MASTER THESIS

Container Building Detailing, Construction and Thermal Analysis

under the supervision of
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Abstract

Global trends of population growth, particularly in the developing world, are exerting pressure for resolutions of their housing crises. This thesis presents modified shipping container constructions as a sustainable building alternative which has recently grown in popularity. Given their availability around port regions, discarded shipping containers are financially feasible to convert into habitable space with common prefabrication practices. Few studies have focused on the thermal performance of the envelope components and detail constructions, but almost none on the specific effects of thermal bridging due to the inherent steel structure. Therefore, this thesis seeks to provide a systematic and up-to-date thermal performance assessment with thermal bridges as a focal point. State of the art numerical thermal bridge simulations were carried out with AnTherm to evaluate temperature distributions, temperature factors, and minimum surface temperatures. A bare steel and minimally modified shipping container construction was used to set the base cases for further evaluations. These detail constructions were iteratively optimized with various insulation designs based on polyurethane foam, mineral wool, and vacuum insulation panels until all thermal performance requirements could be satisfied including climate extremes of -20°C. Wall, roof, and floor envelope components were valuated in 3D environments including their corner constructions. The results indicate that combinations of polyurethane foam with mineral wool or vacuum insulation panels perform best, with minimum interior surface temperatures above 16°C and thermal transmittances below $0.35 W \cdot m^{-2} \cdot K^{-1}$. Temperature factors above the crucial 0.71 threshold could also be achieved consistently with most optimized constructions boasting values around 0.9. The thesis concluded that all thermal bridging effects of shipping container constructions could be alleviated with proper insulation and design, making the envelope components suitable for sustainable low energy buildings. Future efforts should be focused on performing more complex simulations to bring the constructions to a prototype-ready level at which their results should be validated with on-site measurements.

Keywords.
Shipping container construction, building construction detailing, thermal performance, thermal bridge simulation

Kurzfassung

Globale Trends des Bevölkerungswachstums, insbesondere in den Entwicklungsländern, üben Druck auf die Lösung ihrer Wohnungskrisen aus. Diese Diplomarbeit stellt modifizierte Schiffscontainer-Konstruktionen als eine nachhaltige Baualternative vor, die in letzter Zeit an Popularität gewonnen hat. Angesichts ihrer Verfügbarkeit in Hafenregionen sind ausrangierte Schiffscontainer finanziell erschwinglich, um sie mit üblichen Vorfertigungsverfahren in Wohnraum umzuwandeln. Nur wenige Studien haben sich mit dem thermischen Verhalten der Hüllkomponenten und Detailkonstruktionen befasst, aber fast keine mit den spezifischen Auswirkungen von Wärmebrücken aufgrund der inhärenten Stahlstruktur. Daher versucht diese Arbeit, eine systematische und aktuelle Bewertung des thermischen Verhaltens mit Wärmebrücken als Schwerpunkt zur Verfügung zu stellen. Nach dem Stand der Technik wurden numerische Wärmebrückensimulationen mit AnTherm durchgeführt, um Temperaturverteilungen, Temperaturfaktoren und Oberflächentemperaturen zu bewerten. Als Grundmodell für die weiteren Auswertungen wurden eine nackte Stahl- und eine minimal modifizierte Schiffscontainer-Konstruktion verwendet. Diese Detailkonstruktionen wurden iterativ mit verschiedenen Dämmkonstruktionen auf Basis von Polyurethanschaum, Mineralwolle und Vakuumdämmpaneelen optimiert, bis alle thermischen Leistungsanforderungen einschließlich der Klimaextreme von -20°C erfüllt werden konnten. Die Ergebnisse zeigen, dass Kombinationen aus Polyurethanschaum mit Mineralwolle oder Vakuumdämmpaneelen am besten abschneiden, mit minimalen Innenoberflächentemperaturen über 16°C und Wärmedurchgangskoeffizienten unter 0,35$W \cdot m^{-2} \cdot K^{-1}$. Auch Temperaturfaktoren oberhalb der entscheidenden 0,71-Grenze konnten durchweg erreicht werden, wobei die meisten optimierten Konstruktionen sogar Werte um 0,9 aufwiesen. Die Arbeit kommt zu dem Schluss, dass alle Wärmebrückeneffekte von Schiffscontainerkonstruktionen durch geeignete Dämmung und Konstruktionsplanung gemildert werden können, wodurch sich die Hüllkomponenten für nachhaltige Niedrigenergiegebäude eignen. Zukünftige Bemühungen sollten sich auf die Erstellung komplexerer Simulationen konzentrieren, um die Konstruktionen auf ein prototypisches Niveau zu bringen, bei dem die Ergebnisse mit Messungen vor Ort validiert werden sollten.

Schlagwörter.
Schiffscontainer-Konstruktion, Baudetaillierung, Wärmeverhalten, Wärmebrückensimulation

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Contents

1 Introduction

1.1 Overview

According to the United Nations (2019), the world population is projected to grow to 8.5 billion people by 2030, and 9.7 billion by 2050. This growth originates largely from developing regions such as sub-Saharan Africa and India, where a lot of new building demand will emerge. Developed regions such as Europe and North America are expected to see low growth and a strong shift in demographics towards the elderly, with one in four people being over 65 years old by 2050. This will create a lot of pressure on support ratios of working class to elderly and could lead to future funding problems for services such as health care and pensions. Here the problem is not so much in satisfying the new building demand, although this may occur in the form of continued migration for work or as refugees of violence, regional instability, and armed conflict, but rather in retrofitting the existing building stock in a sustainable manner.

The rapid growth in developing nations comes with many challenges of its own, but also presents the vast opportunity of an increasing working-age population to thrive economically. Amongst the greatest challenges are those of drinking water and sanitation, as UNICEF (2019) still reports 2 billion people lacking basic sanitation service and 785 million the access to basic drinking water. The solution to this has long been know as infrastructure building, were basic housing implies that drinking water, sanitation, and hygiene are available to the occupants. To achieve this, developing nations will have to over hall their disadvantaged building construction industries and bridge the knowledge gap by introducing new methods such as lean and prefabricated construction (Omotayo and Keraminiyage 2014). Ofori (2019) highlights that although construction in developing countries is a well established subject with a dedicated global research group, the field requires some revival and that "there is a pressing need to substantially increase the capacity and capabilities of the construction industries in developing countries."

