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Research Article

# A Simulation and Analysis of Sustainable Accommodations: Exploring the Feasibility of Earthships in Cold Regions

**Clara Josefine Schulze Mönking***, **Stefan Schäfer**, **Nikola Bisevac**

Institute of Constructive Design and Building Construction (KGBauko), Technical University of Darmstadt, Franziska-Braun-Straße 3, 64287 Darmstadt, Germany
E-mail: c_schulze.moenking@gmx.de

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**Graphical Abstract:**


**Abstract:** In this paper, the thermal performance of an Earthship in New Mexico, Finland, Germany, and Norway is simulated. After testing various design changes and their influence on thermal performance, a final Earthship model optimised for the Nordic climate is derived. The main findings are that an unheated greenhouse with large windows on the south side of the building stabilises the temperature in the living area and reduces energy consumption and that the wall between this greenhouse and the living area should be well insulated. Thermal mass stabilises the indoor temperature but could also lead to higher heating energy consumption. The results show that incorporating Earthship technology into conventional houses could help reduce their environmental impact and contribute to the green transition of the building sector.

***Keywords***: Earthship, simulation, thermal mass, passive solar design, thermal optimisation

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# 1. Introduction

Earthships are self-sufficient houses that not only provide thermal comfort for their inhabitants, but also generate electricity, produce food and water, and treat wastewater. Developed by architect Michael Reynolds in New Mexico, USA, Earthships were designed for hot and sunny climates. However, while Earthships perform well in these conditions, there is currently insufficient data on their thermal performance in other, less sunny, or cooler regions.

## 1.1 *Earthship principle*

Earthships are designed as self-sufficient dwellings that meet human needs without depleting the planet's resources [1, p. 8]. According to Reynolds, these essential needs are shelter, water, food, electricity, sewage treatment, and waste recycling.

To achieve thermal comfort, Earthships are surrounded on three sides by compacted earth walls, which are enclosed by an earth berm. This provides thermal mass. The south wall is an inclined glass facade to maximise solar gains. A greenhouse runs along this facade, acting as a thermal buffer and helping to regulate indoor temperatures. Ventilation is achieved through cooling tubes that run through the berm, cooling incoming air as it passes underground. These work together with operable roof windows in the greenhouse to create natural airflow. The building's partially buried structure also benefits from the stable ground temperatures below the surface.

To address the remaining needs and enable self-sufficiency, Earthships also include rainwater collection, grey and black water treatment, solar energy generation, and the use of recycled building materials. Earthships are primarily constructed using recycled car tyres, which are filled with earth. These tyres provide both thermal mass and structural stability.

More information on Earthships and their construction process can be found in the three Earthship books by Michael Reynolds [1]-[3]. Additionally, a lot of information on Earthships is provided through the Earthship Academy and Earthship Online Academy by Earthship Biotecture, visited in 2022 [4]. The notes from the lectures at the Earthship Academy are an important source for this work.

Figure 1 shows a typical Earthship in Taos, New Mexico.

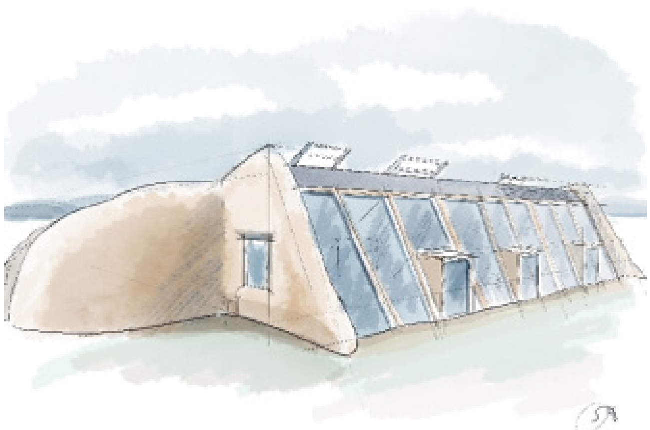

**Figure 1.** Sketch of an Earthship in Taos, New Mexico, based on an illustration in [1, p. 207]

Being quite space-consuming, Earthships are not suited to urban areas, but they could be an alternative to conventional housing in northern European countries. However, Earthships rely heavily on solar energy, and it is unclear how they perform in less sunny areas.

## 1.2 *Related work*

Studies have shown that Earthships in New Mexico succeed in maintaining a stable and comfortable indoor temperature without heating or cooling. Sometimes they overheat, but this could be prevented by solar shading and increased ventilation [5], [6]. There are a few existing studies that simulate an Earthship. Freney et al. and Kruis et al. use EnergyPlus software [5]-[8], while Grindley et al. work with mathematical models [9]. Most information on Earthship focuses on New Mexico or regions with a temperate or sunny climate, such as Australia or central Europe [5], [7].

Some studies include Earthships in the UK, where the weather is less sunny. In [7], it is concluded that Earthships in the UK would need backup heating, but the energy use is on par with Passivhaus standards. Grindley et al. also concluded that an Earthship in the UK would need minimal backup heating [9], but they only used mathematical models and no computer simulation. Ip et al. monitored an existing Earthship in Brighton, UK, and concluded that it would need backup heating, but the monitoring took place shortly after the Earthship was constructed, and the thermal mass had not been fully charged yet [10].

Only Kruis et al. simulated an Earthship in regions north of the UK. The paper states that this Earthship cannot operate self-sufficiently and has no financial advantage compared to a common dwelling [6]. However, the simulated Earthship has an outdated design without a wall between the greenhouse and the living area, which is a key factor for stable indoor temperatures in Earthships [4].

A different concept for very energy-efficient houses is the Passivhaus dwelling, developed by the Institute for Housing and Environment in Germany [11]. It is of great interest to compare Earthships and Passivhaus dwellings to assess whether Earthships are a feasible alternative to the established Passivhaus. Moreno et al. describe the main components and principles of a Passivhaus, as well as experience reports of advantages and disadvantages [11], [12]. More detailed information on Passivhaus principles can be found in [13].

Since Earthships are often inspired by the traditional architecture of the location, it is important to look at traditional New Mexican architecture, such as the pueblos [14]. In order to optimise the Earthship for Finland, elements of traditional Saami architecture are used in this paper [15]. Information on social and ecological aspects and the green trends in architecture can be found in [16], [17].

