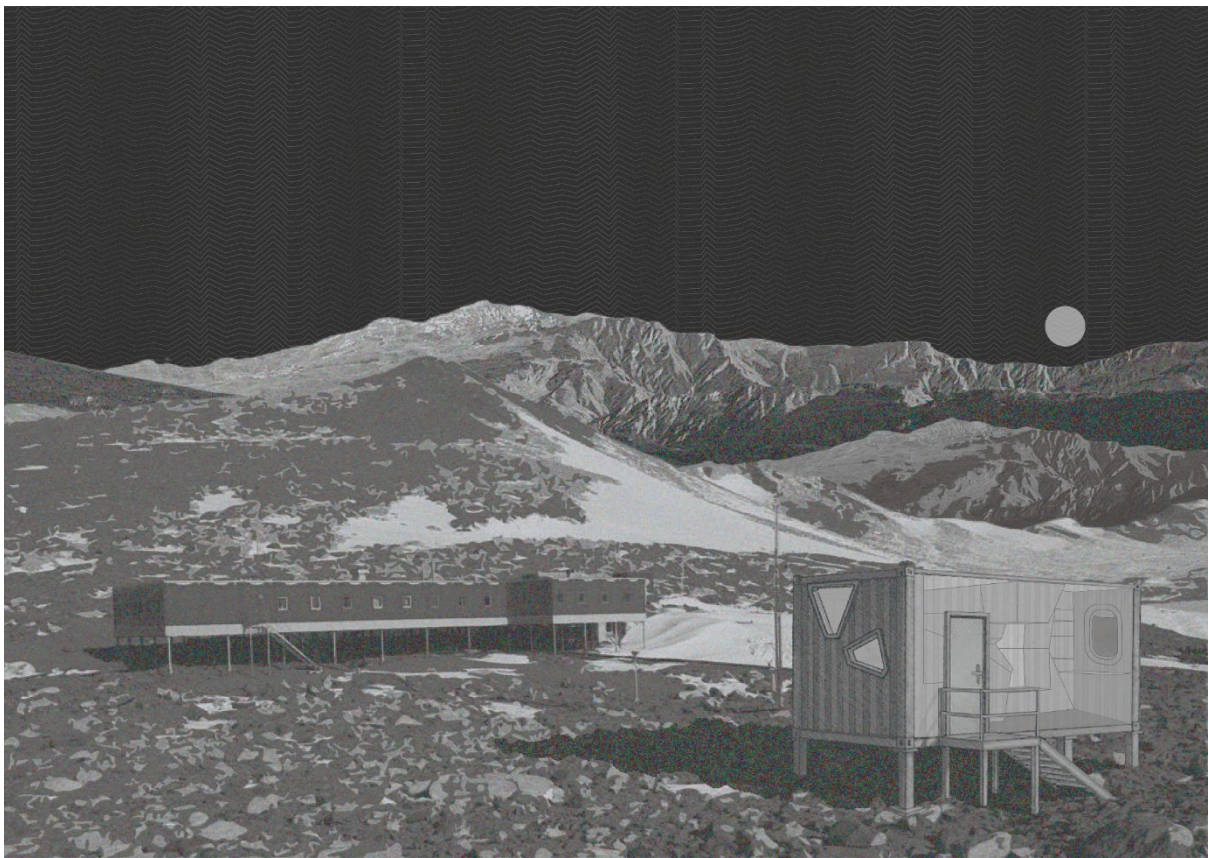


Mission-Driven Habitability

Designing Adaptive Interiors for Confinement Conditions at Troll Station

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Abstract

Research stations situated in extreme polar environments suffer from poor logistic connections and wellbeing challenges related to isolation stress, circadian misalignment, sensory monotony, and prolonged indoor confinement. This paper addresses these concerns by proposing an interior redesign of the standard living container currently employed at the Antarctic-based Troll research station, with particular attention to the most critical winter period, when darkness is continuous and researchers may remain indoors for extended periods.