Another global trend that is impacting the construction industry is the push towards environmentally friendly construction. The obsession with sustainability is largely focused on reducing CO_2 emissions to contain the prognosed climate change to 1.5°C (Masson-Delmotte et al. 2018). Although developed nations' CO_2 emissions are now at relatively low levels not seen since the late 1980s, when electricity demand was one third, this generally balances with the increased emissions seen in developing nations (IEA 2020). In order to decrease CO_2 emissions and meet environmental targets, considerable contributions can be made by low energy buildings (UNe 2019).

An emergent research field, which may provide some of these sustainable solutions to housing crises around the world, has been the study of upcycled and modified shipping containers (SC) for construction. These utilize discontinued steel SCs as the main structural element and modified envelope components with insulation, electrical installations, and cladding to create a habitable space. Their use for disaster relief, temporary housing, or even class rooms has already been recognized as they offer high structural integrity and modularity, whilst remaining economically feasible. The architectural possibilities of shipping containers have been demonstrated thoroughly over the past twenty years with buildings such as the Keetwonen complex in Amsterdam, the Kunsthalle in Berlin, and the Quadrum ski hotel in Georgia (Berbesz and Szefer 2018, Radwan 2015). The low aesthetic value of SCs has been successfully transformed to pleasing design by use of creative modular arrangement. SCs offer a particularly efficient construction method for port regions with an importing bias, as here large sums of discontinued freight SCs are available to be upcycled. Utilizing these for construction also alleviates the problem of their environmentally unfriendly disposal in land fills or energy intensive steel melting.

The potential of SCs for economic and sustainable buildings has been documented for varying climates such as in Egypt, were it was found that prefabricated and mass-produced, this solution could yield up to 50% cost savings for housing (Madkour 2017). An investigation of multiple sites including Johannesburg in South Africa, Copenhagen in Denmark, and Gudauri in Georgia drew similar conclusions, even promoting the possibility of constructing passive houses from upcycled SCs when properly insulated (Berbesz and Szefer 2018). In tropical climates such as Indonesia the benefits of SC constructions are slightly less, but still outweigh the constraints posed by more skilled construction processes such as the large amount of welding and steel work (Ismail et al. 2015).

The current problem of SC construction is one of slow adoption, where only a few companies possess the necessary expertise to make them work efficiently. Furthermore, reliable resources for best practices in the construction process, particularly of welding containers together or envelope component and detail constructions are not readily available. Published literature concerning the thermal performance of shipping containers has only focused on heating demand and U-values, although a majority of these pieces acknowledge the significance of thermal bridges in SC constructions.

1.1.1 Research Questions

1) How do various modified container envelope and detail constructions perform in terms of thermal bridging?

2) What internal surface temperatures occur in modified container constructions given different climates?

1.1.2 Scope of Work

This research will focus on modified 20ft SCs, specifically entailing the construction design of the three envelope components as well as corner details for a thermally habitable environment. Several inside- and outside-insulating constructions variations will be explored under three climate scenarios. Thermal evaluation will be performed on the basis of U-value calculations and state-of-the-art numeric thermal bridge simulations. Iterative optimizations of the constructions will be carried out until all climate conditions can be satisfied. The constructions are to be finalized and presented in BIM format such that they could be used for future prototype development. Further evaluation criteria regarding the constructions' condensation behavior as well as economic viability and environmental footprint will also be considered.

1.1.3 Thesis Organization

The thesis is structured into five sections: Introduction, Methodology, Results, Discussion, and Conclusion. The Introduction highlights the existing knowledge base surrounding SC constructions with a thorough and broad literature review. The second section describes the analysis processes and clarifies terminologies as well as input settings of the utilized software. The third section presents the thermal performance results of the modified base and iterated SC envelope as well as detail constructions. These are then discussed and compared in the following section, also with respect to other non-thermal performance criteria such as sustainability and ease of construction. The fifth section draws the main conclusions of the research to provide the derived answers to the research questions and presents recommendations for different climates.

1.2 Motivation

Pursuing this research is important to concretely establish SC constructions as a sustainable building alternative to alleviate ongoing housing crises around the world. Particularly where discarded containers are readily available to be upcycled, this could significantly reduce the cost housing and create enough inertia to innovate the building sector. In the developing world, cities with rising economic potential are emerging where incumbent building construction companies can no longer keep up with the demand to provide basic residences and could hugely benefit from the advances of prefabrication processes with SC constructions.

This research seeks to determine the most viable envelope and detail constructions for modified SCs within different climates and competing construction goals. The investigation entails the crucial component of simulating multi-dimensional heat flows which cannot be satisfactorily computed by hand and provides solutions to reduce thermal bridges. These simulation based solutions are helpful to make adjustments of detail constructions throughout the planning phase. Such simulations were not to be found in the existing literature although most published pieces reference the importance of thermal bridging when using SCs for construction. This presents a gap between empirical knowledge and the hopeful future applications of this building type.

The findings of this research seek to minimize construction errors by clarifying the container envelope and detail constructions with proven thermal performance. This is intended to further promote the universal viability of SC constructions and call to action the legal and regulatory perspectives to allow for greater building innovation. This in turn would allow more real estate developers and construction companies to utilize SC constructions efficiently to provide affordable sustainable buildings. Improved construction capability and capacity may be the outcome, in which case this enriching knowledge should be shared across all relevant stakeholders and is thereby a worthwhile endeavour.

1.3 Background

1.3.1 General

Malcolm McLean (1954) began the freight shipping revolution with the invention of the intermodular shipping container. This greatly improved international trade as shipping costs were reduced and resulted in considerable global economic growth. In 1970, modern SCs were officially standardized with the introduction of the International Standards Organization (ISO). The relevant standards that apply worldwide are ISO 1161:2016, ISO 1496-1:2013, ISO 2308:1972, ISO 3874:2017, ISO 6346:1995, ISO 668:2020, and ISO 830:1999, which clarify container specifications, structural strength and limitations, serviceability, and applications related to their use as freight carriers. The most common sizes used since then are 20ft, 40ft, 20ft High Cube (HC) and 40ft HC as well as refrigerated variants. These ISO containers' dimensions and load capacities are shown in Table 1, an exploded schematic view in Figure 1, and an overview of the structural components in Figure 2. For their use in freight, SCs have a lifespan of roughly 10 years after which they are replaced by new SCs due to regulations, which is considerably less than their life expectancy of 30 years (Berbesz and Szefer 2018). Structurally they can easily withstand 6 fully loaded 24-ton stacked SCs (Ismail et al. 2015).