Finally, as airtightness plays a crucial role in thermal simulation and real-world performance, this paper refers to DIN/TS 12831-1 [18] and DIN 4108-7 [19], as well as the final report of the Passivhaus Institut by Kah et al. [20].

# 2. Methods

## 2.1 *Approach*

The first step was to develop a simulation model for an Earthship and to calibrate it with data from existing Earthships. However, there is currently no data available on the internal temperature of existing Earthships. For this reason, the study aims to reproduce the results in Freney's dissertation [5], as Freney provides detailed information about his simulation model and the measured temperature data. A simulation model was produced according to Freney's descriptions, and the results were compared with the measured temperature data of the Earthship in Taos, New Mexico, which were recorded for the dissertation.

Subsequently, a number of small experiments were carried out where the individual components were changed, and the results were compared in both New Mexico and Finland.

The options that proved most suitable for Finland were then integrated into a final design that was optimised for the Nordic climate. The performance of the final design was also studied and analysed in Darmstadt, Germany, and Hammerfest, Norway.

Finally, a connection to the Passivhaus principle was made, discussing how Earthship elements could be integrated into conventional residential buildings.

This study focuses solely on thermal performance and does not consider factors such as air quality, humidity, occupancy patterns, or heating from devices, analysing the building in its baseline design without additional internal heat sources or behavioural influences.

## 2.2 *Software and weather data*

The simulation software used is Hottgenroth Energie-Technik-Umwelt (ETU)-Planer (version 4.7.23 (1), Hottgenroth Computer-Aided Design (HottCAD) version 7.4.23 (41), [21]), as it is easily accessible, includes a comprehensive materials database, and is well documented. The student version of the software was used, which provides the full simulation functionality of the professional version. However, it includes weather data only for Germany and Austria. This limitation was addressed by sourcing the necessary weather data from [22].

While ETU-Planer is suitable for detailed building energy simulations, other tools such as EnergyPlus, developed by the U.S. Department of Energy, are also commonly used [23]. However, EnergyPlus typically requires more manual data input compared to ETU-Planer. Given the goal of optimising an Earthship design in a European context, ETU-Planer was chosen for its user-friendliness, built-in databases with standardised U-values, and intuitive Graphical User Interface (GUI).

To investigate the performance of Earthships in Northern Europe, weather data from Taos (New Mexico), Darmstadt (Germany), Vantaa (southern Finland, near Helsinki), and the northernmost city of Europe, Hammerfest (Norway), were used. Finland was chosen as an example of a country with a colder and less sunny climate, but the results should apply to any European location at the same latitude. The Finnish climate is colder than the German climate and less sunny than New Mexico. However, it is still temperate enough that an Earthship could be feasible.

In Hammerfest, there is no sunlight at all for a large part of the year, so it is unlikely that Earthships will work at all in this location. The weather data from Hammerfest is therefore only used for experimental purposes.

The climate of Germany lies somewhere in between the two extremes of New Mexico and Finland, and the optimisation results of the Finnish Earthship should also apply to Germany.

Therefore, the study will focus on Finland and New Mexico.

# 3. Results

## 3.1 *Simulation model details*

The simulation model attempts to reproduce the simulation results of Freney's dissertation [5], as this dissertation contains the most detailed information on the Earthship simulation. The tyre walls were approximated by a 63 cm layer of compacted earth between two 1 cm layers of rubber, as described in [6]. The schematic of the simulated wall can be seen in Figure 2 (not to scale).

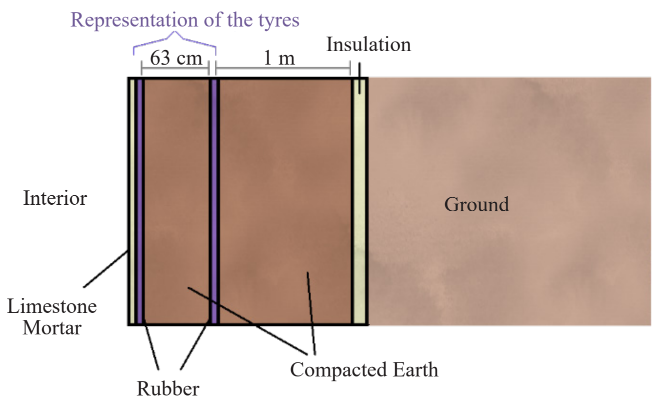


**Figure 2.** A not-to-scale schematic drawing of the simulated wall structure of the tyre wall

In order to account for the thermal mass effects of the ground and the earth berm, the walls were simulated with a 6 m surrounding layer of earth to represent the berm. Systematic testing showed that a 50 m earth layer below the floor yielded the most realistic results.

The model was divided into two zones: one for the greenhouse and one for the living area, which consists of the four remaining rooms. The air exchange rates that provided the most accurate results were 0.3/h in the greenhouse and 0.1/h in the living area, with increased ventilation in the summer to account for open windows. The air exchange rates are lower than the minimum air exchange of 0.5/h in [18] and 0.3/h for Passivhaus dwellings described in [11], but Freney describes even lower air exchange rates in [5, p. 103]. It was also found that the air exchange rates in Passivhaus dwellings are around 0.6/h [20]. The assumption is therefore justified.

As the simulation is supposed to show the raw temperature data of an Earthship, it uses neither heating nor cooling. Activity, lighting, solar shading, and devices are set to zero. There are no sources of humidity, as this is not part of this study.

Since the simulated temperatures were still lower than the temperatures measured in [5], a second layer of insulation was inserted on the outside of the earth berm.

The temperature of the final model matches the temperatures reported in [5] well. However, the model is slightly colder and therefore more conservative in terms of performance in Nordic climates. The results of this study can therefore be seen as a lower boundary for Earthship performance in Nordic countries.

## 3.2 *Testing of components*

To test individual elements of the Earthship and how their adaptation changes performance, a simplified Earthship structure was used. It consists of only two rooms and a greenhouse, surrounded by an earth berm. Figure 3 shows the floor plan of the simplified Earthship.

