volume (Wickman and Anderson, 2009). Their research shown in Table 1 discusses activity-based estimation techniques and methodologies that lead to determining realistic, justifiable, and cost-effective habitable volumes for new spacecraft, which are physically safe and promote sustained behavioral health. Listed area and volume parameters in Table 1 are the input data of the design process for the performance-driven design methodology to generate optimum architectural layouts.

**Table 1:** Summary of volume for functional areas per crew member (Wickman and Anderson, 2009).

| FUNCTION | $m^3$ 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 |
| Exercise and Equipment Area | 3.06 | 1.42 |
| Health / Medical Area | 1.06 | 0.7 |

The architectural parameters for habitat design may vary in every functional requirement for each unique environment and mission, but they can be parameterized into a design system even if they change. The number of functions or area needs must be defined as input data, and the output solution for each input matrix must be refreshed automatically by design tools.

**Structural design parameters for habitation concept**

Structural analysis of generated habitation form under Martian conditions requires considering the main loading factors that directly affect the habitat area's structural framework, as shown in Table 2 and Table 3, are the gravity load, atmospheric pressure, internal air pressure, and temperature variation. The thermal load analyses will be implemented for three thermal condition cases: maximum, lowest, and the average outside of the habitat because of the sunlight variations. Data given in tables are extracted from the research study of Park et al. about structural analysis of designed Martian habitat (Park et al., 2020).

The habitat must create a balanced living atmosphere for astronauts to perform space exploration without wearing extra life maintenance equipment. As listed in Table 2, the gravitational effect on the Mars surface is known to be less than expected since the acceleration of gravity on the Mars surface is much less than it is on the Earth (38% of Earth's gravity), and after the habitat's interior is pressurized to Earth's atmospheric level to ensure a comfortable atmosphere for astronauts within the habitat, the external air pressure on Mars' surface (0.6 percent of Earth's atmospheric pressure) becomes a vital consideration to analyze. According to NASA's standard for human-crewed missions, it is possible to safely decrease internal pressure to values lower than those experienced on Earth, with minimum pressures of 1150 psf (55.06 kPa) and 1100 psf (52.67 kPa) proposed for regular activities on the Moon and Mars, respectively (Park et al., 2020).

**Table 2:** Environmental loads at the Mars surface and the inside of the habitation (Park et al., 2020).

| 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) |

In addition to gravity and internal air pressure, one of the critical load factors for the habitat architecture on Mars is the significant difference in air temperature on the Martian surface, as demonstrated in Table 3. In addition, the thickness of the habitat's shell may result in sizeable thermal expansion stresses. Temperature loads will be simulated in three scenarios with average, lowest and highest temperature difference from interior temperature.

**Table 3:** Temperature differences between Mars surface and habitat interior (Park et al., 2020)

| Loading Case | Mars Surface | Inside of the habitat | 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) |

The surface temperature values of Mars are very low for human comfort conditions compared to Earth. The average temperature on Mars's surface is -63°C, and the maximum measured temperature on Mars is +20°C on the equator for a limited period. Additionally, icy parts of Mars are the possible locations to find a water resource on the poles, but the minimum temperature on Mars is measured on the south pole at -153°C.

The last structural load factor that affects the structural simulation is the chosen construction material for the system. Using in situ materials as a building material is crucial for a habitation design to sustain independence from the Earth. Researchers (Mueller et al., 2014) indicate that Mars appears to have almost no resources to give us, yet it contains a surface of crushed rock, known as the "regolith," covering the ground to a thickness of several meters, and the most apparent use for regolith is for construction materials with additive technologies; however, its use extends into other unpredictable fields. Studies about radiation on Mars suggest that regolith is an excellent thermal ablative and is considered an in-situ heat shield resource for landers reaching the Martian or terrestrial atmosphere(Arnhof, 2016; Wan et al., 2016).

Using Martian soil to build a Mars project is better than sending all of the building materials from Earth at an astronomically high expense. There are many research studies for developing a construction material by using Martian surface data. For instance, since Mars has always been known to be a "sulfur-rich planet," Wan et al. (2016) developed Martian concrete as a novel material for construction on-site composed mainly of synthetic Martian soil and molten sulfur. Its mechanical properties are listed in Table 4, and its other properties, such as easy curing, low-temperature durability, acid and salt environment tolerance, and 100 percent reusability, are all promising for the usage of Martian Concrete as construction material. Different sulfur percentages are investigated in the analysis of the material to find the best mixture concentrations. The optimum Martian Concrete composition comprises 50% sulfur and 50% regolith.

**Table 4:** Properties of Martian Concrete (Wan et al., 2016).

| Property | Unit | Value |
|---|---|---|
| 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 |

Developing a new material for Mars conditions is not the concern of this research project. Defining a methodology that can be implemented quickly to understand any material's behavior under extreme conditions is one of the critical steps to proceed with an autonomous process. The main concern regarding material is that the main research topic is based on extreme environment, and the existing opportunities to provide material from construction site considered as the only option to use for construction material. From this perspective, developed Martian concrete material's mechanical properties will be defined to simulate to show that simulation workflow can be implemented with a local material definition.

When it comes to magnetic fields, the Earth and Mars are fundamentally opposed. On Mars, the average air pressure is just 0.5 - 1 percent that of the Earth. In principle, Earth's magnetosphere serves to deflect the majority of charged particles from the solar wind, which would otherwise damage the ozone layer and expose the planet to harmful radiation. Häuplik-Meusburger and Bannova (2016) suggest an external regolith layer thickness of 91 cm to 182 cm to protect from radiation. Therefore, the habitation's shell thickness's input value will be defined as a range between 91 cm and 182 cm, and the structural analysis will be implemented with the corresponding self-weight.

Gravity, air pressure, thermal loads, and self-weight of structure will be simulated to understand the behavior of the habitation system under three exterior temperature scenarios. Output results will be analyzed separately to understand the effects of temperature differences between habitation shells' interior and exterior.

## 2.2. Generative layout design with a generative space syntax tool: phase 2

The researchers from the Delft University of Technology transformed space syntax theory into an analytical and a parametric process by defining it with algorithms (Nourian et al., 2013). As a result of their research, they developed Syntactic, a plug-in for Grasshopper, also known as Space Syntax for Generative Design. This generative design tool is used to generate a habitation layout. The Syntactic plug-in's parametric tool uses a force-directed graph-drawing algorithm to construct the bubble diagram's "kissing disk" drawing with the highest integration value according to the drawn connectivity diagram. This method is easy to use and displays bubble diagrams in real-time that are precisely structured according to the defined areas and the connectivity graph. The created bubble diagram provides a first impression of how the habitation layout will appear in an architectural context.

Additionally, Syntactic allows designers and researchers to triangulate the augmented connectivity graph to generate and analyze their studies. Four syntactic steps can be computed, which are integration, connectivity, depth, and control value. The following simple meanings are essential for understanding the analyzing procedure (Nourian et al., 2013).

- Integration, also called availability, is a parameter that indicates how a space in its context is linked to other spaces. The main conclusion is that the axis system brings users into the best-interconnected areas in the system. Likewise, less integration means less population and unwanted reality
- Depth/degree of depth is defined as the minimum series of syntactic steps necessary to reach from one space to another (in a topological context).
- Connectivity is the number of neighboring axes that are directly connected to space is measured by connectivity analysis. It determines the number of an axis's immediate neighbors.
- The control value is the sum of the opposite values of the connectivity parameter for all the selected axial line neighbors. It tests the degree to which the defined space blocks access to all the axis line's close surroundings.

There are three steps to generate habitation layouts: drawing connectivity diagrams, transforming connectivity diagrams into bubble diagrams, and generating floor plans from bubble diagram configurations. Before starting layout generations, defined architectural requirements in the previous chapters are inserted into the generative design interface via .csv (comma-separated values) files. From a three-dimensional perspective, the design proposal can be suggested with a horizontal or a vertical design solution to reply to the extreme conditions of environments. These two options are considered from the beginning of the research study, and the resulting outputs provide an opportunity of comparing two different solutions from the aspect of functionality and feasibility. For vertical configuration, floor areas are separated according to functional connections between spaces and four floors' areas.

The first step in layout generations is to create connectivity diagrams. Designers define a series of points that correspond to each functional space, and these points serve as spaces' centers. Then, designers draw lines to connect the points they consider should be directly connected to define their relationships. These connections will eventually illustrate rooms that are adjacent to each other and can be accessed instantly. The resulting outputs as connectivity diagrams are displayed in Figure 2, and each diagram will be used for bubble diagram generation.

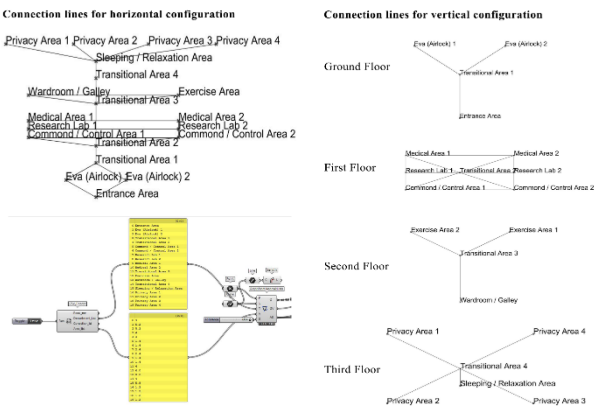



*Figure 2: Generated connectivity diagrams of space-syntax*

In the second step of layout generation, generated connectivity diagrams are used as input data to define force-directed bubble diagrams of habitation layout to find the most integrated and homogeneous layout output. Figure 3 shows an instance of the implemented algorithm to generate the bubble diagrams for horizontal and vertical habitation configurations.