Table 1: ISO 668 (2020) shipping container dimensions and load capacities (Ismail et al. 2015)

Type	Length (m)		Width (m)		Height (m)		Empty Weight (kg)	Net load (kg)
	Internal	External	Internal	External	Internal	External		
20ft	5.898	6.058	2.352	2.438	2.385	2.591	2400	28080
20ft HC	5.898	6.058	2.352	2.438	2.698	2.896	2520	27880
40ft	12.032	12.192	2.352	2.438	2.385	2.591	4000	26480
40ft HC	12.032	12.192	2.352	2.438	2.698	2.896	4200	26280

Seeing the potential of discarded SCs for upcycling and prefabrication advances, Phillip Clark (1987) created the first methods for converting SCs into habitable buildings. These implied temporary buildings, with simple technical sketches to convert SCs into a basic house. This field has since developed into "cargotecture" which also includes the use of non-upcycled SCs specifically made for building construction named Intermodular Steel Building Units (ISBU). The integral component for cargotecture is prefabrication, a technique by which large components of a building are manufactured in factories, ready-made to be assembled on the building site. The preferred container type has become the 20ft HC as these containers have more structural integrity than 40ft. Furthermore the high cube attribute allows for an

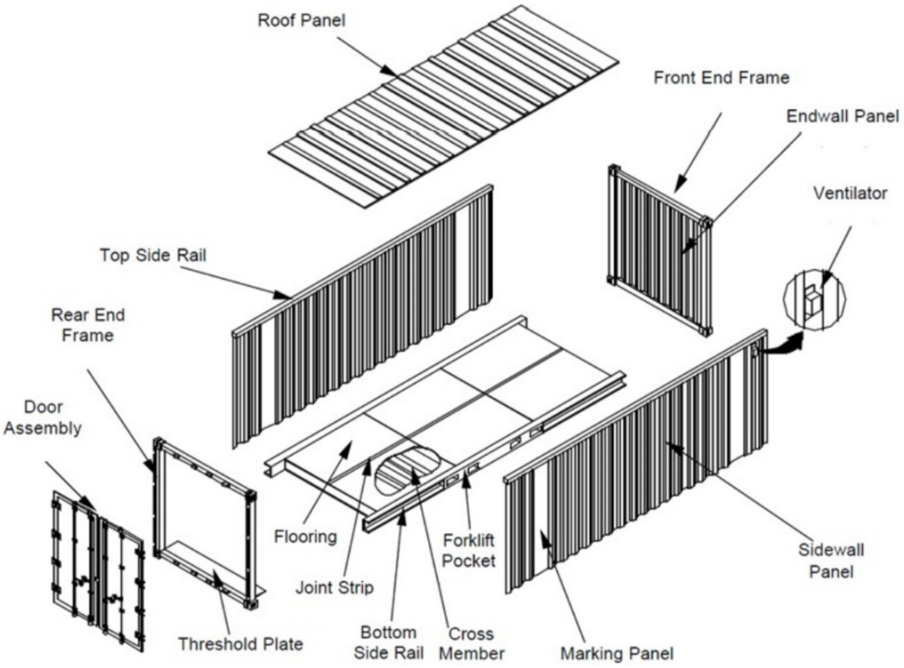


Figure 1: Exploded schematic view of a shipping container (RSC 2019)

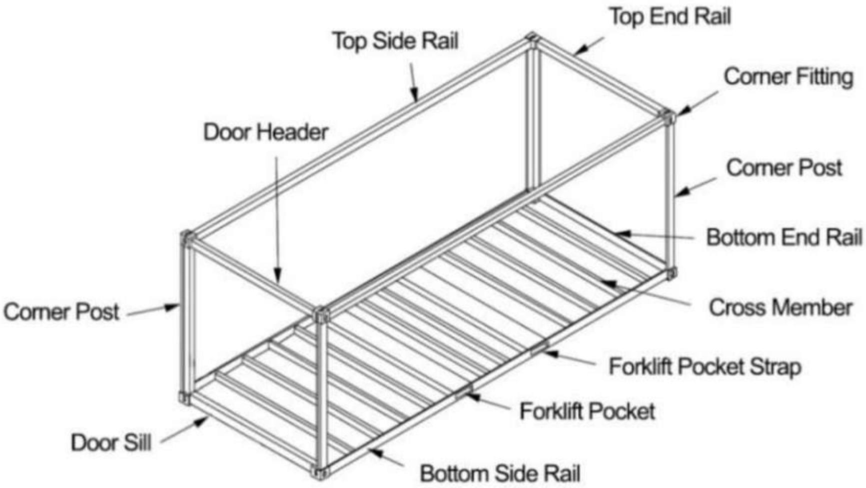


Figure 2: Primary structural components of a 20ft ISO SC (RSC 2019)

inside ceiling height of 2.6m, similar in comfort and perception to that of a regular construction (Ismail et al. 2015). The pricing is governed by technical condition and delivery, but is generally around 2000 Euro for a standard 20ft or 40ft container.

Harbours around the world store about 30 million discarded containers, as it is often not financially viable to transport them without cargo to their home-port (Berbesz and Szefer 2018). Of these, roughly 14 million are estimated to be standardized and in useful condition, with a smaller amount made of superior material: COR-Ten steel. These have often been used for humanitarian efforts such as service modules for natural disaster relief or military applications (Ulloa et al. 2017).

The term ‘container building’ still carries some stigma, often implying a dull steel box used at construction sites for temporary purposes. In reality however, great strides have been made to showcase how discontinued SCs may be modified into permanent and architecturally pleasing structures. Amongst built examples are schools, student housing, hotels, and even a nascent trend of using shipping containers for tiny homes. This shift in application came due to previous triumphs as disaster relief and numerous utilization experiments. One of these was the comparison of ordinary and container classrooms in Austria (Kaveh and Mahdavi 2014), where container constructions were found to be only slightly inferior in terms of heating demand and indoor CO_2 levels. The case for improving these was made by introducing better technology such as temperature controls and reducing the occupancy. However, SC constructions still face a lot of regulatory hurdles as legal frameworks remain vague around the world, varying from classification as purely temporary structures to having a maximum lifespan of 50 years.

1.3.2 Advantages and Disadvantages

Compared to conservative construction methods, modified SC constructions offer sizeable advantages, given regional availability of container stock to be upcycled. The major factor is the utilization of prefabrication whereby the time to construct a quality building can be drastically reduced. Particularly in cold climates, where the construction cycle is short, performing most construction in a warehouse can introduce great flexibility for the industry. Companies have claimed to save up to 40% construction time and 70% costs when using SCs as the main building component (Berbesz and Szefer 2018, Elrayies 2017). Additionally they have begun offering all-in-one solutions for single and multi family homes (Blanford and Bender 2020). This is also due to the ease of transport to a given construction site as well as the fast speed of installation and assembly, as containers must merely be welded together and some final adjustments made such as utility installations. These advantages were demonstrated in Chile after the earthquake and tsunami of 2010 where significant portions of building stock were damaged and partially rebuilt using SC constructions. This was done for schools, offices, homes, and many more types of buildings (Alvarado 2011). Some of these have even turned into tourist attractions such as the Hotel WineBox in Valparaiso, Chile shown in Figure 3 below.