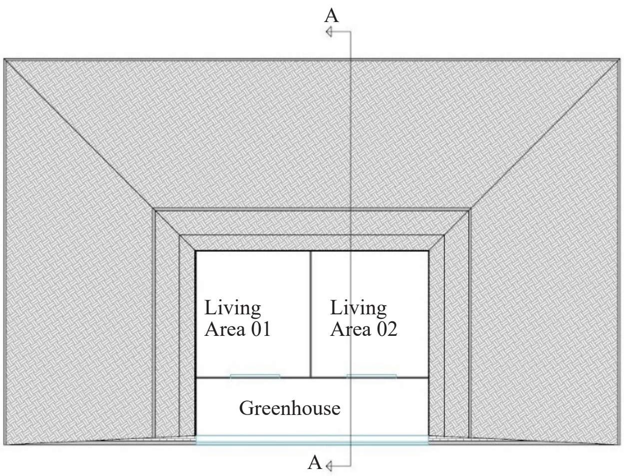


**Figure 3.** The layout of the simplified Earthship

In order to compare the overall performance of the Earthship with that of a conventional building, a reference building, as automatically generated by HottCAD, was also simulated. The materials for the walls, windows, and roof are the same as those used in the Earthship and conform to Passivhaus standards. However, the reference building does not have an earth berm, and in contrast to the Earthship, the floor is well insulated. It consists of only one room, which is the same size as the Earthship's living area.

The following components were tested for the Earthship:

- Configuration of the wall between the greenhouse and the living area
- Roof windows
- Floor insulation
- Multiple floors
- Internal tyre walls
- South facade window size

• Earthship size
• Greenhouse width
• Ventilation.

Any component that flattens the temperature curve is considered an improvement, even if this results in too-cold summer temperatures. The software does not support the opening of windows for heating purposes, even if the temperature of the living area is low while the greenhouse temperature is comfortable or warm. Therefore, it can be assumed that low summer temperatures would not be a problem in reality, and a flatter curve indicates a more stable indoor temperature.

It was found that the configuration of the wall between the greenhouse and the living area has the greatest effect on the indoor temperature. The better the U-value of this wall, the more stable the temperatures in the living area. A well-insulated wall (U-value = 0.20 W $m^{-2}K^{-1}$) yields the best results, with a temperature difference of only 5.7 °C between the coldest average daily temperature in spring and the warmest in autumn, while triple-glazed windows (U-value = 0.8 W $m^{-2}K^{-1}$) are also feasible, producing a slightly wider temperature variation of 7.6 °C. In comparison, the default configuration with concrete walls (U-value = 3.4 W $m^{-2}K^{-1}$ as in [5] and 2 m-wide windows) shows a temperature fluctuation of 11.2 °C. Figure 4 also shows the greenhouse temperatures, illustrating that the low temperatures in the living area during summer would likely not be an issue in practice.

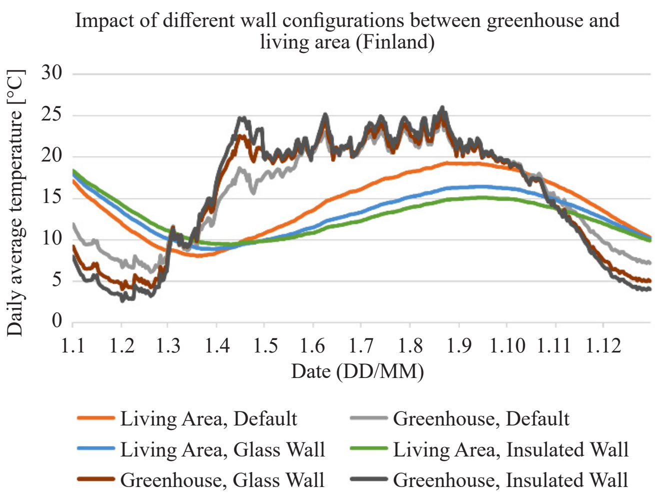


**Figure 4.** Differences in thermal performance in Finland with default internal windows, glass walls, and insulated walls

Another significant difference was observed when replacing the small skylights (0.5 m × 0.5 m) with larger ones (2 m × 2 m) in the living area. The skylights are triple-glazed, with a U-value of 0.8 W $m^{-2}K^{-1}$.

In the colder half of the year, the larger skylights result in only minimally cooler temperatures. For example, in Finland, the minimum average daily indoor temperature in March drops slightly from 8.0 °C (with small skylights) to 7.9 °C (with large skylights). However, in summer and autumn, the interior becomes significantly warmer.

In New Mexico, this means that the Earthship becomes slightly more prone to overheating, but in Finland, indoor temperatures reach 20 °C as early as June, while the model without a skylight remains consistently below 20 °C.

In addition, large skylights allow more light into the living area and could therefore help mitigate the lack of light during winter to a certain extent. Small skylights should still be included in the front part of the house, as they are an integral part of the ventilation system. Figure 5 shows the impact of large and small skylights on the indoor temperature.

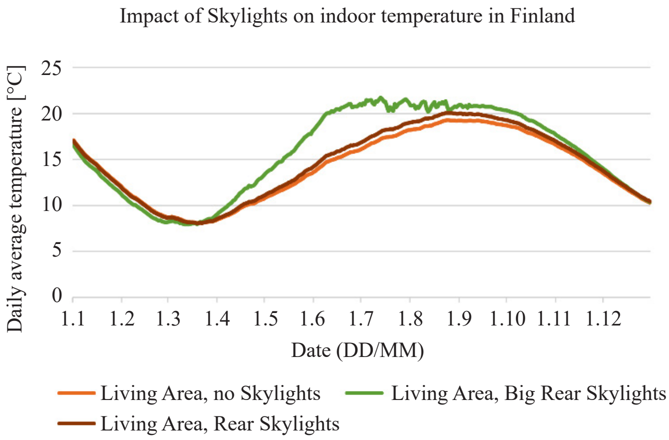


**Figure 5.** Comparison of the impact of differently sized roof windows on indoor temperature in Finland

The Earthship floor takes an unusual approach: instead of using insulation to keep the interior of the building warm, it is typically made of concrete, stone, or brickwork. In the Earthship Online Academy, Michael Reynolds even explicitly warns builders not to insulate the Earthship floor, nor to use wood or cork as flooring, as the floor is the building's main thermal battery and cannot be charged if it is covered with less conductive material.

To investigate this claim, the concrete layer was replaced with perfect insulation (U-value = 0.0 W $m^{-2}K^{-1}$). According to conventional building principles, this should improve performance and make the interior warmer.