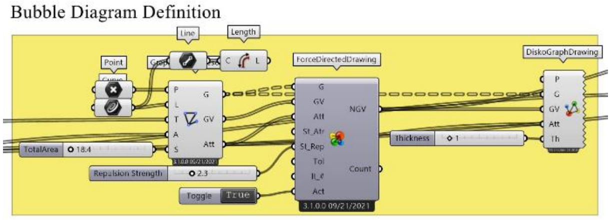



*Figure 3: Bubble diagram algorithm via Syntactic plug-in.*

Figure 4 displays the derived kissing diagrams for both horizontal and vertical habitation configurations and the space-syntax analysis of the horizontal layout configuration as resulted outputs. The result bubble diagrams are constructed independently, and if the defined interconnections between functional areas or the corresponding area values were changed, the result bubble diagram would change simultaneously. Integration analyses show that the greater the value, the more private space is available, and the lower the value, the more communal space is available. Control analysis determines the degree to which a vertex in a graph is superiorly related to other points. The choice analysis demonstrates how often space is on the shortest path between other spaces. Finally, entropy analysis shows how space is interconnected in a system. The higher the value, the more difficult it is to move from one location to another and vice versa.

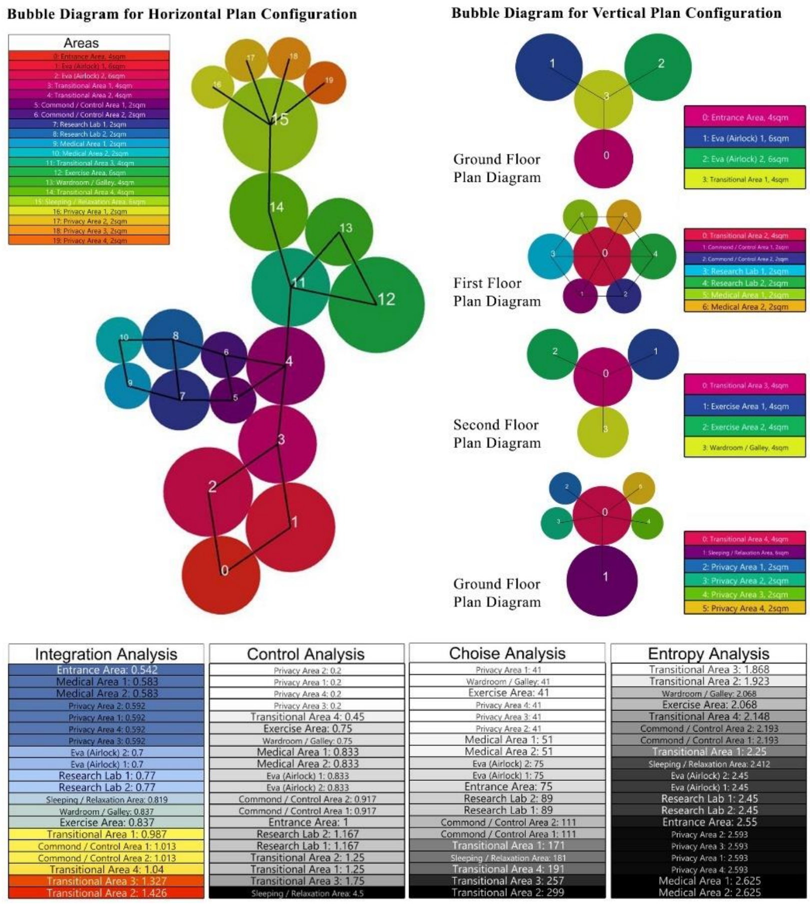



*Figure 4: Bubble diagrams for generated connectivity diagrams and space-syntax analyses for horizontal configuration.*

The last step of layout generation is to transform bubble diagrams into floor plans by defining a generative design algorithm. There are no specific site properties to execute the bubble diagram configurations to generate a floor plan in developing a habitation for any location. In this research phase, the most challenging step is to simulate a boundary curve for generated diagrams. The boundary curve has to be recalculated automatically when the configuration of a conceptual diagram is regenerated with a different requirement input.

The bubble diagram algorithm provides center points for each circle, and each circle's radius values are calculated from each space's areal data using math formulas in Grasshopper. After that, center points and radius values are used as input data for the Metaball tool of the Grasshopper, and a meatball geometry is generated as a consequence of merged circle definitions. The radius values are optimized to obtain the closest boundary curves to the bubble diagram. The isocurve with the index number zero is selected to define a boundary for the habitation proposal. At the final step, the circles of the bubble diagram are approximated angular geometries with an algorithm to fit bubble diagrams into the generated boundary. The process for floor plan generation and output results can be seen in Figure 5 with an instance parametric algorithm definition of one of the vertical habitation's floor plans.

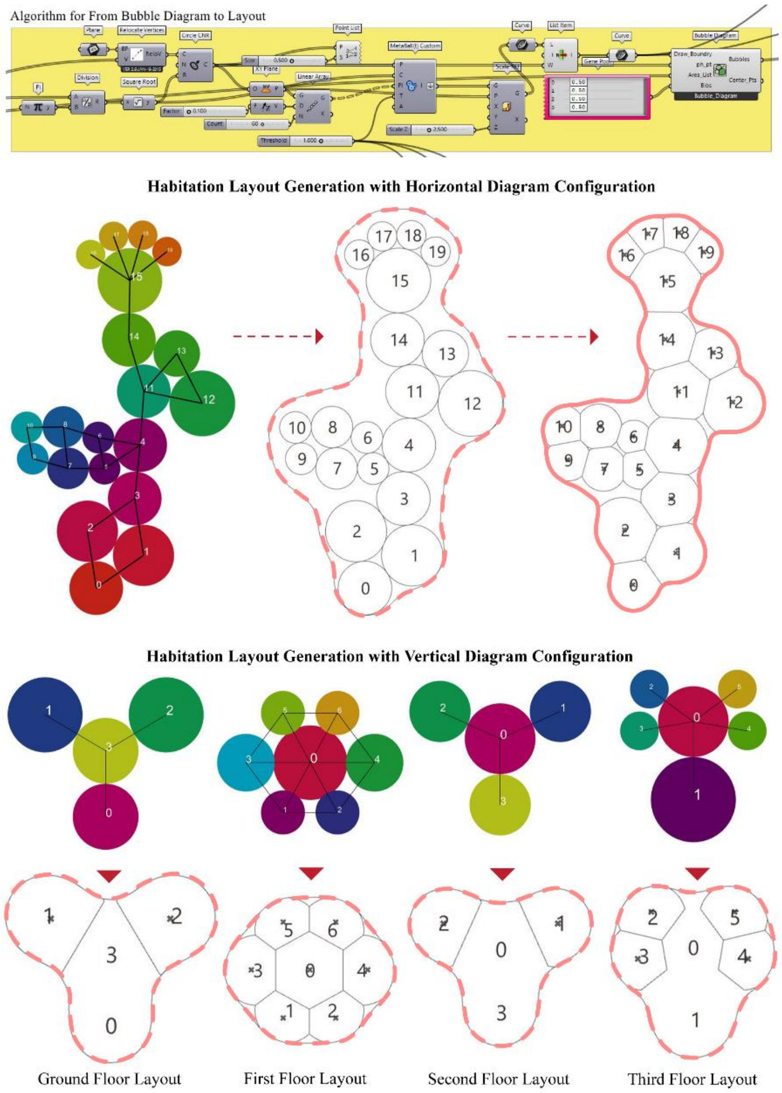



*Figure 5: Layout generation process and algorithm based on metaball methodology.*

## 2.3. Form finding simulations for layout generations: phase 3

This chapter introduces a series of significant achievements to integrate applications of space-syntax methodologies and volumetric design approaches by using generative design tools to suggest an autonomous form-finding process for a habitation proposal for extreme conditions where human has limited resources to design and construct a habitable structure. In contrast to other form-finding design methodologies that use morphological, structural, or environmental data as inputs to create a formal aesthetic, this article presents a procedure that is solely based on architectural requirements and their spatial configurations that provide the highest integration values of the possible layout generations while defining habitation envelope autonomously. Additionally, this process allows the designer to use output concept design to input the structural and environmental analysis to sustain the design cycle.

During the last decade, a broad spectrum of form-finding tools and other experimental, computational techniques have been incorporated in the architectural design process's early stages. However, they are commonly oriented to design forms but seldom related to any deeper consideration for architectural layout planning. Architectural planning is at the core of architectural design thinking and has been one of the main drivers in the discourse within architecture throughout the 20th century. Besides, the current use of digital tools is often mono-functional and aiming to solve and optimize only specific questions like structure, penalization, solar gain, or similar.

According to Sumini and Mueller (2017), the design of a floor-plan is a stage in the architectural form design process that happens between the schematic design phase and the design development phase to provide architectural form morphologies as an input parameter. They proposed a form-finding process for an inflatable exploration habitat design based on an optimized three-dimensional layout diagram with spheres indicating the proportional volume of each functional space (Sumini and Mueller, 2017). According to this process, by packaging the spheres, the optimal diagram defines an external metaball envelope around them. Their proposed form-finding simulation approach eliminates the need for human iteration, and the resultant geometry was used for structural calculations with a structural simulation tool called Karamba3D. This research study follows Sumini's and Mueller's approach, but instead of employing spherical volumes to build a metaball envelope, it proposes using the resulting space-syntax diagrams.

For vertical layout configuration, layouts are aligned according to their centroid to create a soft surface with their boundary curves for the vertical habitation. Following that, the lofted surface is rebuilt to redefine its surface UV map and regularize its face parametrization. The Kangaroo grasshopper tool is then used to optimize mesh design by creating minimal surface characteristics. When the space-syntax diagram is changed, the resulting envelope will be updated, and the floor plan diagrams will be wrapped. Figure 6 depicts the form-finding algorithm used for vertical habitation.