Figure 3: Hotel WineBox in Valparaiso, Chile designed by architect Camila Ulloa using 25 recycled SCs, constructed in 2017 (win 2019)

Moreover, SCs are very affordable in raw materials whilst offering high quality COR-ten steel which can withstand any atmospheric pressure and is inherently corrosion resistant. There are no problems in terms of air tightness or weathering. This strength and durability comes in modular format almost like LEGOs and requires only simple foundations if the number of storeys is not too high. This enables great versatility for building construction as many types of SCs such as standard, HC, open top, and open side may be combined to create unique designs. SCs are also ideal for building construction, because they can be sustainable and setup as low energy or even net zero energy buildings (NZEB) with some more expensive modifications. Applying a coherent modular design strategy could further improve the efficiency of SC constructions if implemented industry wide (Sun et al. 2017).

Furthermore SC constructions can perform well in terms of fire protection, as steel components are assigned to building material class A (non-combustible building materials) according to DIN 4102-1:1998. However, during fires, temperatures often occur at which steel parts deform and lose their load-bearing capacity. If they twist and bend in the process, severe damage can be caused to adjacent components by tension. To prevent this, fire resistance classes F30-A (fire-retardant) to F60 (highly fire-retardant) according to DIN 4102-2:1977 are desirable such that load-bearing components can withstand the fire test for 30 to 60 minutes respectively. This can be achieved by coating the steel with special plastic dispersions.

The dominant disadvantage of using SCs for construction is the requirement of excessively importing ports. Although SCs are mass produced, their regionally limited availability or long distance transport can significantly reduce their economic feasibility. Alongside this, their functionality is slightly hindered by structural limitations such that cantilevered designs, sloping sites and excessive side panel removal for creating large windows cannot be recommended (Blanford and Bender 2020). Since SCs are made of high density steel, sound can easily propagate through them, indicating a need for acoustic insulation. Another drawback to overcome is that in order to increase interior space by application of external modifications, the inherent air tightness and corrosion resistance of SCs is lost and extra attention must be paid towards weather protection.

Constructions based on SCs also have notably higher uncertainty regarding their lifespans compared to regular buildings, with habitable lifetime expected to last 10-50 years based on construction quality (Ismail et al. 2015). The oldest SC constructions are in use since about 20 years and there is no assurance on how they will perform for the next 20 years. Furthermore, there is a general lack of technical building data accessibility and there are no clear frameworks for the use of SCs for construction within normative standards (Olivares and Andres 2010). Safety guidelines for using SC constructions exist only vaguely as reinforcing limits and building code regulations are largely unknown for modified SCs (Giriunas et al. 2012).

Using SCs for construction also introduces intensive labour, particularly steel work. This requires skilled workers for cutting, welding, and handling heavy machinery such as cranes. This poses a distinctive pitfall for developing nations were the construction professionals are not used to such work (Ismail et al. 2015, Olivares and Andres 2010) and a general lack of construction knowledge persists (Omotayo and Keraminiyage 2014). The widening knowledge gap between developed and developing nations for adopting new construction methods and vague regulatory landscape could see modular SCs as forms of extreme prefabrication fail.

The final hurdle of SC construction is that the idea is still considered unusual and requires more clarification and improvement before having a meaningful impact on the construction industry. The unpopular stigma of steel boxes must be overcome with design, enhanced project support systems, planning, optimizing functions, and governance whilst considering each nations unique perspective on housing problems.

1.3.3 Sustainability

According to the World Meteorological Organization (2020), the global climate has been 0.2°C warmer on average for the 2015-2019 period compared to the previous 5 years. Greenhouse gases within the atmosphere have continued to rise, with CO_2 levels reaching beyond 400ppm, methane 185ppb, and nitrous oxide 330ppb. The oceans have seen a rise in stored heat energy and acidification has worsened. Extreme weather events and natural disasters have become more frequent and expensive, leaving many unprepared and heavily impacted in terms of food security and housing. The world disasters report (2020) quantifies the increase of natural disasters over the past 30 years at 35%, with 77% being climate related. These have affected billions of people, particularly in vulnerable countries with poor international funding. The report highlights that building resilience to minimize the impacts of extreme events is very important.

The Intergovernmental Panel on Climate Change (2018), which played a key advisory role for the Paris Agreement, has performed extensive research of over 6000 publications to make the argument for differentiating between 1.5 and 2°C of global warming. Given 1.5°C, sea levels are expected to rise 0.26-0.77m by 2100, seriously impacting the livelihoods, food security, water supply, human security, and economic growth of the human populace. To achieve this less drastic scenario they suggest a net zero CO_2 goal for 2050 that relies on strong incentive structures and acknowledges the trade-offs and opportunities including those within the building sector.

Similar conclusions were drawn by the United Nations Emissions Gap Report (UNe 2019), highlighting the need to do more in the face of the new CO_2 emissions high of 55.4Gt CO_2 equivalent in 2018. The new target of 1.5°C requires a 7.6% annual CO_2 emission reduction, which shall be brought about with a shift towards renewable energies and increased energy efficiency in the power, building, and transport sectors, which can deliver emission reductions of over 16Gt CO_2 equivalent. It calls for less incremental change and more transformational action as well as focus on embedded and consumption-based emissions with clear distinctions of territorial versus imported CO_2 emissions. Also brought to attention is the global imbalance, by which G20 members account for 78% of all CO_2 emissions, with the largest total contribution being China, but on a per capita basis the USA and Russia.

The International Energy Agency (2020) brings some hopeful news, as global energy related CO_2 emissions have flattened in 2019 at around 33Gt. This can be attributed to sharp declines in CO_2 emissions from the power sectors of advanced economies thanks to the growing role of renewable energies, predominantly solar and wind. The switching to natural gas, away from coal, and higher nuclear outputs, with Japan and Korea leading the way, also contributed. The largest decline in energy related CO_2 emissions was seen in the United States, where emissions dropped to 4.8Gt, which is 1Gt less than their peak in 2000. Europe's emissions dropped by 5% to 2.9Gt with Germany at the forefront, where emissions fell to levels not seen since the 1950s when their economy was 10x smaller. These reductions were offset by developing economies where CO_2 emissions grew by 400Mt, mostly in Asia where coal demand has been steadily increasing. China's emissions only saw a slight rise, as they launched seven new nuclear reactors to meet their increasing demand.