However, a perfectly insulated floor leads to significantly less stable indoor temperatures. As shown in Figure 6, overall indoor temperatures in New Mexico rise from a range of 21 °C-34 °C to peaks exceeding 43 °C, indicating overheating. In Finland, the Earthship overheats to over 29 °C in August, while the indoor temperatures drop to nearly 0 °C in February.

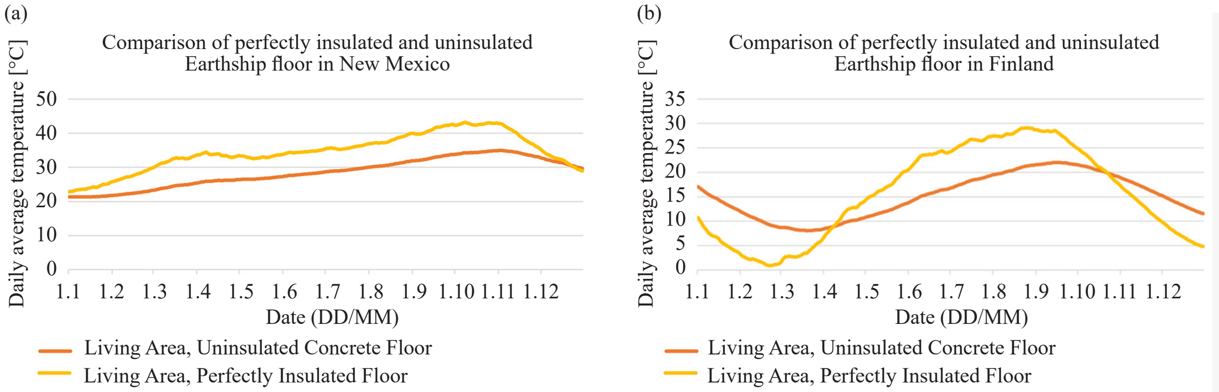


**Figure 6.** The thermal performance of an Earthship with an uninsulated concrete floor versus an Earthship with ideal floor insulation in New Mexico and Finland

Earthships with multiple storeys do not perform as well as single-storey Earthships. The temperature on the ground floor is stable and, on average, 0.9 °C warmer than in a normal Earthship. On the upper floor, however, the temperature curve is less stable, being colder in winter and warmer in summer. Despite this, the overall performance surpasses that of the reference building. Since a warmer Earthship in Finland is a better Earthship, a two-storey version could be a viable option. This is an important realisation, as one of the main challenges with Earthships is the large amount of space they require. A greenhouse that extends over two floors would be particularly appealing, as trees could grow in it. However, such a construction would be difficult to realise, and further studies would be needed to develop a working concept.

The simulation results show that the inside temperature in the living area becomes more stable with internal tyre walls. Instead of constructing only the outer walls from earth-rammed tyres, many Earthships are designed as a series of U-shaped modules connected in a row, each formed entirely from tyre walls. This increases the thermal mass within the living area.

In [6], Kruis et al. decreased the glazing area of the Earthships in colder regions to minimise radiative heat losses. However, simulations show that smaller greenhouse windows only lead to overall cooler indoor temperatures in both the greenhouse and the living area. In Finland, reducing the glazing area by half results in an average temperature drop of about 1.4 °C in the living area, while in New Mexico, the drop is around 3.1 °C. In contrast to the assumptions of [6], a decreased front window size could be recommended for sunny areas, while Earthships in less sunny regions should use floor-to-ceiling windows. It should be noted that this study uses triple-glazed windows in the simulation. If double- or single-glazed windows are used, an increased window size could lead to higher heat losses.

Concerning the size of the Earthship, it can be said that a deeper Earthship with a longer living area extending toward the back leads to more stable temperatures. However, as this barely increases winter temperatures and primarily reduces summer peaks, it is a better option for New Mexico than for Finland. Higher ceilings, as well as a wider Earthship, result in less stable indoor conditions. For colder, less sunny areas, low ceilings and smaller room sizes are recommended, as they reduce the air volume that needs to be heated.

A wider greenhouse between the south facade and the living area lowers the indoor temperatures. In regions where Earthships are prone to overheating, a slightly wider greenhouse could be an option.

Freney reports in [5] that ventilation has a significant impact on internal temperatures. Dynamically increased ventilation during the summer months lowers indoor temperatures in both New Mexico and Finland. In New Mexico, this significantly improves performance and prevents overheating in the living area. In general, it can be assumed that ventilation improves performance, even though overheating is less of a concern in Finland.

## 3.3 *Final design*

The final design implements the results of the simulation experiments in a more realistic floor plan with different rooms, a bathroom, and a kitchen.

As the traditional building material in Nordic countries is wood [15], a timber frame construction that is inspired by the exterior timber wall shown in [13] was used for the front walls.

Unlike the classic Earthship design, doors have been added between the rooms, as the greenhouse can get quite cold, especially at night. For the same reason, the bathroom is located in the kitchen instead of the greenhouse.

The final layout and section of the Nordic Earthship are included in the appendix. The CAD blocks for the furniture were taken from [24]. The tyre wall on the rear side steps back with each tyre to counteract the weight of the soil. The water is collected by the roof and stored in water tanks inside the berm. Figure 7 and Figure 8 show concept sketches of a Nordic Earthship in Finland and its living room.

A simulation of the Nordic Earthship in the Finnish climate shows that the temperature curves of the living area are quite stable. The lowest temperature measured in the living area is 7.748 °C in the kitchen, which is the coldest room in the Earthship. The temperature in the living room does not drop below 8.859 °C. This is impressive, given that the outside temperature is only 1.35 °C and had been colder for quite some time. However, from a living comfort point of view, these temperatures are still too cold, and auxiliary heating would definitely be required.

In Taos, New Mexico, the Earthship overheats significantly. This cannot even be completely avoided during the months in which ventilation is simulated.

The temperature of the living area in Germany is fairly stable throughout the year, even though the greenhouse overheats and would require solar shading. In the living area, the temperature does not drop below 14 °C. The highest temperature in the living area is 30.179 °C, but this occurs in the bathroom, where higher temperatures can be considered acceptable. Solar shading could also be an option here. In the living room, bedroom, and kitchen, 24.5 °C is not exceeded.