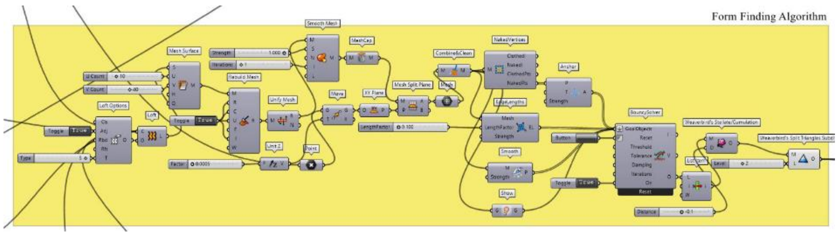



*Figure 6: The defined form-finding algorithm for vertical configuration.*

For horizontal layout configuration, the meatball component of Grasshopper is used to define the habitation's volume. The functional areas' center points are used as input data to describe the corresponding volumes for the horizontal habitation, and the total volume is calculated. Then, at periodic intervals, isocurves surrounding this volume are estimated to produce a cocoon-like envelope to use as a shell against extreme conditions. The volumetric shell envelope is formed in the final step according to the generated isocurves. The final outputs of the space-syntax-based form generation process are shown in Figure 7.

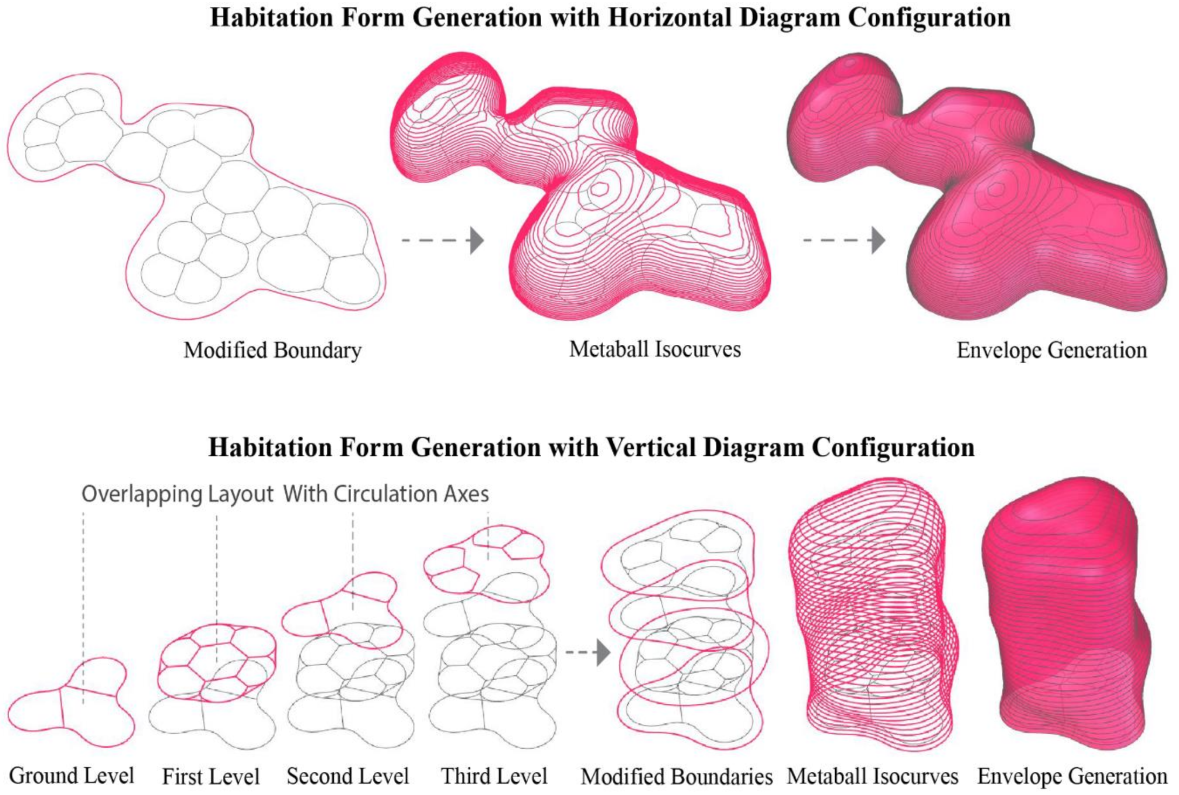



*Figure 7: The illustration of the habitation shell's form generation process.*

## 2.4. Structural simulations for Mars conditions: phase 4

The structural design requirements were formulated according to the system's materials selection, structural, mechanical, and thermal load in this research phase. Defined structural loads, mechanical properties, and environmental loads are simulated as input data of the project's shell form and structural simulation process to measure generated habitation shell options' performance. Structural stability, tension, and stress will be further examined for the generated envelope.

This research article used numerical finite element modeling (FEM) to accomplish the analysis/creation phase of a Mars habitat utilizing the Karamba3D structural analysis tool in the Grasshopper interface to synchronize the habitation's shell design's structural requirements. Karamba3D enables researchers to use FEM to investigate spatial trusses, frames, and shell structures to understand better their structural behavior under relevant loads such as gravity loads, atmospheric pressure, internal pressures, temperature fluctuation, and material properties.

## Structural simulation set-up with an in-situ material

A numerical finite element modeling (FEM) was conducted in this research paper to perform the analysis/creation phase of a Martian habitat using the Karamba3D, a structural analysis tool in the Grasshopper interface, to synchronize habitation design structural requirements. Karamba3D helps researchers to analyze spatial trusses, frames, and shell structures with FEM to understand their structural behavior under relevant loads like gravity loads, atmospheric pressure, internal pressures, temperature variation, and material properties

A shell structure is made up of solid material that has been formed into a particular shape to provide structural rigidity. In this research study, generated habitation form was analyzed as a shell structure since the system must be formed with solid in-situ material, and the shape's behavior must exhibit rigidity like a shell structure under extreme environmental conditions. Generated habitation form is based on an explained form-finding methodology, but its shape has to be simulated directly for the flow of structural and environmental forces, so the shell structure has to be designed based on its weight against constant stresses.

In the structural simulation set-up of a shell structure, the first algorithm definitions are needed to be material and shell cross-section algorithms. As explained before, in 2016, Wan et al. developed a novel material named Martian concrete by suggesting the usage of sulfur as a construction material in Mars conditions. This material is chosen as a possible construction material for the structural simulation set-up, and the material's properties are formulated via Karamba3D, as shown in Figure 8.

In the book Space Architecture Education for Engineers and Architects (Häuplik-Meusburger and Bannova, 2016), authors have suggested that the habitat should resist projectile penetration with a probability of 99% over a 10-year mission period, and the commonly proposed strategy often requires the use of an external regolith layer with a thickness of 3 feet (91 cm) to 6 feet (182 cm). The thickness of the shell cross-section was simulated as 91 cm by defining a range between 91 cm and 182 cm.

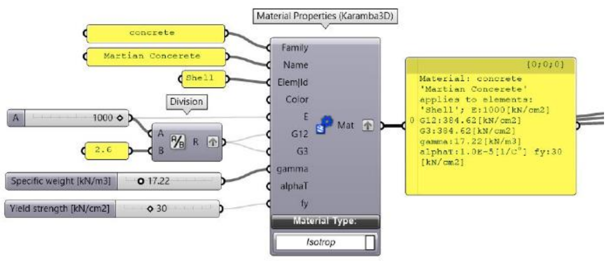



*Figure 8: Material definition with the parametric algorithm.*

The next step of the simulation set-up is to specify support types and locations, as illustrated in Figure 9. As supports, a sequence of points in the XY plane and the shape's edges are set. The MeshToShell (Karamba3D) component is used to obtain the vertices. The support conditions are defined with six degrees of freedom (dofs) in the Support (Karamba3D) component, three rotational and three translational. Six dofs are specified as fixed since all supports on the habitation shells are considered to be fixed.

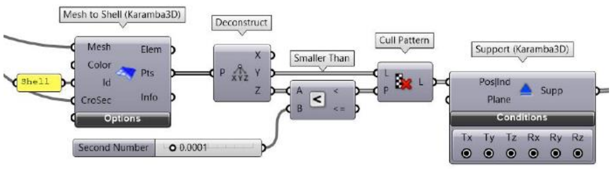



*Figure 9: Definition of structural supports.*

After defining support properties, the specification of load types is required according to derived data from the literature review. Defined algorithmic definitions of loads for gravity, atmospheric pressure, internal air pressure, and temperature variations are shown in Figure 10, and they are applied with the shell structure's self-weight to simulate the habitation shell's structural behavior on Mars. The gravity load is set to 3.721 m/s$^2$, the atmospheric pressure is fixed to 0.6 kN/m$^2$, the internal air pressure is assigned as 52.67 kN/m$^2$, and the temperature loads are separately calculated for conditions of the lowest, average, and highest temperatures on Mars surface. The habitation's interior temperature is presumed to be a temperature of 25°C.

Temperature fluctuations from extreme cold to extreme heat are among the most challenging conditions to live in outer space structures. Without sufficient protection, the temperatures on the Moon, Mars, asteroids, and other celestial bodies are inhospitable to humans. The habitat should have a "shirt-sleeve environment," a term used in aircraft design to describe an aircraft's interior where no unique clothing is needed.

The lowest temperature measured on Mars is -153°C on the south pole of the planet, which causes a 178°C temperature difference between the inside and outside of the habitation.

The average temperature on Mars's surface is -63°C, and even the average value causes an 88°C temperature difference between the inside and outside of the habitation.

On the other hand, the highest temperature that has been measured on Mars is 20°C on the equator of the planet, and a location on the equator may provide thermal convenience for habitation construction, but water and ice resources become far away. Effects of defined temperature variations will be implemented separately to simulate the difference between each condition.