We implemented three key strategies to address these conditions: (1) a self-supporting Voronoi-based internal fit-out with integrated foldable furniture, (2) 3D-printed construction components derived from the station's plastic waste, and (3) AI-based lighting that responds to individual needs, physiology, and environmental conditions. The project preserves the orthogonal logic of the container envelope while introducing a Voronoi-based infill system capable of organising adaptive interior surfaces across multiple scales, from inhabitable spatial configurations to panel-level structural and acoustic modulation.

The internal fit-out was designed using the parametric design tool Grasshopper for Rhino. The AI model for responsive lighting was developed in Python using the Scikit-learn library and was subsequently translated into both digital simulations and physical prototypes through Arduino-based control and an HTML interface. The project ultimately argues that habitability in extreme environments depends not only on technical shelter, but also on the capacity of space, light, and environmental responsiveness to support agency, privacy, sleep, and psychological endurance over time.

Keywords: adaptive interior, mission-driven confinement, Voronoi geometry, responsive lighting, Antarctic habitation

1 Introduction

In Antarctic research environments, habitation extends beyond technical survival. While the container serves as an efficient and durable architectural unit for remote logistics, its standard configuration often fails to provide adequate conditions for prolonged occupation under psychological and environmental stress. Troll Station presents a particularly relevant architectural context for this issue. Rather than serving as an external case study, the station defines the project's framework: it is a site where container-based architectures are already integrated into the built environment, necessitating the development of new forms of inhabitation from within this logic rather than in opposition to it [1].

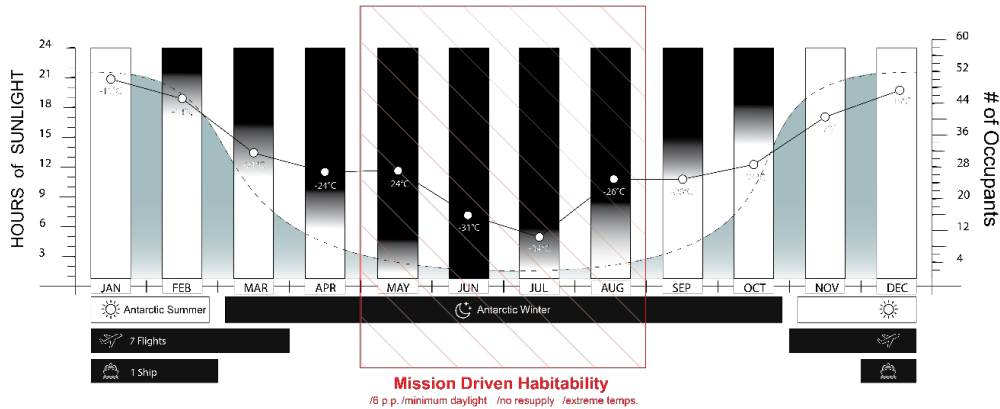


Figure 1: TROLL Station – Hours of Sunlight, # of occupants, monthly temperatures, seasons, resupply.

The project addresses the most critical seasonal condition at the station: the period of maximum winter isolation, characterized by the absence of natural light, restricted external mobility, and increased temporal distance from resupply periods, all of which intensify the sense of confinement. Within this context, the design adopts a worst-case scenario in which two researchers must remain continuously inside a single container for seven days. This scenario serves not as a literal prediction, but as a stress test to reveal the spatial, environmental, and psychological demands of mission-driven confinement. The challenge extends beyond fitting activities into a limited volume; it involves creating an interior capable of accommodating changing rhythms, overlapping routines, and moments of both co-presence and withdrawal.