**Figure 7.** A concept sketch of the interior design of the living area in the Nordic Earthship

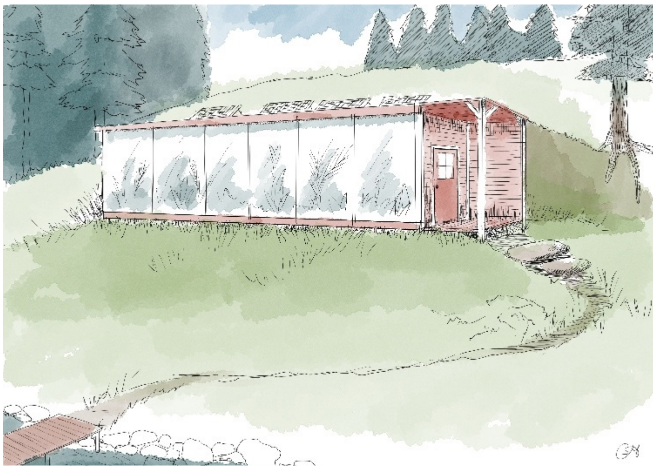

**Figure 8.** A concept sketch of the Nordic Earthship in a Finnish landscape

Simulating the Earthship in Hammerfest, where there is no sunlight for almost half of the year, is more of an experiment to show the limits of Earthships. Nevertheless, the Nordic Earthship succeeds in moderating the outside temperatures and performs much better than the reference building. The lowest temperature in the kitchen is 5.322 °C, which is very cold, but still a respectable result for outdoor temperatures that are below 0 °C for almost half of the year and the complete lack of sun in winter.

The temperature curves for the living area of the Earthship in Finland and Germany can be seen in Figure 9. The graphs show that the temperatures inside the Earthship are significantly more stable than in the reference building, where they drop to below -5 °C in Finland and nearly 0 °C in Germany.

To show the performance improvement compared to the original design from [5], Figure 10 shows the temperature curves of the living room of the final design and the living area of the calibration model from Section 3.1. In Finland, the minimum temperature is 7.6 °C higher, and in Germany, 5.6 °C higher, while the maximum temperature remains almost unchanged in both cases.

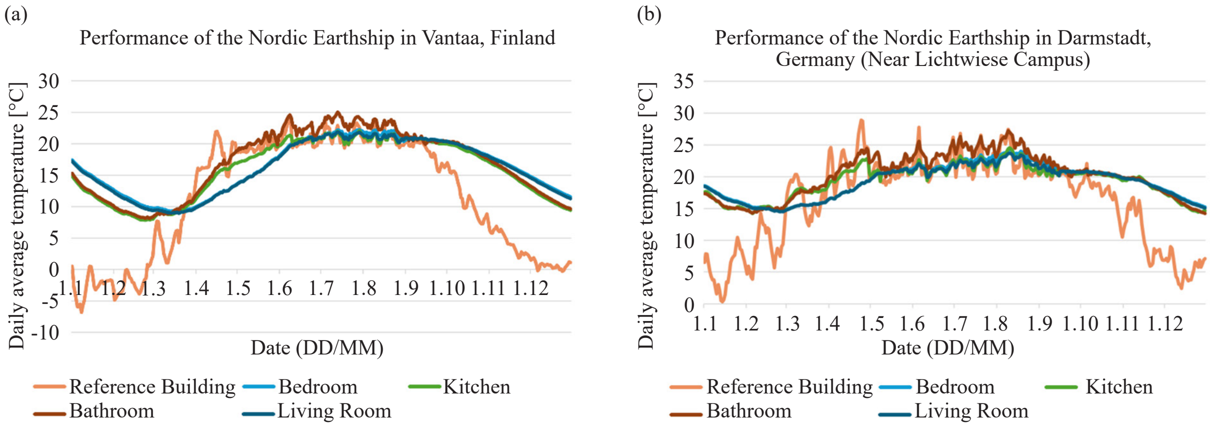


**Figure 9.** Performance of the individual rooms of the Nordic Earthship as well as a reference building in Finland and Germany

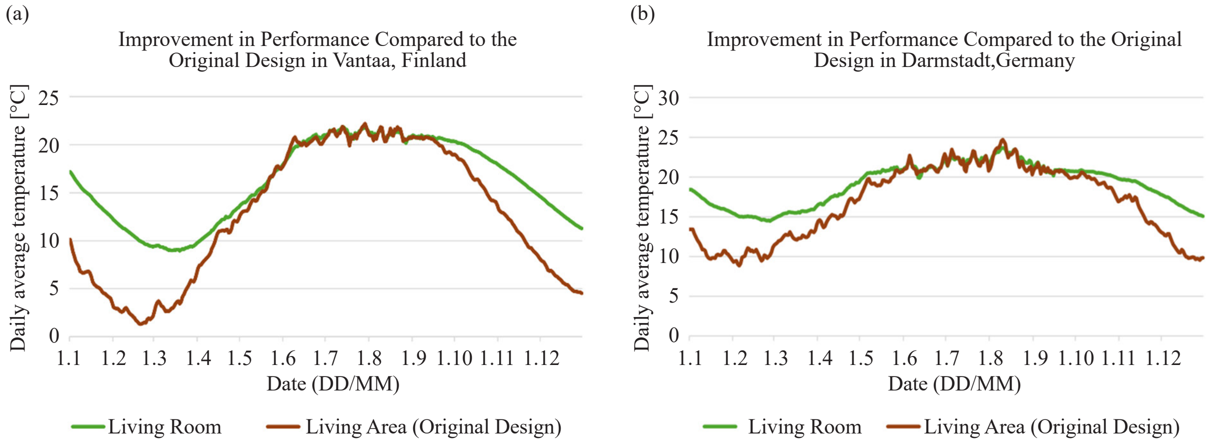


**Figure 10.** Improvement in thermal performance compared to the original design from [5]

### 3.4 *Energy consumption*

Surprisingly, the results show that the Nordic Earthship in Finland requires 32.1 kWh $m^{-2}year^{-1}$, which seems quite high considering that the indoor temperature is very stable without heating. This is more than the reference building, which uses 25.3 kWh $m^{-2}year^{-1}$, despite its poor performance without heating or cooling. In Germany and New Mexico, the Earthship uses less energy than the reference building, but the difference is too small to be considered a significant improvement.