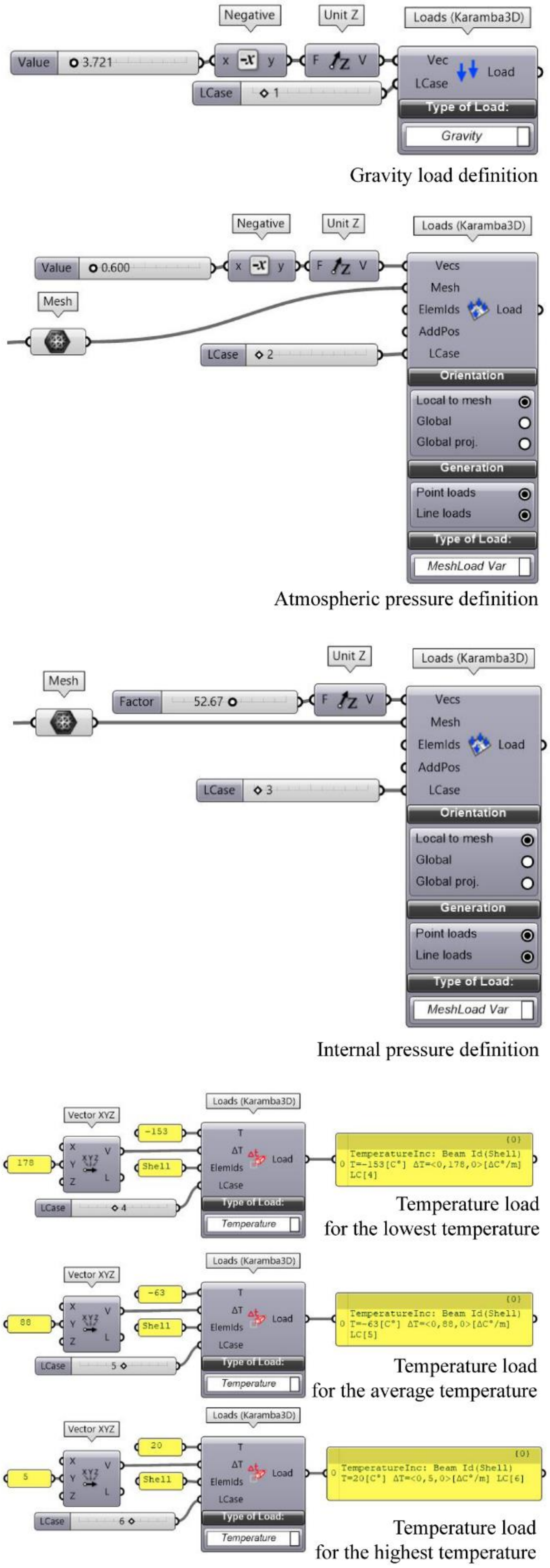


*Figure 10: Structural load parameters.*

**Structural simulation results and discussion**

The analysis aims to explore a strategy in which the load simulations and structural analyses are performed automatically, and the findings can be visualized in structural analysis or modeling software. Designers would like to find the most appropriate research knowledge to implement structural modifications to a project to assist the architect in designing decisions. For instance, the architect may want to consider various material solutions for constructing a shell structure. After conducting the implementation of analysis, the architect may receive many analysis results, including shell deformation, reactions at the supports, bending moments, and internal force diagrams.

The gravity load is defined to simulate the self-weight of Martian concrete used in the shell construction. The dead load acted on the surface of the shell in a negative z-direction. According to the literature review, the shell's thickness was assigned as 91 cm, but the parameter is defined with a range between 91 cm and 182 cm to optimize the shell's cross-section thickness after environmental radiation analysis for further research studies.

In the following structural analysis performed, the dead loads were considered to simulate environmental loads to act on the shell structure. These include atmospheric air pressure, internal pressure, and the loads caused by temperature variations that considerably affect shell structure. These loads are calculated using pressure coefficients acting over the shell's surface, and temperature loads are applied for three different load situations. The assemble component of the Karamba3D interface gathered all necessary information and created a static model. Based on the simulation performed via Karamba3D, it was possible to predict the behavior of the construction under loads and the stress that shell elements experienced.

Two typologies of habitation design are tested with defined structural loads in the previous chapters. Structural simulations were implemented for 25°C interior temperature to analyze the habitation proposal for the different exterior temperatures at -153°C, -63°C, and +20°C. The habitation proposal was evaluated in the following data: principal forces, moments, shear forces, maximum displacements, and material utilization.

The first typology with a vertical circulation orientation shown in Figure 11 results with 1.86 cm, 0.798 cm, and 0.183 cm maximum displacement values at -153°C, -63°C, and +20°C. Although gravity, atmospheric and internal pressure values are the same for the cases, estimated forces and moments are highly different and increase exceptionally from higher to lower temperatures due to temperature loads.

With effects of temperature loads, maximum principal forces increase by 143%, maximum principal moments increase by 147%, and maximum shear force values in the x and y directions all increase by 142% when the temperature is lowered from -63°C to -153°C, but the model responds differently when the temperature is increased to +20°C. When the exterior temperature parameter is increased from -63°C to +20°C, the maximum principal forces decrease by 93%, the maximum principal moment values decrease by 94%, and the maximum shear force values x and y directions decrease by 33% and 65%, respectively.

The cross-section material utilization is the ratio of applied stress over the material's yield strength to achieve a target utilization between -50% to +50%. The used material named Martian concrete from the literature shows an effective behavior under extreme conditions of Mars. The material utilization value for vertical habitat design is between -11.2% and +10.3% at -153°C, between -4.8% and +4.0% at -63°C and between -1.9% and +1.3% at +20°C.

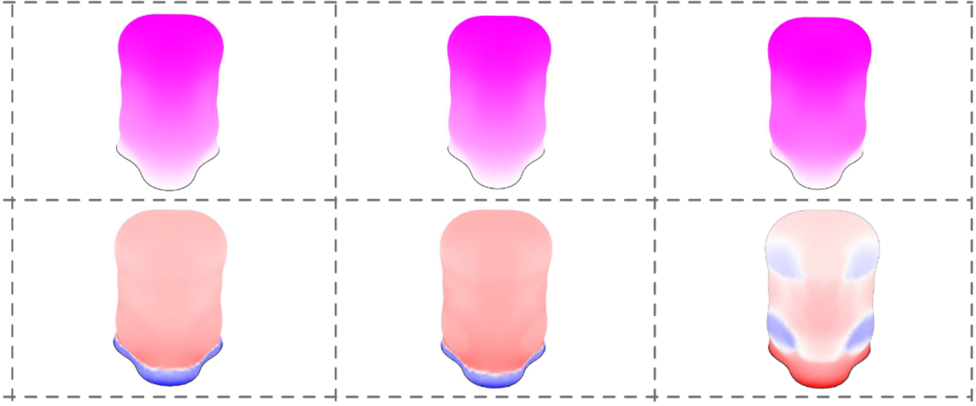
| Interior Temperature: +25 °C | Exterior Temperature: -153 °C | Exterior Temperature: -63 °C | Exterior Temperature: +20 °C |
|---|---|---|---|
| Displacement Simulation (cm) + |  | | |
| Utilization Simulation (%) − + | | | |
| Min & Max Principal Forces (kN) | -263.40 to +19669.39 (kN) | -263.40 to +8093.28 (kN) | -990.50 to +579.10 (kN) |
| Min & Max Principal Moment (kNm) | -1095.80 to +4036.08 (kNm) | -513.46 to +1632.06 (kNm) | -214.63 to +99.65 (kNm) |
| Min & Max Shear Force in X (kN/m) | --795742.03 to +368052.41 (kN/m) | -328741.53 to +152142.12 (kN/m) | -46975.14 to +101936.70 (kN/m) |
| Min & Max Shear Force in Y (kN/m) | -806722.94 to +715928.84 (kN/m) | -333231.63 to +295936.86 (kN/m) | -91389.07 to +103432.57 (kN/m) |
| Maximum Displacement (cm) | 1.86 (cm) | 0.798 (cm) | 0.183 (cm) |
| Material Utilization (%) | -11.2% to +10.3% | -4.8% to +4.0% | -1.9% to +1.3% |

*Figure 11: Structural simulation result comparison for vertical habitation design.*

The maximum displacement values for the second typology shown in Figure 12 for a horizontal circulation orientation are 1.13 cm, 0.468 cm, and 0.143 cm at -153°C, -63°C, and +20°C, respectively. Maximum principal forces increase by 143%, maximum principal moments increase by 149%, and maximum shear force values in the x and y directions rise by 142% and 143% 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 88%, the maximum principal moment values decrease by 86%, and the maximum shear force values x and y directions decrease by 71% and 81%, respectively. The material utilization value for horizontal habitat design is between -10.9% and +11.8% at -153°C, between -4.6% and +4.6% at -63°C and between -2.0% and +1.5% at +20°C.