The European Environment Agency (2019) also bares positivity as the 2018 CO_2 emissions are already down 23% compared to 1990, which is more than the EU target of 20% by 2020. They also intend to introduce new measures and policies to reduce CO_2 emissions by a further 40% by 2030. Amongst theses solutions are curious ideas such as the 'EU Emissions Trading System' and 'Effort Sharing Decision' which essentially charge countries for their emissions, but also the common practices of investing in renewable energies and improving energy efficiency. With these the EU intends to contribute to the Paris Agreement objectives and attain climate neutrality. The countries most on track include Sweden, Portugal, Greece, and Germany. The Agency also points out the opportunity within the residential and commercial sector which produced about 570Mt CO_2 equivalent emissions or 13% of the EU's total emissions.

Rousselot (2018) explored the building sector's energy efficiency to find consumptions of 41% and 60% of the final energy and electricity respectively in the EU-28. This predominately originates from space and water heating, but can be drastically lower in other developed nations, such as New Zealand where these percentages were found to be around 20% (Olivares and Andres 2010). Conventional housing is also responsible for 1/4 of forest logging, burns 2/5 of our liquid fuels, and consumes 1/6 of our fresh water resources (Berbesz and Szefer 2018). By using upcycled SCs for housing these wastes can ideally be reduced by 30-50%, as well as the great difference in energy required for the disposal versus upcycling process of SCs at 8000 and 400kWh respectively (Islam et al. 2016). Factoring in this energy required for melting the steel containers into newly usable steel format can make SC constructions carbon neutral or even slightly positive (Madkour 2017). In expensive super recycled scenarios, SC constructions have even been shown to reduce CO_2 emissions by 86% (Jewwll 2013) and utilize 75% recycled materials by weight (Howard 2013). More reasonable constructions such as a high performance single family housing complex based on SCs in Virginia have shown that they can be 49% more energy efficient than conventional homes (Battaglia and Lee

2020). It is also well documented that SC constructions can be designed to be fully self-sufficient when properly insulated and equipped with roof rainwater harvesting and solar photovoltaics (PV) (Kristiansen et al. 2020).

Performing life cycle assessments (LCA) always involves small assumptions in methodology such as defining the system boundaries and maintenance scenarios, making their comparisons less than stellar. However, many researchers have chosen to study this field and found partially contradictory results. In Australia it was shown that SC construction's global warming potential (GWP) was merely 14.2kg CO_2 eq$\cdot m^{-2} \cdot yr^{-1}$ and construction waste was reduced by 70% compared to traditional methods (Islam et al. 2016). The main energy consuming processes, namely sand blasting, window cutting, replacing floors, transportation, and welding were evaluated and the use of eco-friendly materials such as wool, recycled cotton, mud and straw blades discussed. These may be used for insulation, but cause condensation problems depending on the climate. It was also demonstrated that upcycled SCs for average houses can save almost 2 tons in timber framing, but concluded that LCA sustainability of SC constructions was not fully confirmable and heavily dependant on the situation, climate and execution of construction processes.

Another LCA in New Zealand (Olivares and Andres 2010) compared SC to regular timber and concrete constructions which have GWPs of 22.3 and 38kg CO_2 eq$\cdot m^{-2} \cdot yr^{-1}$ respectively. The SC constructions considered in this assessment featured new ISBUs which were not upcycled and only insulated with fiberglass reinforced panels. This, combined with poor design and a small sample size, yielded major energy consumption and CO_2 emissions compared to traditional constructions.

In Europe, Directive 2010/31/EU (2010) is stimulating new approaches in the building design process and renewable energies exploitation through the concept of nearly zero energy buildings (nZEB). SCs as nZEBs were explored in Italy (Schiavoni et al. 2016) to find that vacuum insulating panels (VIP) were necessary to reach passive house standard and plywood cladding would work best for this climate in terms of energy consumption and LCA. In China (Satola et al. 2020) the ideas were pushed further to also include off-grid and net zero energy buildings (NZEB), with NZEBs showcasing the lowest life cycle impacts and reducing water consumption by 26% and GWP by 86% compared to a basic design SC. The designs under investigation varied in insulation and PV-systems with the base design being internally insulated with mineral wool and 8mm of VIP. The low energy design increased the insulation to 24mm of VIP and the NZEB as well as off-grid versions appended 5 and 10 kW PV systems respectively. The low energy design used 34% less energy and showed 29% less GWP than the base design for a reasonable price increase, whilst the NZEB and off-grid variants were considerably more expensive. A sensitivity analysis also showed that climate change would only have minor influences on LCA.

In Canada, the claim has been made that SC constructions can be cheaper passive houses and help achieve thermal comfort with minimal energy use and CO_2 footprint (Bowley and Mukhopadhyaya 2019). This can be accomplished via meticulous design and selection of efficient envelope components and appliances in modified SCs to meet the passive house requirement of less than $15\text{kWh}\cdot \text{m}^{-2} \cdot a^{-1}$ energy demand in all cold climates except the Arctic. Special attention should be paid towards the SC construction's alignment and quality to ensure habitable lifetime of at least 50 years.

Overall it should be noted that SCs are inherently not sustainable, but can be converted to low energy or passive houses with reasonable effort and sustainable feasibility drastically improves with scale.

1.3.4 Summer Overheating

As SC constructions are still a relatively fresh field of study, many have focused on the problem of overheating during the summer months. This applies to most climates were humans have settled and the temperatures reach beyond 30°C. Thermal comfort modeling was carried out by several researchers to find the appropriate utilization of passive solar direct gains, internal heat gains, and window shading (Shen and Zhang 2019). In hot and dry climates like Egypt, it was found that green roofs and external shading are definitely required (Elrayies 2017). In a direct comparison of a SC office with and without green roof in Australian subtropical climate, the green roof proved itself clearly superior with a 4°C temperature difference compared to the regular roof (Anwar et al. 2020). This is because the plants on the green roof can significantly reduce the amount of solar energy reaching its construction and thereby serve as an insulation barrier. This can greatly reduce CO_2 emissions caused by air-conditioning and allow for energy savings up to 11.7%. Summer overheating is thereby no longer considered a constraint for SC construction, so long as climate specific solutions are implemented.