These results are unexpected, as [7] reports an energy consumption below the Passivhaus standard of 15 kWh $m^{-2}year^{-1}$ for each climate tested. Therefore, these results will be investigated and discussed in Section 4.

## 4. Discussion

The results of the simulation experiments show many constructional details that can optimise the thermal performance of Earthships. However, without heating, Earthships cannot maintain a comfortable temperature in northern countries. The simulation also indicates that, at least in the first year, Earthships use more heating energy than a conventional house that conforms to Passivhaus standards.

### 4.1 *Recommended construction details*

The element that proves to have the highest positive impact on the Earthship performance is the well-insulated wall between the greenhouse and the living area. For Nordic countries, it is recommended to use large skylights in the living area, which lead to more direct light and warmer temperatures. The floor should not be insulated, and the south-side windows in the greenhouse should be as large as possible, as the thermal gain is greater than the heat loss. Internal walls should have a high density to act as thermal mass, which leads to more stable temperatures.

### 4.2 *Possible reasons for high energy consumption*

Several factors may explain the higher energy consumption observed, which contrasts with the findings of [7]. One factor is thermal mass: the Earthship Academy teaches that thermal mass takes a few years to fully charge, at which point it can maintain a stable temperature with minimal heating or cooling. Simulations support this, showing that while a room with ideal insulation for walls uses 35.8 kWh $m^{-2}year^{-1}$, a room with Earthship walls consumes 266.8 kWh $m^{-2}year^{-1}$. However, the energy is not lost because of the perfect external insulation—it's stored in the thermal mass and will eventually be released.

Another reason for the too-high energy consumption could be the flawed ventilation between the living area and the greenhouse. Since the ventilation cannot be simulated accurately, it is possible that the heating will be activated in the living area, while the greenhouse temperature remains above 25 °C.

The final aspect to consider is the possible positive effect of an unheated hallway. To avoid bias, the reference building was simulated with a heated living area and an unheated hallway on the south side. However, simulations show that a smaller reference building without the unheated hallway on the south side consumes significantly more energy than both the Earthship and the two-part reference building. This is an important finding as it indicates that Earthship components, like the unheated hallway on the south side, can also be implemented in conventional homes to reduce energy consumption.

### 4.3 *Comparison to conventional dwellings*

Compared to conventional dwellings, Earthships have three main disadvantages: their size, which makes them unsuitable for urban areas, their unusual form, leading to an unusual construction process as well as more bureaucracy, and the heightened amount of maintenance that is needed for the water and electricity system.

However, they maintain a fairly stable temperature, for example, in the case of a heating failure, and can especially moderate the warm summer temperatures. Even if they cannot work self-sustainingly, they can cover at least a part of the heating, cooling, food, water and electricity needs. The sewage system and the recycling of waste as building material have benefits for the planet.

### 4.4 *Earthship and passivhaus*

The results raise the question of whether Earthships or Passivhaus dwellings are more suitable for Nordic countries.

While they are often seen as distinct concepts, a closer look at the Passivhaus principles outlined in [11] reveals that many of them are not in conflict with Earthship design. There is significant potential for the two approaches to complement each other.

For example, Passivhaus standards prioritise small, well-insulated windows to reduce heat loss, which can limit daylighting [11]. Earthships, by contrast, use large south-facing windows for passive solar gain and natural light. Similarly, Passivhaus homes may suffer from overly dry air due to mechanical ventilation (see [12, p. 5]), while Earthships may face humidity issues from greenhouse spaces. Overheating in Passivhaus buildings has also been reported [12, p. 5], while Earthships, with their thermal mass and earth-bermed walls, are better at regulating high temperatures.

An Earthship can even meet Passivhaus criteria if energy consumption is sufficiently low. Rather than choosing one over the other, a hybrid design incorporating Earthship features, such as passive solar design and recycled materials, with the energy efficiency of Passivhaus could lead to more resilient and sustainable buildings. Further research should explore this integration.

## 4.5 *Sustainability and global relevance*

In light of current global developments and the challenges posed by climate change, it is highly relevant to examine how Earthships align with contemporary trends in green architecture and the United Nations Sustainable Development Goals.

The United Nations Sustainable Development Goals (SDGs) are a set of global objectives aimed at addressing critical challenges such as climate change, sustainable development, and energy access [25]. This study aligns with several SDGs, particularly SDG 11: Sustainable Cities and Communities, SDG 13: Climate Action, and SDG 7: Affordable and Clean Energy. Earthship-inspired designs contribute to these goals by promoting energy-efficient, climate-resilient buildings that reduce dependency on non-renewable energy.

The thermal mass, passive solar design, and natural ventilation principles used in Earthships support SDG 7 by increasing energy efficiency in buildings. Their use of sustainable materials like tyres and earth also advances SDG 12: Responsible Consumption and Production by reducing resource consumption. The potential of recycling tyres is also emphasised by Kang et al. in [16]. Furthermore, Earthships' ability to stabilise indoor temperatures in extreme climates underscores their potential role in climate resilience, an essential aspect of SDG 13, especially given the growing unpredictability of weather patterns due to climate change.

These principles also reflect broader global trends in sustainable architecture, such as the integration of passive design strategies, use of renewable or recycled materials, and incorporation of on-site clean energy systems [17]. Earthships inherently support many of these practices through site-sensitive planning, rainwater harvesting, and closed-loop waste systems, while their off-grid capabilities align with current goals for resilience and energy independence.

Ultimately, the integration of Earthship principles into both new constructions and existing homes can significantly contribute to the development of net-zero energy buildings, promoting sustainability, reducing environmental impacts, and helping to achieve the broader objectives of global energy and climate action.

## 4.6 *Limits of study*

This study focuses on the simulation of temperature. For a complete view of the Earthship principle and performance, an analysis of water collection, sewage treatment, electricity, and food production is necessary. Especially, indoor air quality and humidity challenges should be investigated in further studies.

Some of the results, like the improved performance without floor insulation and the high energy consumption of the final model, seem unrealistic and should be verified with other software. In addition, the initial temperature of the materials should be investigated to determine if this is the reason for either too cold or too warm temperature results in the beginning.