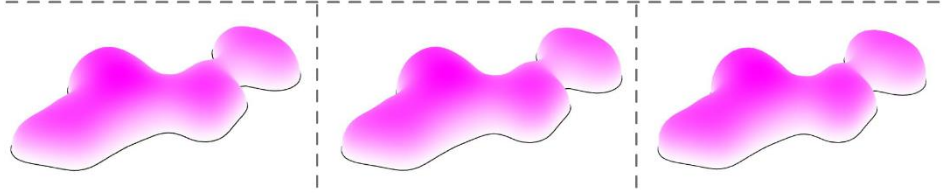
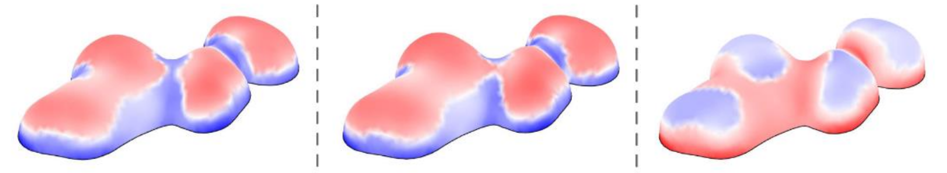
| Interior Temperature: +25 °C | Exterior Temperature: -153 °C | Exterior Temperature: -63 °C | Exterior Temperature: +20 °C |
|---|---|---|---|
| Displacement Simulation (cm) + |  | | |
| Utilization Simulation (%) – + |  | | |
| Min & Max Principal Forces (kN) | -108.25 to +17378.86 (kN) | -108.25 to +7154.71 (kN) | -1563.47 to +815.27 (kN) |
| Min & Max Principal Moment (kNm) | -2093.17 to +4242.55 (kNm) | -899.29 to +1700.42 (kNm) | -275.19 to +234.65 (kNm) |
| Min & Max Shear Force in X (kN/m) | -189916.35 to +215583.07 (kN/m) | -77879.03 to +89023.65 (kN/m) | -27692.24 to +25444.26 (kN/m) |
| Min & Max Shear Force in Y (kN/m) | -468481.13 to +806933.81 (kN/m) | -192079.53 to +331501.71 (kN/m) | -106952.32 to +62824.15 (kN/m) |
| Maximum Displacement (cm) | 1.13 (cm) | 0.468 (cm) | 0.143 (cm) |
| Material Utilization (%) | -10.9% to +11.8% | -4.6% to +4.6% | -2.0% to +1.5% |

*Figure 12: Structural simulation result comparison for horizontal habitation design.*

Two habitation shell typologies receive the structural requirements of the extreme environment of Mars. However, the simulation results reveal that while designing a habitation shell with a vertical configuration causes less principal forces, moments, and shear forces on its surface than horizontally generated habitation design, the illustrated maximum displacement on the vertical proposal is greater than the horizontal one. These are two specific differences that should be re-evaluated for every unique condition's design requirements before deciding on one of the designs. On the other hand, material utilization will be different for each in-situ material of specifications, and its properties can be optimized according to needs.

Generated habitation shell designs were stable under the dead and environmental loads. However, even if the simulation modules are a helpful method for visually inspecting the structure's output under a given load, researchers must be able to derive quantitative data from the model to integrate this analysis into the environmental simulations to optimize, and the optimization process should be implemented to reconstruct each design automatically to adapt it environmental conditions of the site. Four primary outputs from the structural analysis are primarily used in the optimization process for the environmental conditions:

• Model size or mass are reduced to a minimum to create the smallest or lightest structure possible while still achieving the required value;

• Minimizing the maximum model displacement, or the maximum amount of load transferring for any structural element to tackle the design limitations that show how much load the structure can bear under defined loads;

• The reduction of stress in the model is to stay within material properties limits. The overall stress of an element is dependent on the material limit. Researchers want to define a specific protection factor of the structural limit of the material to cover the stresses in all the elements of the model,

• Shell cross-section thickness optimization according to sun path orientation is to reduce affected radiation surface area.

Integrating structural outputs with further research phases will provide a holistic design process to self-oriented and self-optimized progress for different functional requirements and environmental conditions.

## 3. Conclusion and Future Work

This research presents different phases of designing habitation shell proposals for the most extreme environment, Mars, to define an autonomous process with performance-driven design methodologies. A new design methodology for extreme environment habitation has been performed to optimize the functionality and feasibility of every unique habitation project. The internal layout generations, form-finding studies, structural simulations with Mars load conditions have been completed.

Layout configurations are generated with the bubble diagrams created with space-syntax generative tools to find optimum defined spatial relationships. For output layout options, a self-generated habitation envelope algorithm is specified with parametric design tools to rebuilt itself when layout configuration is changed due to a difference in connectivity definitions. As a result of this algorithm, habitation forms are generated for different layout options. For analyzing generated designs, habitation envelopes are transformed into a Finite Element Model as a shell structure due to the need to use in-situ materials and evaluated with unique load conditions of Mars.

For future works, indoor radiation analysis will be conducted to evaluate the habitation shell's cross-section thickness, and thickness value will be optimized to provide maximum radiation protection. The wind is a significant concern to be considered on Mars; that is why a wind simulation will be implemented to analyze structural behavior, and site orientation of habitation will be optimized at once for wind and radiation simulations. After completing the relevant simulation processes, structural window places on the habitation surface will be defined according to stress analysis. Windows will be opened where structural stress lines are minimum. At the end of the research project, a performance-driven shell design methodology will be provided to provide a rational, sustainable, and, most importantly, autonomous.

## Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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This paper and the findings would not have been achievable without my supervisor's and tutor's exceptional supports, Professor Massimiliano Nastri and Professor Pola Caputo. Professor Ingrid Paoletti, the founder of Material Balance Research Lab, not only provided the opportunity to be a family member of her research group, but she also has supported me in creative research activities from the beginning. Thanks to them, I managed to carry my research study forward without a doubt. Lastly, I thank the Ministry of Education of Turkey for encouraging and support me during the research period.

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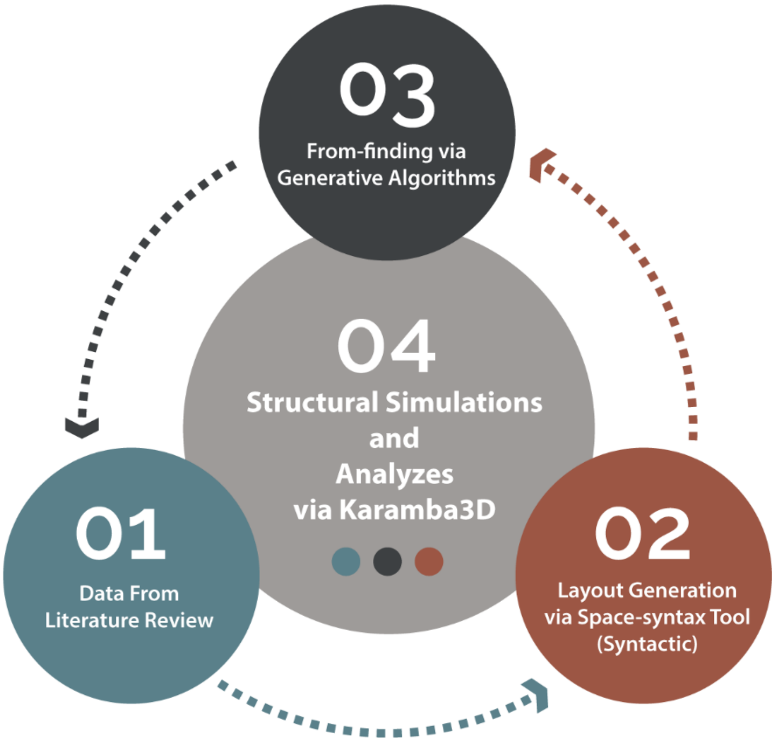



Figure 13: Diagrammatic illustration of the proposed methodology.

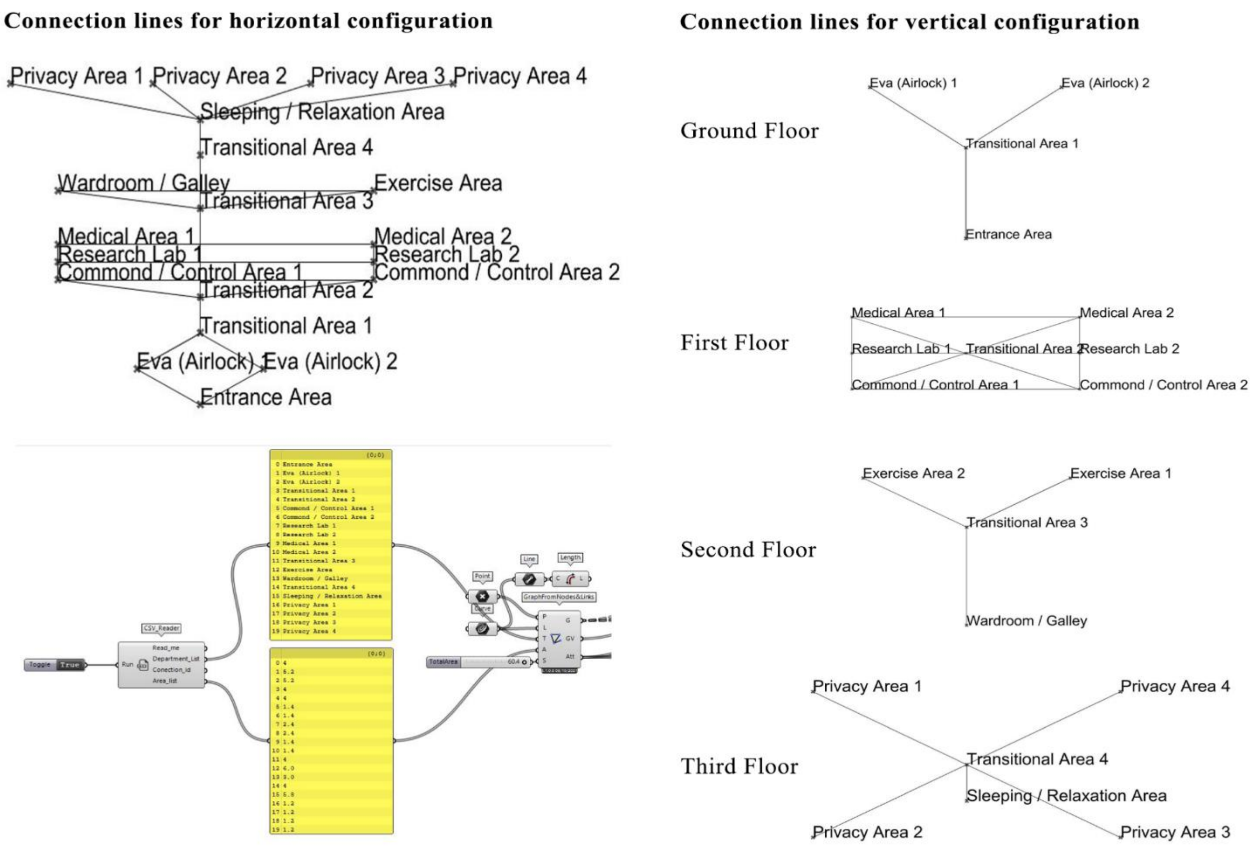



Figure 14: Generated connectivity diagrams of space-syntax analysis.