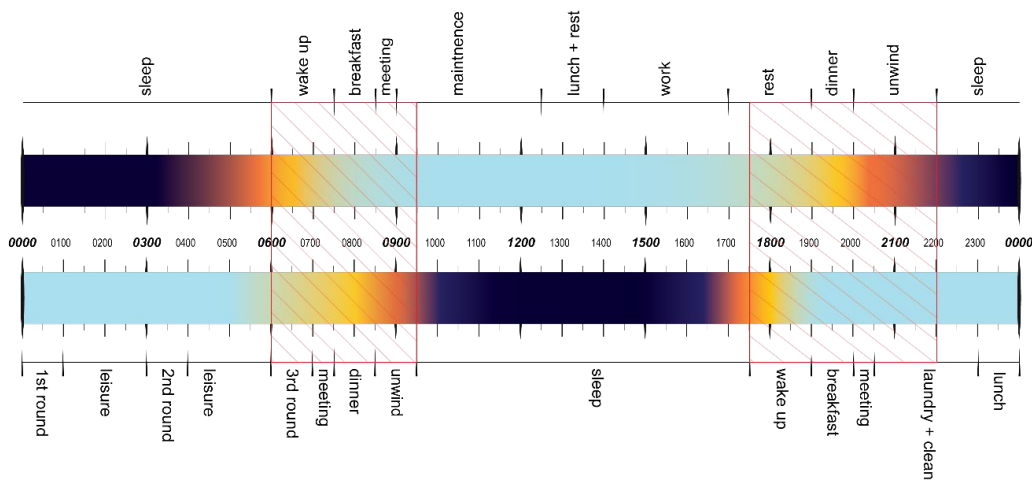


Figure 2: Hypothetical 2-person Schedule – Emphasis on Schedule overlap.

Three criteria guided the project from its inception: agency, privacy, and sleep. These were identified as the minimum requirements for an interior to remain inhabitable under confinement. Agency denotes the users' ability to modify or appropriate space in response to changing needs. Privacy addresses the possibility of temporary separation and retreat despite spatial constraints. Sleep is considered not only a biological necessity but also a spatial and environmental condition closely linked to light, routine, and recovery. Collectively, these criteria position the project as an adaptive system: a habitat capable of responding autonomously to changing conditions and inputs, rather than relying solely on explicit user commands.

Within this framework, light serves as a central architectural medium. During the polar night, artificial lighting is not merely supplementary; it becomes a primary means of structuring time, mood, focus, and rest [2], [3]. Consequently, the project integrates lighting into the core of spatial design, developing a predictive workflow that links circadian requirements, environmental inputs, and selected physiological indicators to the regulation of illuminance and correlated colour temperature. The proposal unifies geometry, environmental control, and prototyping within a single integrated design system to support habitation under the specific constraints of Troll Station.

Design driver	Problem in confinement	Design response
<i>Agency</i>	Reduced control in a compact shared interior	Reconfigurable furniture and adaptable occupation
<i>Privacy</i>	Constant co-presence and overlap of routines	Differentiated zones and retreat conditions
<i>Sleep</i>	Circadian disruption and conflicting schedules	Adaptive lighting and temporal zoning
<i>Environmental support</i>	Sensory monotony and low daylight	Integrated light-responsive interior system

Table 1: Main design drivers and corresponding spatial and environmental responses.

2 Research Methodology

The project employed an iterative methodology that integrated scenario definition, activity mapping, computational design, environmental modelling, and physical prototyping. The initial phase identified the period of maximum environmental and logistical stress within the annual cycle of Troll Station. Instead of designing for average conditions, the project intentionally addressed the most challenging winter interval, characterized by continuous darkness, reduced occupancy, and increased reliance on the architectural interior. Based on this analysis, a confinement scenario was established in which two occupants continuously inhabited the container for a seven-day period. This scenario provided the operative framework for evaluating spatial needs, lighting requirements, and environmental performance.

The subsequent phase involved mapping daily activities and their corresponding spatial and lighting requirements. Activities such as sleeping, working, retreating, informal interaction, and shared use were analysed as time-based and bodily conditions that could overlap within the same spatial volume, rather than as fixed room functions. This analysis established three guiding criteria for the project: agency, privacy, and sleep, and highlighted the necessity for a reconfigurable spatial system instead of static zoning. Concurrently, literature on circadian lighting informed the temporal logic of the proposal, particularly in relation to the absence of daylight during the polar night and the need to support focus, rest, and psychological well-being through artificial illumination [2], [3].

The computational design phase translated these requirements into geometric form. Using Grasshopper scripts, a spatial system was developed that combined an orthogonal container logic with a Voronoi-based infill logic. The orthogonal framework maintained the container's structural and dimensional stability, while the Voronoi system was generated by manipulating point distributions to create surfaces, cavities, and interior conditions suitable for the identified activities. The aim was to establish a controlled adaptive system in which geometry supports inhabitation at multiple scales, rather than producing a free-form interior.