There are some software limitations concerning the accurate simulation of ventilation and solar shading, realistic ground temperatures, and the temperature of walls or floors. This possibly leads to a poorer performance in the simulation than in reality.

To get more accurate temperature predictions, it is also necessary to collect data on occupancy, equipment, heat emission, moisture, etc.

All simulations were carried out for only one year. However, as noted by Ip et al. [10], thermal mass requires several years to fully charge before reaching its maximum potential. Therefore, future studies should include long-term simulations to better capture this delayed thermal response and assess its true impact on energy performance.

All in all, the results of this study can give a general direction as to what makes an Earthship warmer or cooler and how it can be optimised for a particular climate. This is a remarkable insight for future construction. However, simulations have their limitations and can only approximate real-world conditions. The true effectiveness of the Earthship concept can only be fully validated through real-world construction and testing. Further research is needed to obtain precise data and refine these findings.

## 5. Conclusion

The study succeeds in finding several elements that optimise the performance of Earthships. Especially the insulation of the wall between the greenhouse and the living area is an important factor.

By including these elements in a final design, it is possible to create an Earthship that is tailored to the Nordic climate. Without heating or cooling, the simulation results in Finland are better than the results of the unadapted model and significantly better than the results of the conventional reference building. The indoor temperature remains fairly stable and moderates the outdoor temperature.

In Germany as well as in Finland, the summer temperatures remain comfortable, even without cooling or solar shading. However, the winter temperatures are still too low to be considered comfortable in both Germany and Finland. Backup heating would therefore be necessary, but solar shading would be sufficient to keep the house cool during summer.

A simulation with heating and cooling shows that the energy consumption of the Earthship is low compared to a normal house, but it does not meet the Passivhaus requirement in every climate, which is at odds with the results of previous studies. The Earthship's energy consumption is higher or equally high as the energy consumption of a reference building with an unheated hallway on the south side, whose walls, ceiling, and floor meet the Passivhaus standard. However, it is lower than the energy consumption of a similar reference building without an unheated hallway on the south side.

Even if an Earthship cannot be operated completely self-sufficiently in the Nordic climate, Earthship elements could help to improve overall performance when integrated into conventional buildings or Passivhaus dwellings. Some aspects could work particularly well with Passivhaus principles, e.g. a design with larger windows to let in more light and plants as a humidifier.

For further research, it would be of great interest to develop new green designs that implement both Passivhaus and Earthship principles. Future simulations should be conducted over at least three years to investigate the charging of thermal mass in Earthships. Considering the high level of airtightness, the simulation of humidity and air hygiene would be very important as well, as mould growth is still a major concern for Earthships in less sunny climates. It might be interesting to explore the use of alternative, sustainable building materials, such as Hempcrete. And finally, a simulation can only predict reality up to a certain point. Ultimately, there is no better proof of the Earthship concept than building an Earthship in real life and testing whether and how well it works.

Whilst Earthships as a whole have not always been the best-performing option, they are definitely a well-performing option. And all existing designs can be improved by incorporating Earthship technology. Therefore, the results of this study could provide a direction for the future development of self-sufficient houses.

## Conflict of interest

The authors declare no competing financial interest.