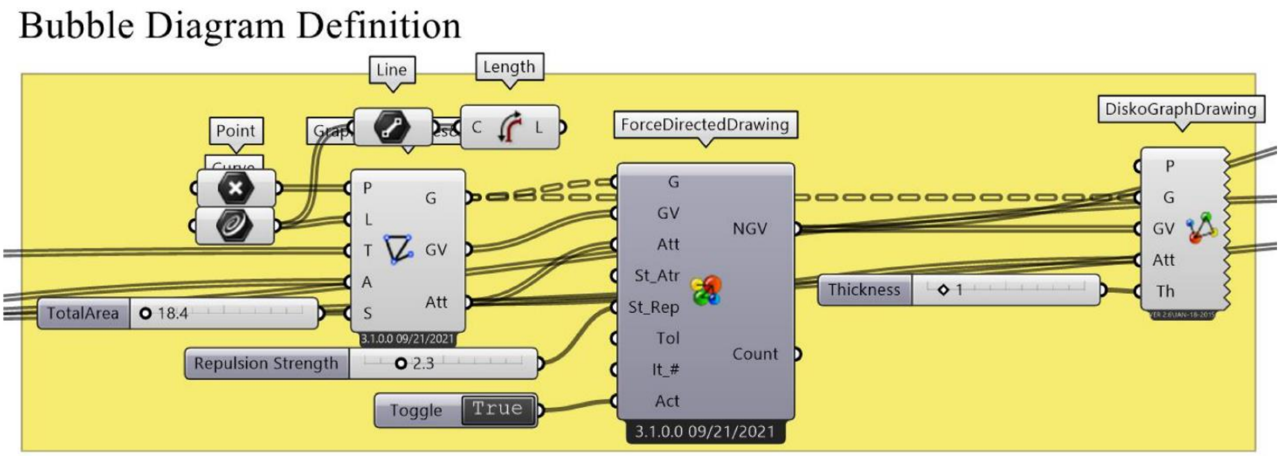
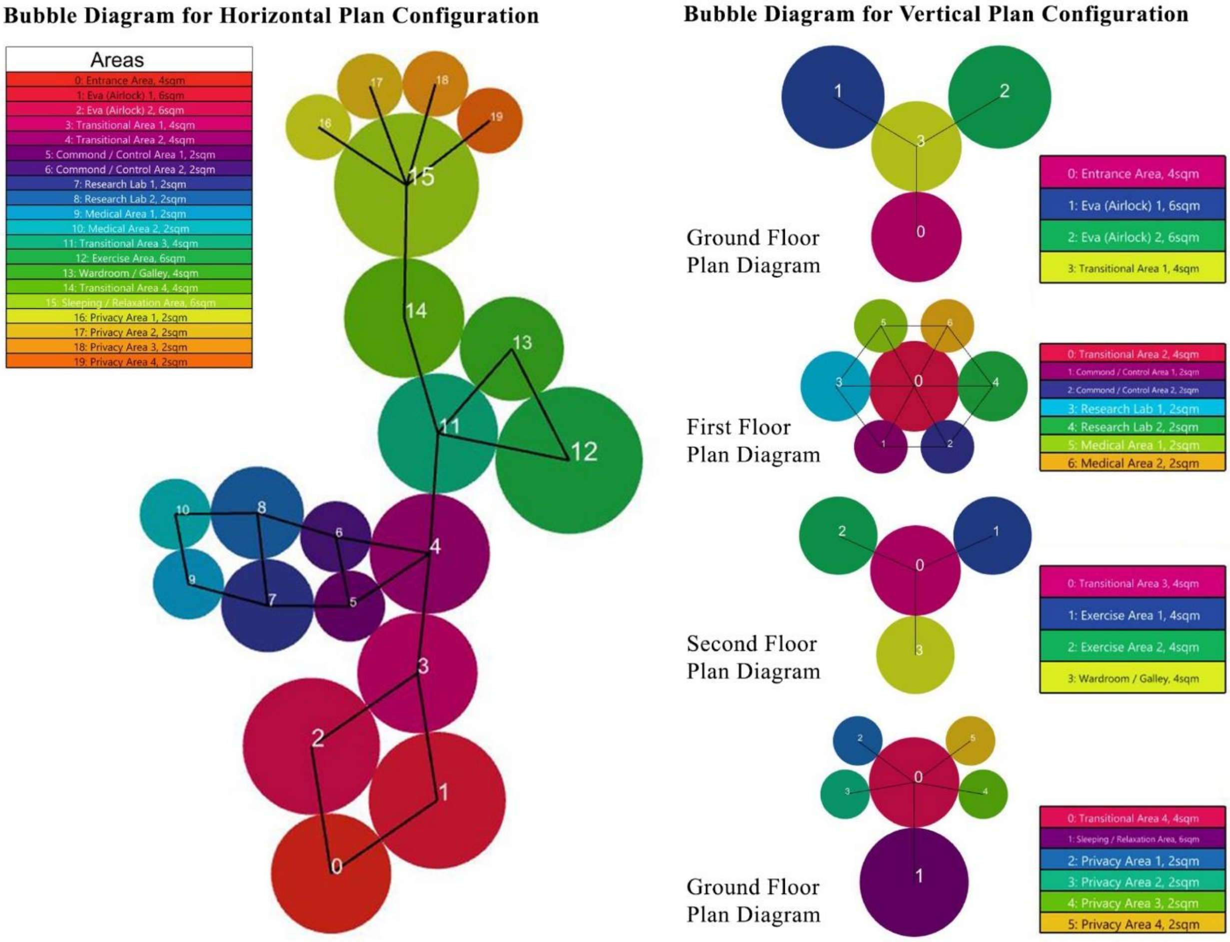



Figure 15: Bubble diagram algorithm via Syntactic plug-in.




| Integration Analysis | Control Analysis | Choise Analysis | Entropy Analysis |
|---|---|---|---|
| Entrance Area: 0.542 | Privacy Area 2: 0.2 | Privacy Area 1: 41 | Transitional Area 3: 1.868 |
| Medical Area 1: 0.583 | Privacy Area 1: 0.2 | Wardroom / Galley: 41 | Transitional Area 2: 1.923 |
| Medical Area 2: 0.583 | Privacy Area 4: 0.2 | Exercise Area: 41 | Wardroom / Galley: 2.068 |
| Privacy Area 2: 0.592 | Privacy Area 3: 0.2 | Privacy Area 4: 41 | Exercise Area: 2.068 |
| Privacy Area 1: 0.592 | Transitional Area 4: 0.45 | Privacy Area 3: 41 | Transitional Area 4: 2.148 |
| Privacy Area 4: 0.592 | Exercise Area: 0.75 | Privacy Area 2: 41 | Commond / Control Area 2: 2.193 |
| Privacy Area 3: 0.592 | Wardroom / Galley: 0.75 | Medical Area 1: 51 | Commond / Control Area 1: 2.193 |
| Eva (Airlock) 2: 0.7 | Medical Area 1: 0.833 | Medical Area 2: 51 | Transitional Area 1: 2.25 |
| Eva (Airlock) 1: 0.7 | Medical Area 2: 0.833 | Eva (Airlock) 2: 75 | Sleeping / Relaxation Area: 2.412 |
| Research Lab 1: 0.77 | Eva (Airlock) 1: 0.833 | Eva (Airlock) 1: 75 | Eva (Airlock) 2: 2.45 |
| Research Lab 2: 0.77 | Eva (Airlock) 2: 0.833 | Entrance Area: 75 | Eva (Airlock) 1: 2.45 |
| Sleeping / Relaxation Area: 0.819 | Commond / Control Area 2: 0.917 | Research Lab 2: 89 | Research Lab 1: 2.45 |
| Wardroom / Galley: 0.837 | Commond / Control Area 1: 0.917 | Research Lab 1: 89 | Research Lab 2: 2.45 |
| Exercise Area: 0.837 | Entrance Area: 1 | Commond / Control Area 2: 111 | Entrance Area: 2.55 |
| Transitional Area 1: 0.987 | Research Lab 2: 1.167 | Commond / Control Area 1: 111 | Privacy Area 2: 2.593 |
| Commond / Control Area 1: 1.013 | Research Lab 1: 1.167 | Transitional Area 1: 171 | Privacy Area 3: 2.593 |
| Commond / Control Area 2: 1.013 | Transitional Area 2: 1.25 | Sleeping / Relaxation Area: 181 | Privacy Area 1: 2.593 |
| Transitional Area 4: 1.04 | Transitional Area 1: 1.25 | Transitional Area 4: 191 | Privacy Area 4: 2.593 |
| Transitional Area 3: 1.327 | Transitional Area 3: 1.75 | Transitional Area 3: 257 | Medical Area 1: 2.625 |
| Transitional Area 2: 1.426 | Sleeping / Relaxation Area: 4.5 | Transitional Area 2: 299 | Medical Area 2: 2.625 |

Figure 16: Bubble diagrams for generated connectivity diagrams and space-syntax analyses for horizontal configuration.