The final methodological phase integrated prediction with implementation. An AI-based model was trained to correlate environmental and physiological inputs with lighting outputs, specifically illuminance and correlated colour temperature. These outputs were exported as datasets and subsequently applied in digital simulations and physical prototyping. The workflow progressed from CSV-based values to RGB and brightness conversion, followed by Arduino control, LED actuation, and browser-based interaction. This methodology established a continuous link from design intent to environmental performance, enabling the project to be tested both as a representation and as an operational proof of concept.

3 Geometric development

The geometric strategy of the project relies on the coexistence of two distinct yet complementary systems: an orthogonal structural container and a Voronoi-based infill. These systems do not function as equivalent spatial fields within the same void; instead, they operate through a relationship of envelope and content. The orthogonal system establishes the primary order of the container, maintaining constructive clarity, dimensional boundaries, and infrastructural logic. Within this stable framework, the Voronoi system serves as an internal layer that enables occupation, modulation, and differentiation. Its function is not to replace the container, but to transform the possibilities for inhabitation within it.

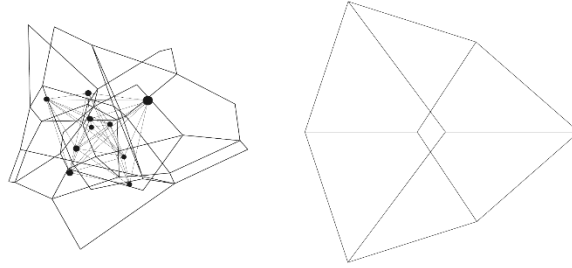


Figure 3: Two geometrical systems, Voronoi and orthogonal

The design process commenced with the definition of a general habitat for two occupants and progressively focused on a specific area where critical relationships among routines, proximity, and environmental support could be spatially evaluated. By manipulating the point cloud in Grasshopper, the Voronoi geometry was refined to achieve the desired surfaces and spatial conditions. The objective was to develop a configuration that remained legible, adaptable, and dynamic while maintaining architectural coherence. This approach generated a family of surfaces capable of supporting both inhabitable variation and constructive refinement.

A significant aspect of the project is the application of Voronoi geometry at multiple scales. At the macro scale, it informs the spatial articulation of the interior, generating differentiated zones and occupiable surfaces within the orthogonal shell. At the micro scale, it defines the composition of individual panels. In this context, Voronoi logic is not solely spatial but also performative, contributing to the internal organisation of the panel through acoustic texture, material differentiation, and structural optimisation. Thus, the geometry functions as a multi-scalar design principle that integrates inhabitation, environmental modulation, and fabrication logic.

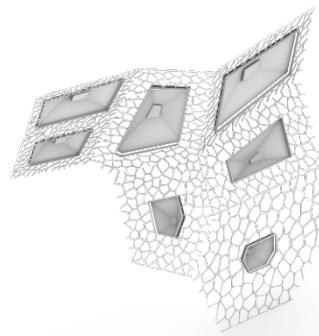


Figure 4: Voronoi patterns implemented at multiple scales.

This smaller-scale development underwent further evaluation through structural analysis in Grasshopper, focusing on selected panels and portions of the overall volume. The analysis aimed to determine how the internal pattern could optimise material distribution while preserving structural integrity. The findings informed the design of the prototyped panel, which was produced at both 1:5 and 1:1 scale. In the 1:1 prototype, the geometric system also incorporated a luminous component, demonstrating that the Voronoi panel can integrate form, performance, and environmental actuation. Geometry thus becomes the medium that unifies inhabitable logic, structural behaviour, acoustic potential, and lighting integration within a continuous system.

The structural analysis was conducted using Karamba, a plugin for Grasshopper for Rhino (see figure x). The yellow colour grading indicates the 1st principal stress, and the black lines indicate compression and tension lines, working perpendicularly across the planes. A comparison between a panel with and without a central cutout was conducted (see figure x). It was found that the introduction of the central cutout pushed the stress lines to the edges of the panel. This suggested that including a cutout may be result in a reduction of material requirements in the 3D printing process.

A Grasshopper script was then used to produce a Voronoi-based infill which responds to the stress lines and principal stress (see figure 6). As expected, the panel with the cutout produced a looser infill. Thus, the cutout configuration was favoured for the panels in the project.