1.3.5 Heat Losses during Cold Seasons

The dominant thermodynamic indicator for constructions currently is the amount of energy required for heating, with significant demand occurring throughout the winter. This is due to the construction loosing its internally generated heat through the envelope components, which is most heavily influenced by the type of insulation installed and the climate. For warmer climates, where winters only reach 0°C, it may be enough to insulate a SC construction with 15 cm of rock wool and still achieve annual energy requirements $< 50kWh/m^2$. This of course is not the case for colder climates such as central Europe where buildings must be designed to perform consistently down to -10°C, or in even colder climates -20°C. In such conditions it is necessary to also consider the effects of thermal bridging to ensure energy efficient operation of the construction. Thermal bridges occur where heat flows form higher to lower temperature areas faster locally compared to the imminent surroundings. Where this happens the internal surface temperature may be too low and pose a condensation risk. Therefore thermal bridges have both thermal and moisture protection implications which inherently affect both comfort and health of the construction. To enable quality usage of SC construction during cold seasons, great attention should be given to the highly conductive steel and any mounting bolts that may lead to thermal bridging and make sure these issues are addressed with additional insulation.

1.3.6 Construction and Thermal Performance of SC Envelope Components

The body of a SC has a distinctive shape to strengthen it structurally. This consists of a trapezoid construction of 1.6-2mm thick continuously corrugated steel sheets (ISO 668:2020). A section view of this form is shown in Figure 4. The corrugated steel sheets are butt welded together to form panels which are continuously welded to the corner posts and the side rails. Thicker 6mm and 4.5mm pressed steel is used for the corner posts and side rails respectively.

The basic sectional wall view of a modified SC construction from Phillip C. Clark's (1987) patent is shown in Figure 5 below. It shows a thermally insulated construction, which is indispensable for SC habitation, with a decorative interior layer and a weather resistant outer layer. The corrugated steel wall (133) has outside and inside raised surfaces (135) & (137) upon which plastic foam sheet insulation is adhered (139) & (141). The outside is sealed with a weather resistant layer (143) attached through the construction by connectors (147). The interior decorative layer (145) is similarly attached by connectors (149) and commonly made of plywood. This construction is efficient at reducing heat flows and can allow for basic habitation in both cold and hot climates. In some cases it could also be recommended to build in a vapor barrier. It should be noted that these constructions do not feature space for utility installations, but dependant on building purpose, these may be integrated with use of basic timber framing.

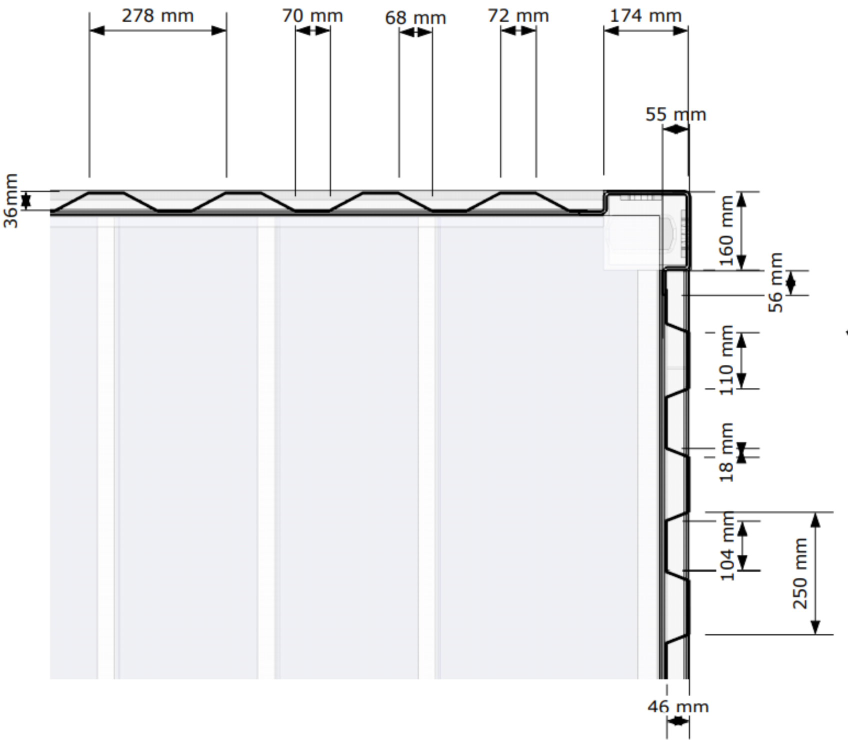


Figure 4: Corrugated steel section view

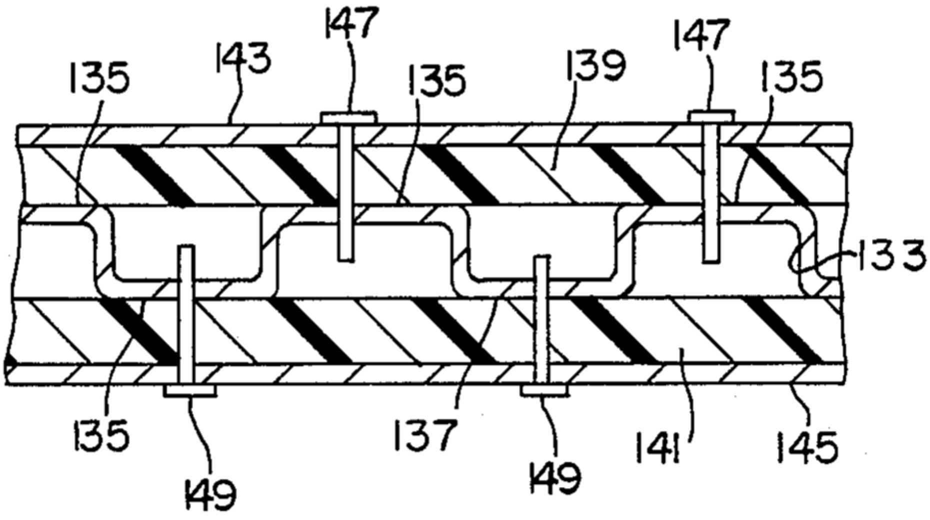


Figure 5: Basic wall construction (Clark 1987)

The simplest insulation SCs have before modification is that of refrigerated units which utilize fiberglass reinforced panels with a thermal resistance of $1.2m^2 \cdot K \cdot W^{-1}$ depending on their thickness (Olivares and Andres 2010). Most modified SC constructions however use uninsulated container types as their starting point. For military activities and disaster relief all envelope components are minimally internally insulated with a layer of polyurethane to achieve U-values of 0.41, 0.31, and $0.54W \cdot m^{-2} \cdot K^{-1}$ for wall, roof, and floor respectively (Ulloa et al. 2017). These rudimentary thermal transmittances are only slightly inferior to other common modular constructions used in east Asian climates of $0.18W \cdot m^{-2} \cdot K^{-1}$ (Park et al. 2019).