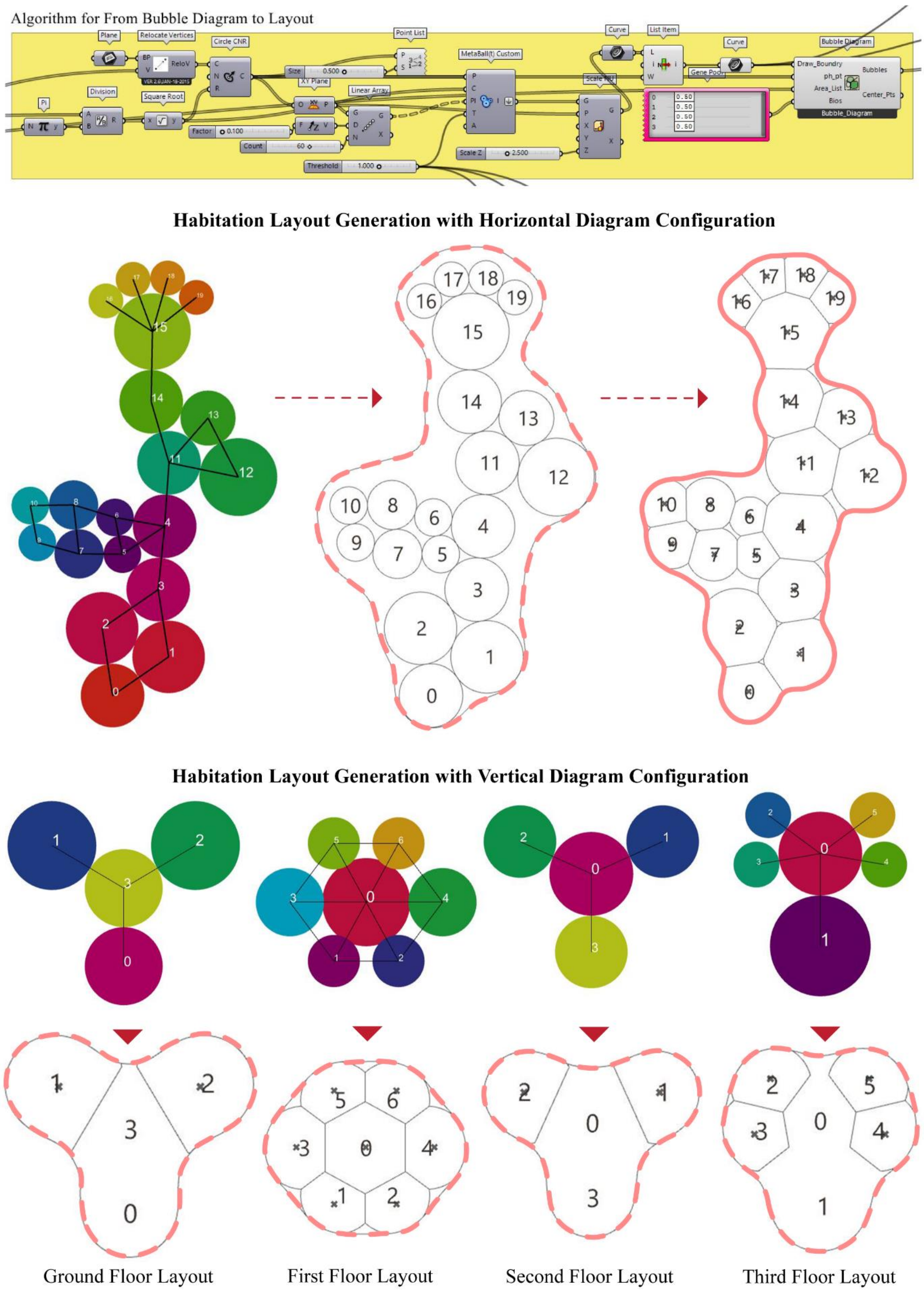



Figure 17: Layout generation process and algorithm based on metaball methodology.

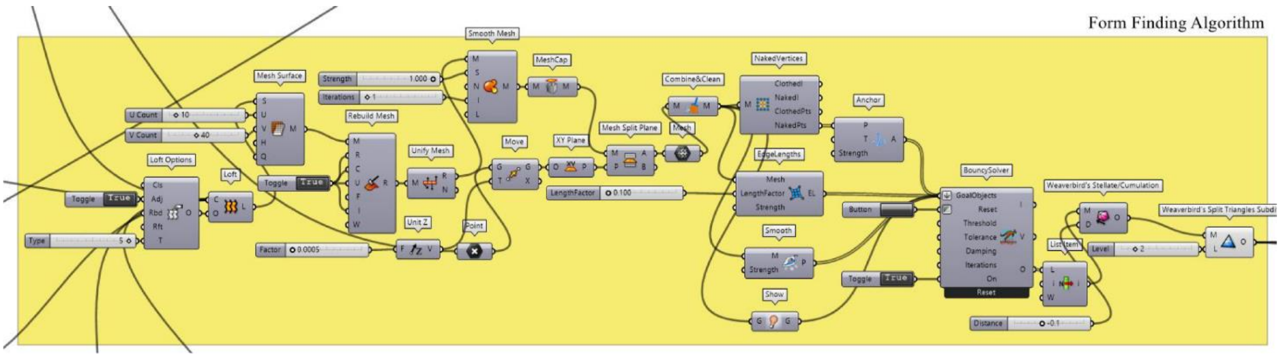



Figure 18: The defined form-finding algorithm for vertical configuration.

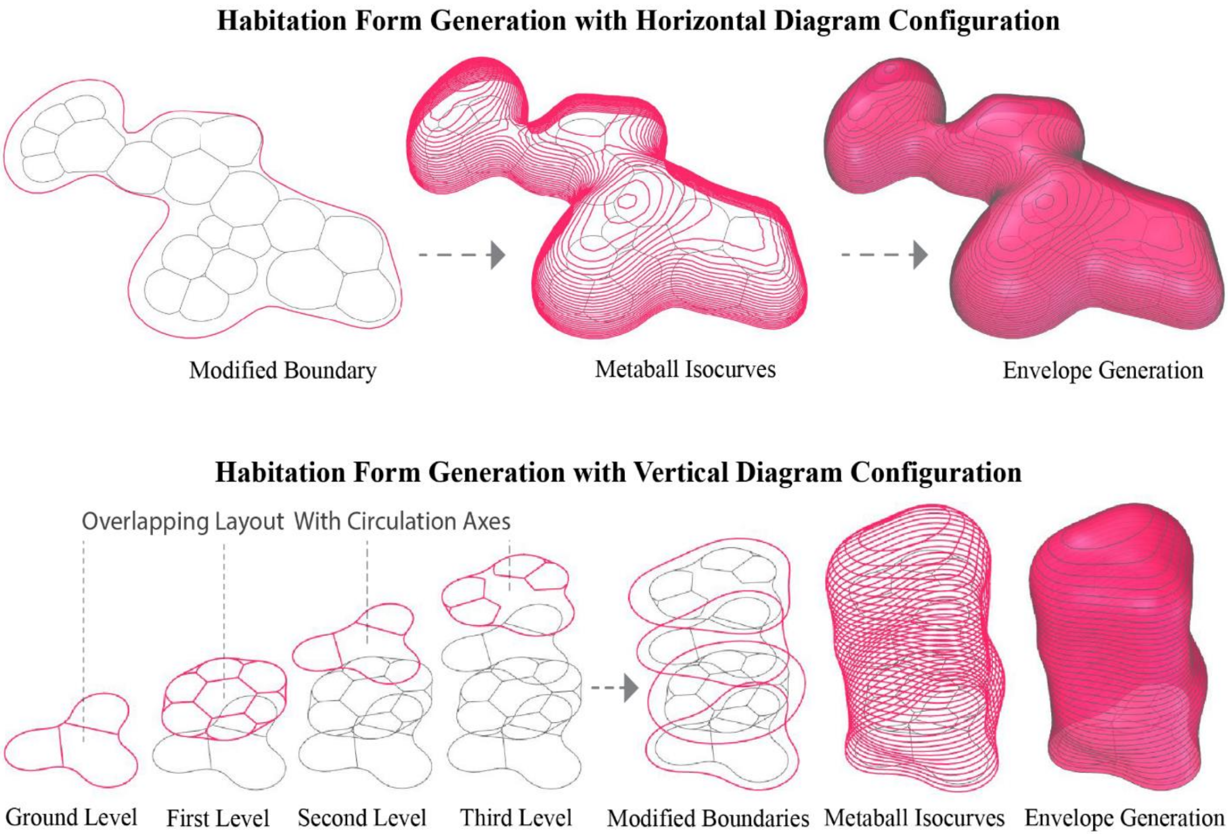



Figure 19: The illustration of the habitation shell's form generation process.

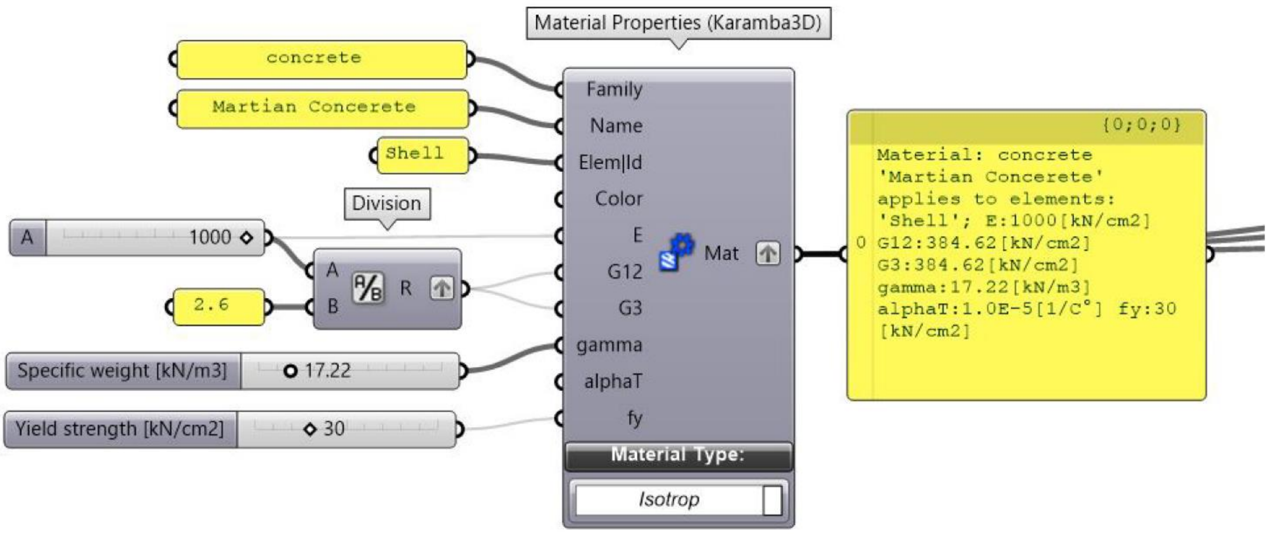



Figure 20: Material definition with the parametric algorithm.