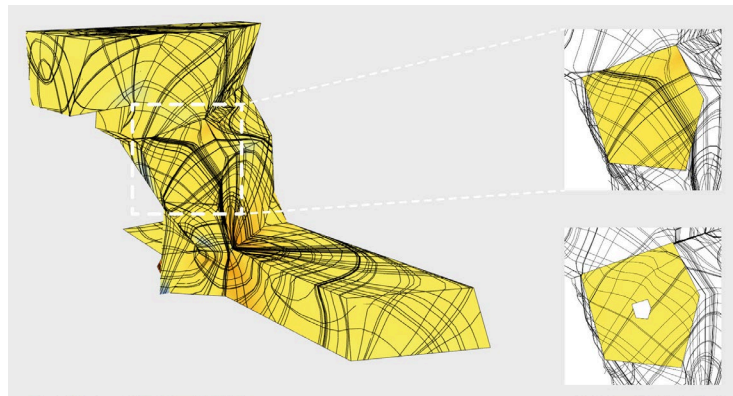


Figure 5: (left) Structural analysis of proposed central fixture, (top right) panel without cutout, (bottom left) panel with central cutout.

4 AI-based predictive lighting workflow

To address the environmental and psychological challenges of confinement during the polar night, this project developed a predictive lighting workflow utilizing machine learning. The decision to implement artificial intelligence was motivated by the need to regulate lighting through a system capable of integrating multiple dynamic inputs, rather than relying on static pre-set scenes. Accordingly, the model was designed as a calibration tool to adjust the lighting environment based not only on circadian principles and weather data, but also on selected physiological indicators associated with stress, activation, or bodily state.

This was possible by using an artificial neural network. It is a subset of artificial intelligence made up by input, output and hidden node layers. With the help of training data, it can become the predictive tool needed to create the desired dynamic lighting environment. The workflow commenced with the selection and organization of available environmental and biometric data, including variables related to atmospheric conditions, such as direct normal illumination, total sky cover and infrared radiation. The chosen physiological parameters which reflect changes in human state are as follows: heart rate bpm, respiratory rate, skin conductance and hrv rrmssd. The data was plotted and compared in order to identify redundancies and to isolate the variables most relevant for predicting illuminance and correlated colour temperature. Following this selection, the dataset was normalized and divided into a training set and a test set in a 70/30 ratio. Two separate regression models were subsequently trained: one for illuminance and one for correlated colour temperature.

After training, the model generated predicted values that could be exported as CSV datasets for use in subsequent stages of the design workflow. This process represents a shift from reactive to predictive logic. Instead of responding solely to direct user commands, the lighting system infers suitable values based on the relationships among environmental conditions, physiological inputs, and desired luminous states. In the project presentation, the model achieved approximately 93% accuracy for illuminance prediction and 81% for correlated colour temperature, indicating that the workflow demonstrated sufficient reliability for experimental deployment in both digital and physical prototypes.

Conceptually, this predictive layer reinforced the project's adaptive objectives. The environment was conceptualized not as a passive background awaiting manual control, but as a responsive system capable of interpreting conditions and adjusting accordingly. However, the project acknowledges that predictive intelligence is not neutral. The use of physiological data raises important questions regarding interpretation, monitoring, and autonomy, which are addressed later under study limitations and ethical considerations.

Stage	Input/operation	Output
<i>Feature selection</i>	Weather and biometric variables	Reduced input set
<i>Data preparation</i>	Normalization and 70/30 split	Training and testing datasets
<i>Model training</i>	Neural network regression	Predicted illuminance and CCT
<i>Export</i>	Test predictions	CSV files
<i>Translation</i>	CCT/illuminance conversion	RGB and brightness values

Table 2: Main stages of the predictive lighting workflow.

The result of the operation was taken from the CSV file and imported into a grasshopper algorithm in order to create a visual representation for the lighting. It is worth mentioning, however, that at present McNeel's Rhino and Grasshopper are not equipped to deal with models that have colour changing lighting. Without deleting and baking each frame individually, the light object will not change its characteristics. If the aim is to show the way the colour changes, then changing the colour of the object is possible and visible without baking.