To attain comfortable habitability, further insulation is of high priority. When choosing internal insulation several general options are available: batt insulation with high density glass wool, sprayed insulation with a low-toxic material such as polyurethane, or structural insulated panels made of OSB plates with a polymer foam insulation core (Berbesz and Szefer 2018). The most stable and time-tested insulation method offered by construction companies utilizes mineral wool as shown in Figure 6 or spray foam and rigid board insulation as shown in Figure 7.

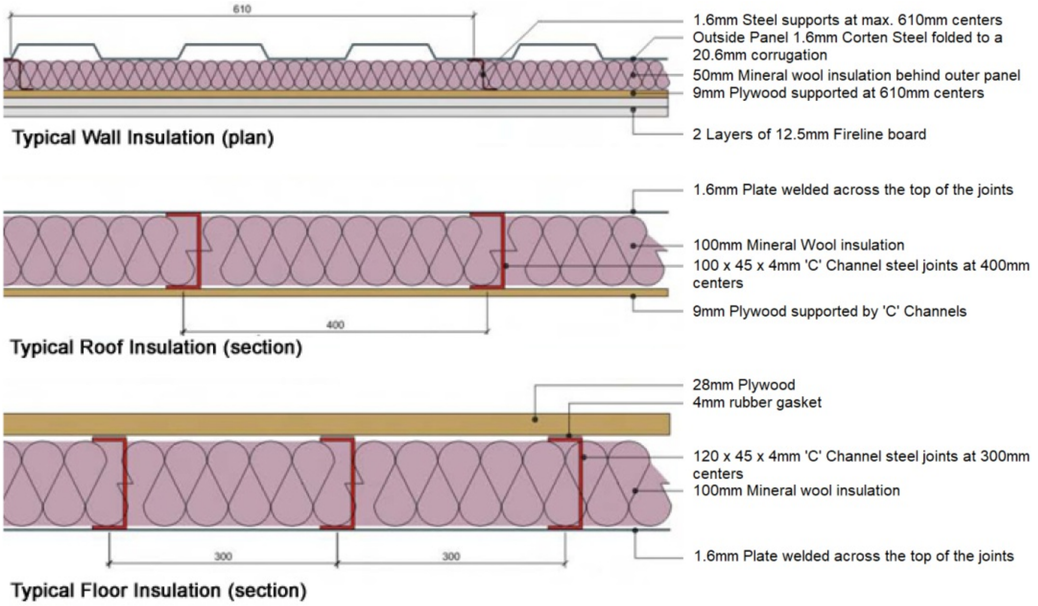


Figure 6: Typical SC envelope insulation (RSC 2019)

Vacuum insulation panels (VIP) are amongst the emerging materials, with a proposed SC wall construction shown in Figure 8 (Shen and Zhang 2019). Similar VIP constructions used to insulate the roof and floor achieved

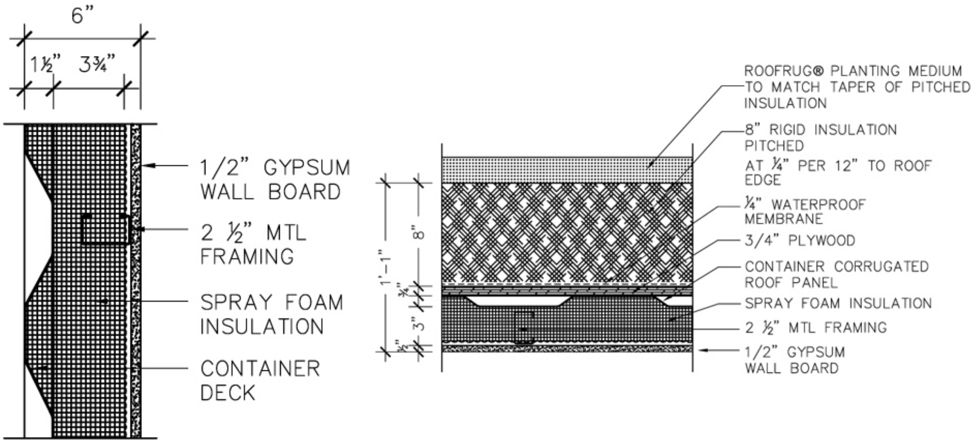
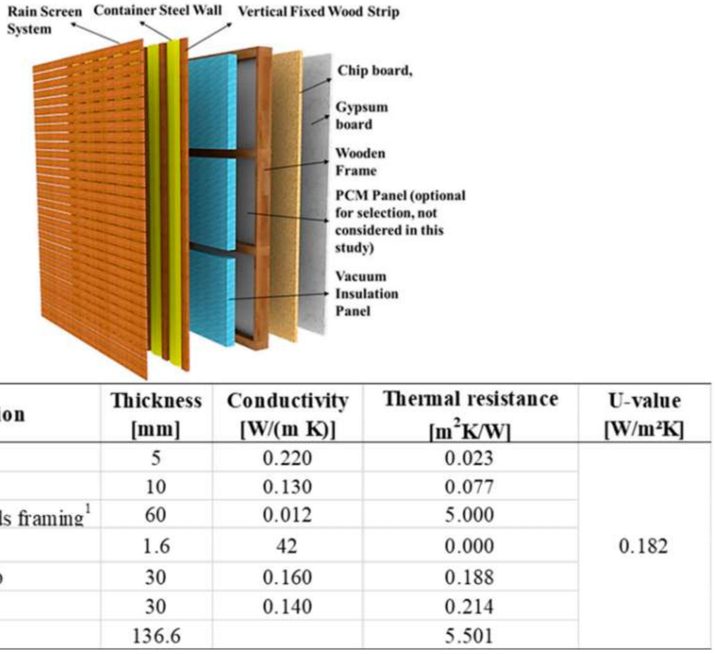


Figure 7: Typical SC wall and roof insulation (RSC 2019)

U-values of 0.196 and $0.193W \cdot m^{-2} \cdot K^{-1}$ respectively. A closed cell spray-foam and cellulose interior insulation variant is shown in Figure 9 (Battaglia and Lee 2020). This construction is particularly good at moisture control and sealing window penetration with galvanized steel hoods.