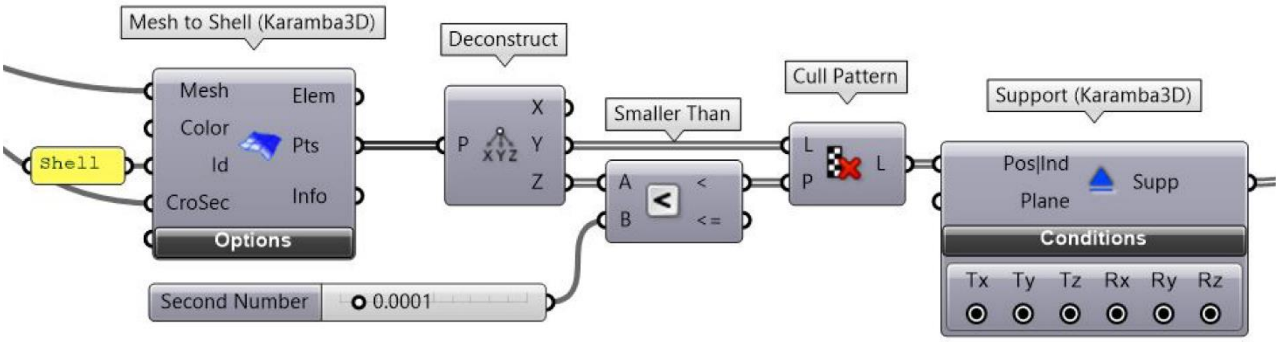
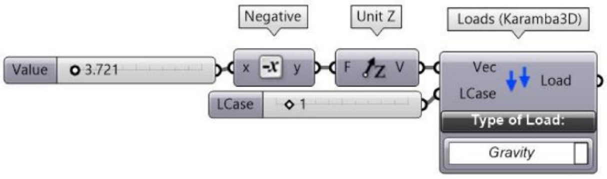
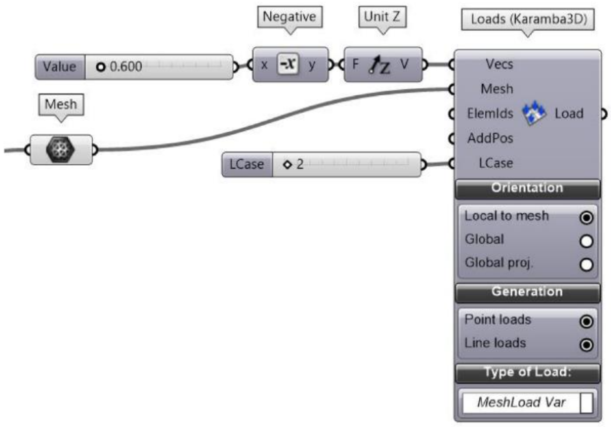


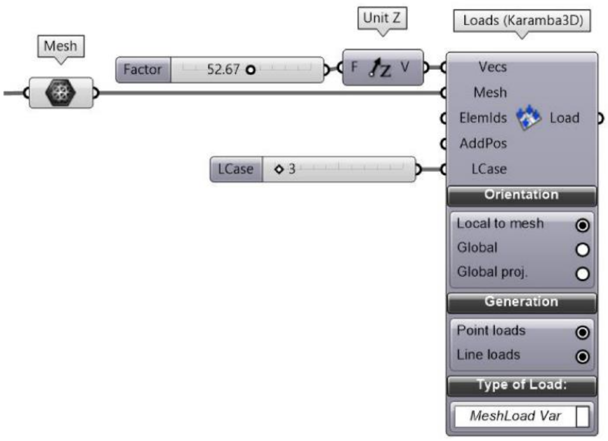

Figure 21: Definition of structural supports.



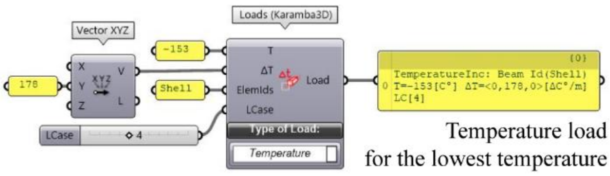

Gravity load definition



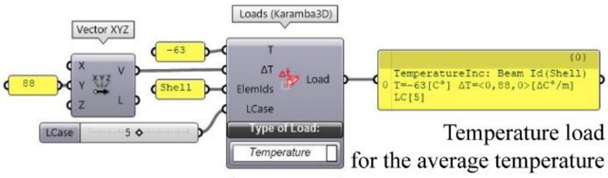

Atmospheric pressure definition



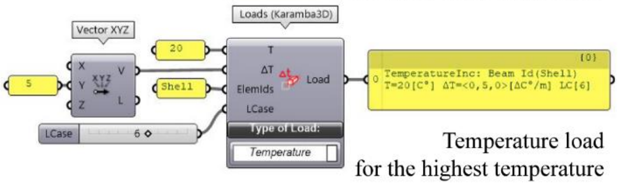

Internal pressure definition




Temperature load
for the lowest temperature




Temperature load
for the average temperature




Temperature load
for the highest temperature

Figure 22: Structural load parameters.

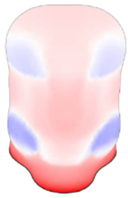
| Interior Temperature: +25 °C | Exterior Temperature: -153 °C | Exterior Temperature: -63 °C | Exterior Temperature: +20 °C |
|---|---|---|---|
| Displacement Simulation (cm)   |  |  |  |
| Utilization Simulation (%)   |  |  |  |
| Min & Max Principal Forces (kN) | -263.40 to +19669.39 (kN) | -263.40 to +8093.28 (kN) | -990.50 to +579.10 (kN) |
| Min & Max Principal Moment (kNm) | -1095.80 to +4036.08 (kNm) | -513.46 to +1632.06 (kNm) | -214.63 to +99.65 (kNm) |
| Min & Max Shear Force in X (kN/m) | --795742.03 to +368052.41 (kN/m) | -328741.53 to +152142.12 (kN/m) | -46975.14 to +101936.70 (kN/m) |
| Min & Max Shear Force in Y (kN/m) | -806722.94 to +715928.84 (kN/m) | -333231.63 to +295936.86 (kN/m) | -91389.07 to +103432.57 (kN/m) |
| Maximum Displacement (cm) | 1.86 (cm) | 0.798 (cm) | 0.183 (cm) |
| Material Utilization (%) | -11.2% to +10.3% | -4.8% to +4.0% | -1.9% to +1.3% |

Figure 23: Structural simulation result comparison for vertical habitation design.

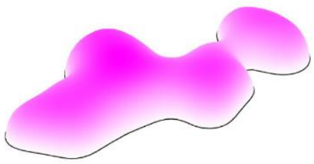
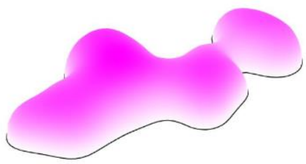
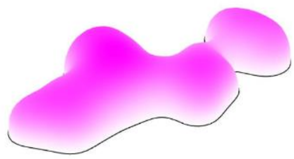
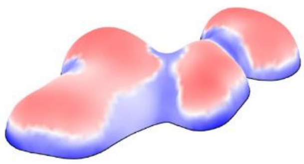
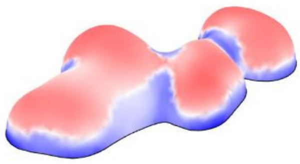
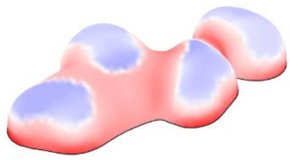
| Interior Temperature: +25 °C | Exterior Temperature: -153 °C | Exterior Temperature: -63 °C | Exterior Temperature: +20 °C |
|---|---|---|---|
| Displacement Simulation (cm) + |  |  |  |
| Utilization Simulation (%) − + |  |  |  |
| Min & Max Principal Forces (kN) | -108.25 to +17378.86 (kN) | -108.25 to +7154.71 (kN) | -1563.47 to +815.27 (kN) |
| Min & Max Principal Moment (kNm) | -2093.17 to +4242.55 (kNm) | -899.29 to +1700.42 (kNm) | -275.19 to +234.65 (kNm) |
| Min & Max Shear Force in X (kN/m) | -189916.35 to +215583.07 (kN/m) | -77879.03 to +89023.65 (kN/m) | -27692.24 to +25444.26 (kN/m) |
| Min & Max Shear Force in Y (kN/m) | -468481.13 to +806933.81 (kN/m) | -192079.53 to +331501.71 (kN/m) | -106952.32 to +62824.15 (kN/m) |
| Maximum Displacement (cm) | 1.13 (cm) | 0.468 (cm) | 0.143 (cm) |
| Material Utilization (%) | -10.9% to +11.8% | -4.6% to +4.6% | -2.0% to +1.5% |

Figure 24: Structural simulation result comparison for horizontal habitation design