5 Lighting implementation and prototype translation

The implementation phase translated the predictive model's outputs into a system that could be tested both digitally and physically [2], [3]. At this stage, the project moved from the AI output domain to the LED input domain. The trained model produced two lighting variables: correlated colour temperature (CCT) and illuminance (lux). These values were meaningful from an environmental and circadian perspective, but they could not be sent directly to the prototype. The LED strip required a different set of parameters, namely RGB colour values and brightness. The core task of this phase was therefore to construct a reliable translation chain between these two domains, preserving as much as possible of the environmental logic embedded in the AI predictions.

The first step was to convert CCT to RGB and illuminance to brightness. This was not a neutral or one-to-one transformation. CCT describes the tonal quality of white light, whereas the LED strip operates through additive red, green, and blue channels. Similarly, illuminance expresses a photometric condition in lux, while the prototype required a scalar brightness value suitable for digital control. For this reason, the raw outputs had to be interpreted rather than simply transferred. The resulting plots, developed to inspect the converted data over a full 24-hour cycle, show two important tendencies. First, brightness remains extremely low during the night phase, rises rapidly in the early morning, stabilises at much higher values throughout the active central portion of the day, and drops again in the evening. Second, the RGB plot reveals a clearly red-dominant behaviour: the red channel remains close to its maximum value throughout most of the cycle, while green and especially blue vary more substantially. This is consistent with the fact that the translated CCT range remains within a warm-to-cool white spectrum rather than across fully chromatic values. In this context, colour-temperature modulation is achieved less by suppressing red than by progressively increasing or reducing blue and green, while red remains structurally high. The plot is therefore useful not only as a visualisation of the data, but also as a verification that the prototype was not interpreting light as a sequence of arbitrary colours, but rather as a calibrated modulation of white-light conditions.

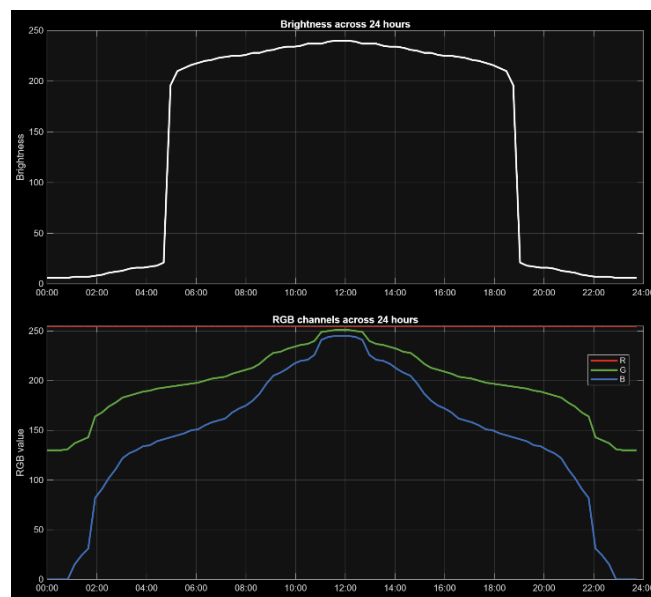


Figure 6: 24h of data, Matlab plot.

After conversion, the data required a second refinement stage before implementation. The purpose of this step was to make the values operationally stable and compatible with the limitations of both the rendering workflow and the physical hardware. In the digital model, null values were removed, and CCT values were bounded and rounded to the nearest available points within the target range, approximately 2700 K to 6500 K. These bounded values were then mapped to a controlled colour gradient in Grasshopper. Illuminance values followed a parallel process and were remapped to the interval required by the visualisation environment, so the dynamic behaviour of light could be read directly in the Rhino model. In the physical prototype, the converted RGB values were additionally scaled by the corresponding brightness parameter, so that colour and intensity remained correlated rather than operating as independent channels. This refinement phase was essential: without it, the model output would have remained too abstract, too noisy, or too numerically unstable to become a usable luminous script.