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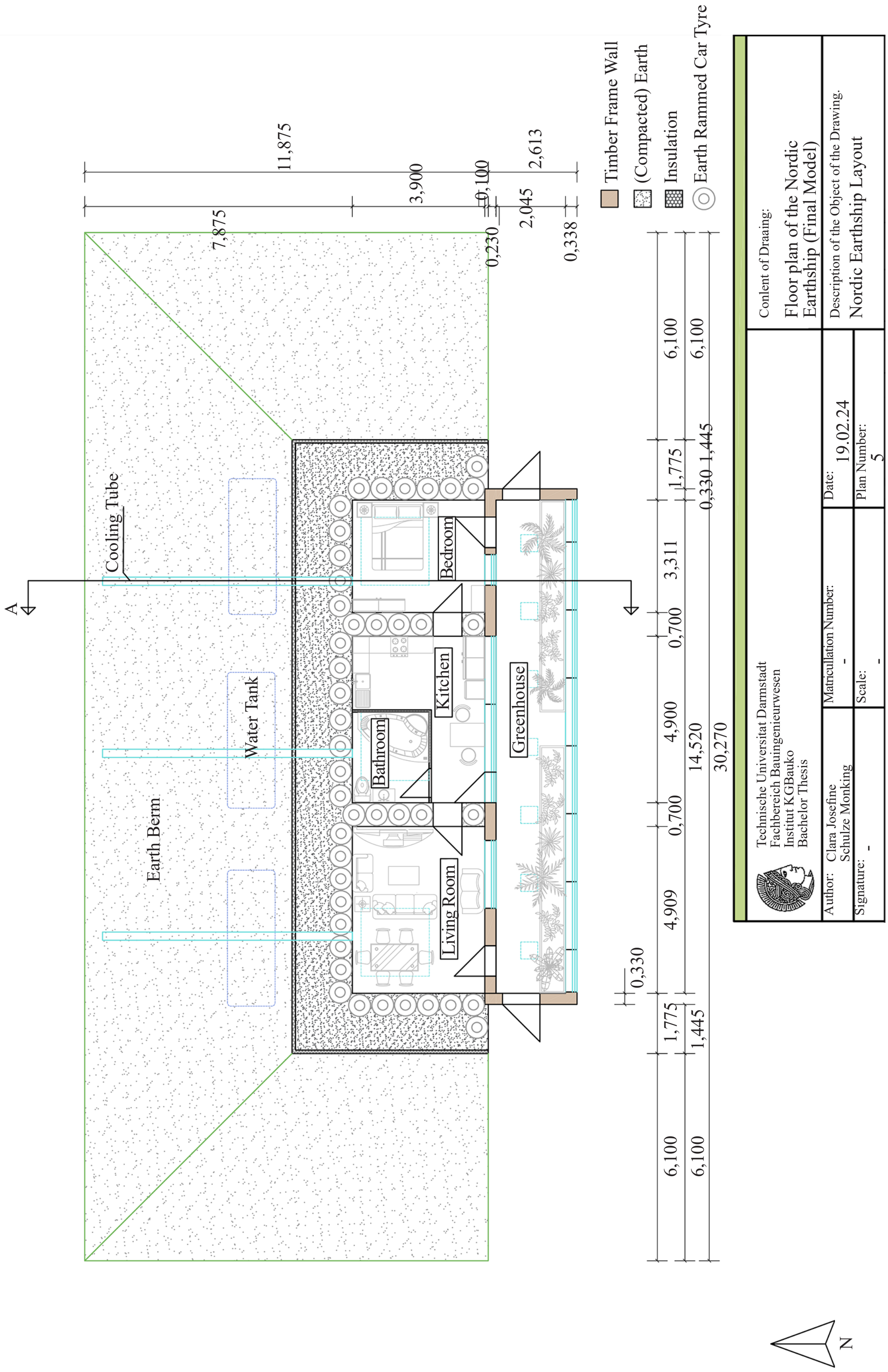
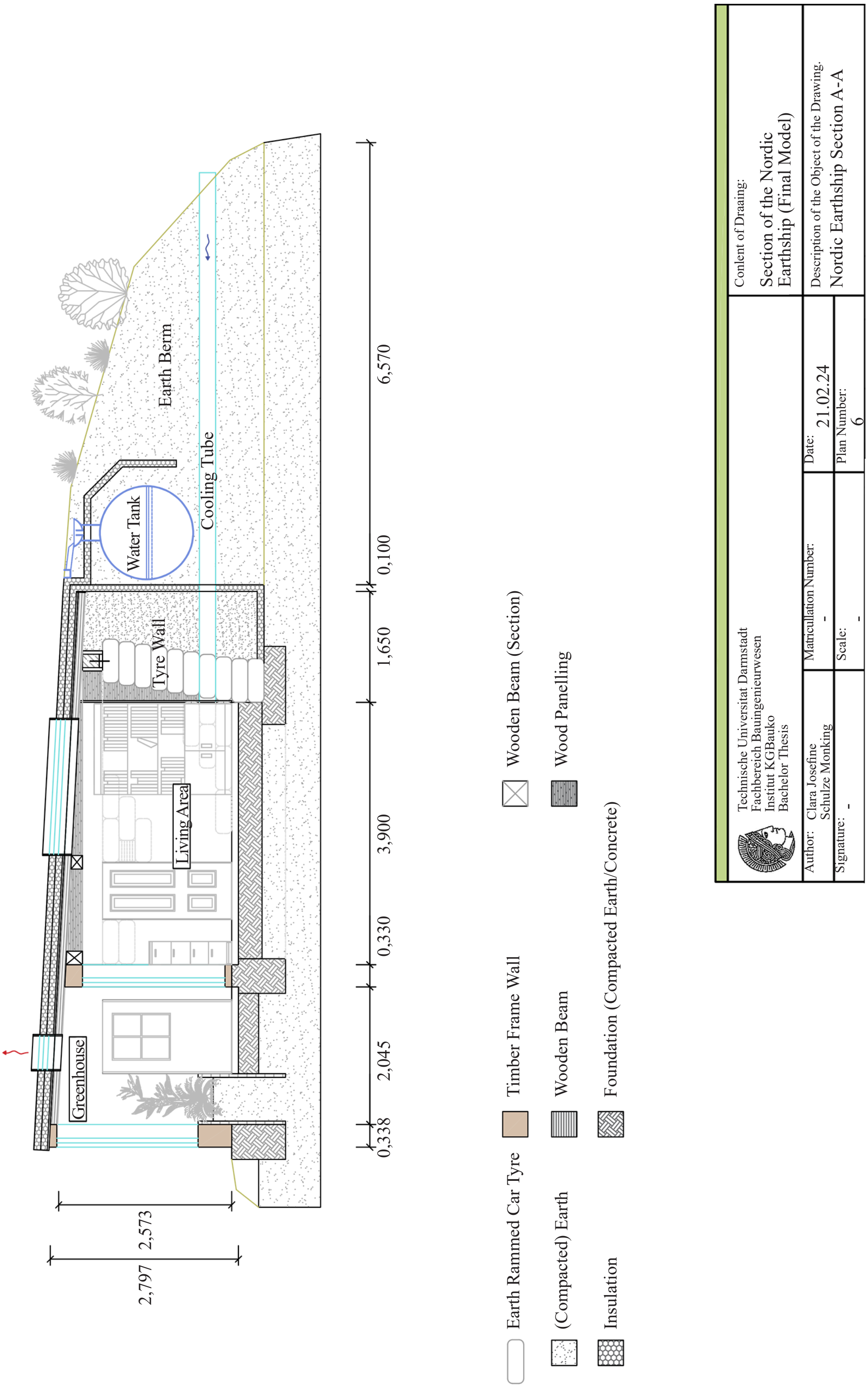
# Appendix


Earth Berm
Water Tank
Cooling Tube
Bedroom
Kitchen
Bathroom
Living Room
Greenhouse
A
Timber Frame Wall
(Compacted) Earth
Insulation
Earth Rammed Car Tyre
11,875
7,875
3,900
0,100
0,230
2,045
2,613
0,338
6,100
1,775
1,445
0,330
3,311
0,700
4,900
4,909
14,520
30,270
Technische Universitat Darmstadt
Fachbereich Bauingenieurwesen
Institut KGBauko
Bachelor Thesis
Author: Clara Josefine Schulze Monking
Signature: -
Matriculation Number: -
Scale: -
Date: 19.02.24
Plan Number: 5
Conlent of Draaing:
Floor plan of the Nordic Earthship (Final Model)
Description of the Object of the Drawing.
Nordic Earthship Layout
N


Earth Berm
Cooling Tube
Water Tank
Tyre Wall
Living Area
Greenhouse
6,570
0,100
1,650
3,900
0,330
2,045
0,338
2,573
2,797
Earth Rammed Car Tyre
(Compacted) Earth
Insulation
Timber Frame Wall
Wooden Beam
Foundation (Compacted Earth/Concrete)
Wooden Beam (Section)
Wood Panelling
Technische Universitat Darmstadt
Fachbereich Baungenieurwesen
Institut KGBauko
Bachelor Thesis
Conlent of Draing:
Section of the Nordic
Earthship (Final Model)
Description of the Object of the Drawing.
Nordic Earthship Section A-A
Author: Clara Josefine
Schulze Mönking
Matriculation Number:
-
Date:
21.02.24
Signature:
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Scale:
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Plan Number:
6