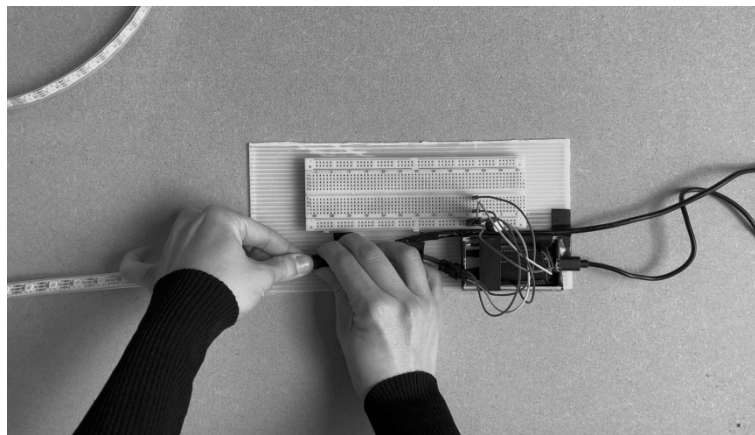


Figure 7: Hardware set-up.

The refined dataset was then implemented in Arduino as the basis for the physical prototype. Here, the project operated through two complementary modes. In Setting A, a CSV-like dataset was hardcoded into the sketch, storing sequential rows of R, G, B, and brightness values. The code looped through these rows at fixed intervals of 3 seconds, compressing an entire 24-hour cycle into approximately 4 minutes and 27 seconds. This mode allowed the prototype to act as a time-based demonstration of the full circadian scenario. The values were not sent to the strip as raw RGB triplets; they were first modulated by the brightness parameter, so that each colour channel became a brightness-weighted version of its original value. In other words, the final LED instruction was not simply R, G, B, but R(brightness), G(brightness), and B(brightness), ensuring that colour temperature and luminous intensity remained coupled in the output. This mechanism made the simulation legible as an environmental sequence rather than a collection of isolated snapshots. In Setting B, the system moved from scripted simulation to live control. The ESP32 created a local Wi-Fi network and exposed HTTP endpoints that the prototype could use to receive input from an HTML interface. When the internal server received a request containing a JSON payload, the sketch parsed the incoming values, scaled the RGB channels according to the brightness parameter, and sent the resulting output to the LED strip. This architecture enabled testing the project not only as a fixed, precomputed sequence but also as a responsive device. In this sense, the HTML interface did not function as a decorative add-on but as the user-facing layer of the adaptive system. The PhysioApp interface organised the input logic through four presets (calm, focus, stress, overload), four activities (sleep, eat, leisure, work), and two response scenarios (mirror and compensate), all converging toward a single luminous output. The

distinction between mirror and compensate is particularly important. In the first case, the environment reflects the detected internal condition; in the second, it counterbalances it, producing a corrective rather than a mimetic response. This confirms that the project's ambition was not merely interactive. It was adaptive in the stronger sense: the environment was designed to interpret a physiological condition in relation to a target activity and generate an appropriate luminous atmosphere rather than requiring constant manual adjustment.

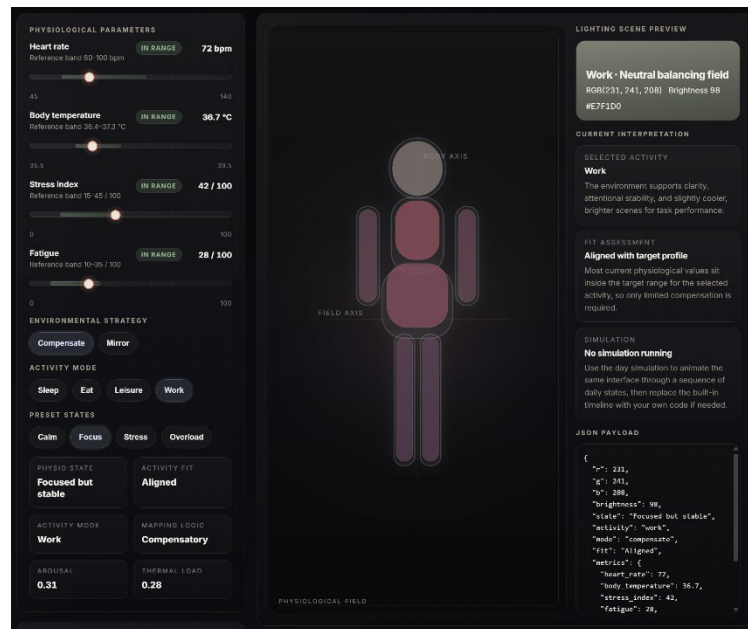


Figure 8: Physio.App interface used to translate physiological state, activity, and response strategy into a single luminous output.

Taken together, these steps demonstrate that the prototype is not simply a visualisation of AI outputs, but the material translation of a longer chain of reasoning. Environmental and physiological inputs are first interpreted by the predictive model, then converted into prototypical lighting parameters, refined for hardware compatibility, implemented as code, and finally exposed through a live interface. The result is a luminous system that links circadian logic, bodily state, and spatial atmosphere within a single operational workflow. What is tested through the prototype is therefore not only the behaviour of a light source, but the feasibility of an adaptive architectural environment in which data, code, and inhabitation are directly connected.

6 Conclusions

This project investigates the potential for reimagining the container architecture of Troll Station as an adaptive interior tailored to mission-driven confinement. Rather than regarding the container as a neutral technical shell, the proposal conceptualizes it as an environment that must actively support occupation during the critical period of winter isolation. Within this framework, social contact, privacy, and sleep are established as the minimum conditions for inhabitation and are translated into a system that integrates spatial reconfiguration, environmental and personal biodata responsiveness, and multi-scalar geometric development.

A primary contribution of the project is the integration of geometry with performance. The orthogonal container frame and the Voronoi-based infill operate not as competing systems but as complementary layers. The frame establishes a stable constructive order, while the infill enables internal differentiation, adaptive occupation, and panel-level integration of structural, luminous and acoustic functions. Consequently, geometry is positioned as more than a formal language; it serves as the medium through which the project organizes inhabitable variation and environmental support.

Another significant contribution is the development of a predictive lighting workflow. By linking circadian principles, environmental conditions, and selected physiological indicators to the regulation of illuminance and correlated colour temperature, the project positions light as a dynamic and responsive architectural layer. This approach not only enhances visual comfort but also expands the role of lighting as a mediator of routine, mood, recovery, and spatial identity during the polar night. The translation of these outputs into Grasshopper simulations, Arduino logic, and physical prototypes demonstrates that the project advances beyond conceptual speculation by testing its premises through implementation.

Ultimately, the proposal contends that habitability in extreme environments relies on more than technical enclosure. It depends on the capacity of architecture to organize support systems that respond to human rhythms, bodily states, and psychological needs over time. In this context, the project does not present a finalized solution for Antarctic living, but rather a design methodology in which adaptive space, predictive lighting, and prototyped environmental behaviour could be addressed as interconnected aspects of the same architectural challenge.

6.1 Study Limitations and Ethical Considerations

This project presents several methodological and practical limitations. First, the confinement scenario functioned as a design stress test rather than being validated through extended in-situ observation at Troll Station.

Second, the predictive lighting workflow depended on a curated and processed dataset, rendering its outputs indicative rather than fully validated under authentic Antarctic conditions. Third, although the prototype demonstrates the feasibility of translating data into luminous behaviour, it does not evaluate the complete system at architectural scale or during actual long-duration occupation.

Beyond these limitations, the project raises ethical concerns regarding the use of physiological data as an environmental input. Systems that monitor bodily parameters to adjust lighting conditions may enhance responsiveness and reduce the need for manual control; however, they also risk normalising

continuous surveillance within domestic or semi-domestic settings. This dynamic introduces a fundamental tension in adaptive design: the same intelligence that enables environments to respond to individual needs may also diminish user autonomy or blur the distinction between support and control. Consequently, future development should address issues of consent, transparency, data management, and the extent to which adaptive environments are permitted to infer or regulate human states.

Acknowledgements

The authors would like to thank the course professor, Henriette Bier and tutors, Arwin Hidding, Vera Laszlo, and Lisa-Marie Mueller, for their guidance throughout the workshop, as well as the LAMA laboratory for its support in the prototyping phase. Their contribution made it possible to connect computational design, environmental testing, and physical fabrication within a single integrated workflow.

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