Envelope configuration		Thickness [mm]	Conductivity [W/(m K)]	Thermal resistance [m^{2}K/W]	U-value [W/m²K]
Wall	Gypsum	5	0.220	0.023	0.182
	Chip board	10	0.130	0.077	
	VIP within wooden studs framing[1]	60	0.012	5.000	
	Container steel panel[2]	1.6	42	0.000	
	Air in 30 mm Vent. Gap	30	0.160	0.188	
	Wooden rainscreen	30	0.140	0.214	
	Total	136.6		5.501	

Figure 8: SC wall construction with U-value estimation (Shen and Zhang 2019)

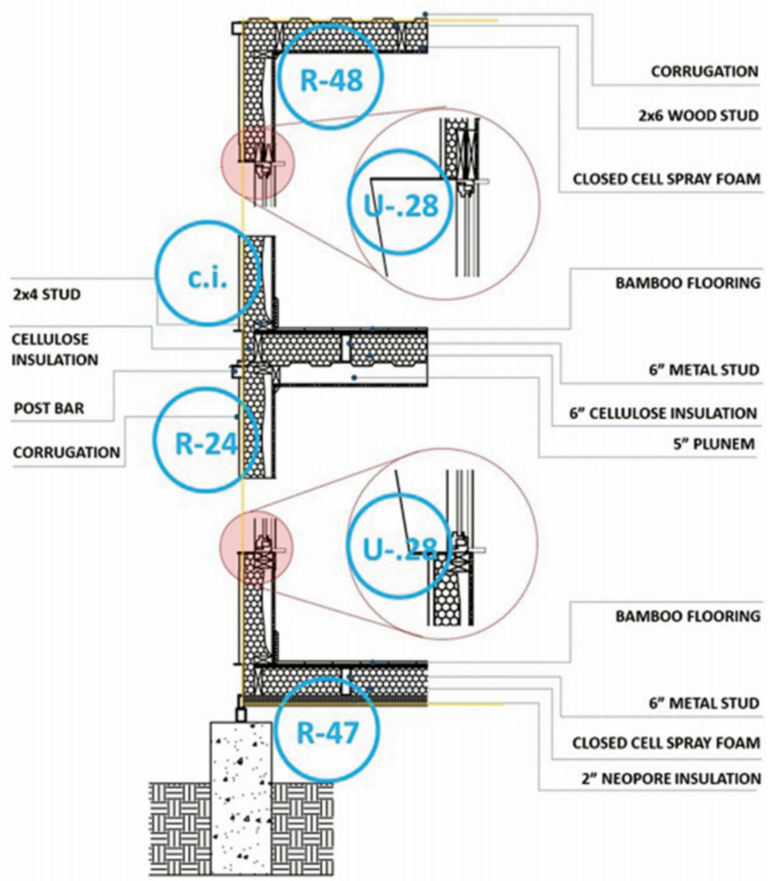


Figure 9: Wall section details (Battaglia and Lee 2020)

Choosing to insulate on the exterior can also be interesting as this greatly improves internal dimensions and takes advantage of SC thermal inertia. It does however require new water proofing and can hinder transportability. Material flexibility ranges from rock wool, closed-cell spray, polyurethane foam all the way to eco-friendly materials such as wool, recycled cotton, mud or straw blades. Blanket insulation featuring rock wool or rigid mineral wool can be very cheap and provide fire resistance as well as sound proofing whilst remaining open to vapour and allowing moisture to dry. When using wool or cotton as blanket insulation extra attention should be paid to condensation and when using mud only hot and dry climates can be recommended. Spray foam insulation is more expensive for good reason, as it can create smooth and seamless barriers preventing corrosion and mold whilst having a high heat flow resistance. The application of spray foam is also very straight forward and fast. Rigid insulation panels offer mid tear insulation and are slightly more expensive than blanket insulation. Their disadvantage is the requirement of studs for structural support which contribute to thermal bridging (Elrayies 2017).

In the hot-humid climate of Egypt, externally insulating with 100mm of polyurethane foam was determined as the best suitable insulation with the lowest too hot/cold discomfort (Elrayies 2017). This yielded U-values of $0.23 W \cdot m^{-2} \cdot K^{-1}$ for the relevant envelope components. This climate also required a green roof, insulated floors and external shading for habitation. In the subtropical climate of Australia a typical green roof construction may consist of a waterproofing membrane, drainage, fabric filter, a growing medium, and plants placed on the existing roof construction (Anwar et al. 2020).

Externally insulating with VIPs is also possible and was done in Italy with 3 types of wall coatings (Schiavoni et al. 2016). The wall and ceiling construction from inside to outside consisted of 15mm OSB, a layer of polyurethane foam, 1.8mm steel container element, another layer of polyurethane foam, 50mm of VIP and an outer cladding, where plywood is preferred. The steel element was surrounded in polyurethane foam to mitigate thermal bridging. VIPs were chosen as the insulating material due to their high thermal resistance in order to attain passive house requirements. This construction achieved U-values of $0.085 W \cdot m^{-2} \cdot K^{-1}$ for wall and ceiling which are much lower than those of common residential houses. A similar construction was used for the floor, consisting of 3mm epoxy resin, 1.8mm steel, 30mm plywood, 50mm VIP, and 30mm outer wood cladding to achieve a U-value of $0.099 W \cdot m^{-2} \cdot K^{-1}$. The one drawback noted was that VIP and polyurethane constructions are not good at sound insulation.

Using VIPs to insulate internally has helped reduce winter heat loads by 40% in Shanghai and performed great against thermal bridges (Kristiansen et al. 2020). The chosen construction for wall and roof consisted of 2mm outer steel, 50mm mineral wool, 8mm VIP and 3mm Bamboo yielding a U-value of $0.26 W \cdot m^{-2} \cdot K^{-1}$. Figure 10 shows the wall cross section of this construction. The U-value could be reduced further to below $0.1 W \cdot m^{-2} \cdot K^{-1}$ by tripling the VIP layer to 24mm. The same constructions were discussed to achieve low energy requirements in other regions of China (Satola et al. 2020), whilst stating the concern that VIPs are expensive and fragile in design. In Canada, a slight variation of this construction was employed by removing the mineral wool and instead placing the VIP insulation between two 12.5mm rigid polyurethane foam boards to achieve a U-value of $0.105 W \cdot m^{-2} \cdot K^{-1}$ (Bowley and Mukhopadhyaya 2019). This was done to reduce thermal bridges, which are the key to energy-efficient and passive house buildings in colder climates.

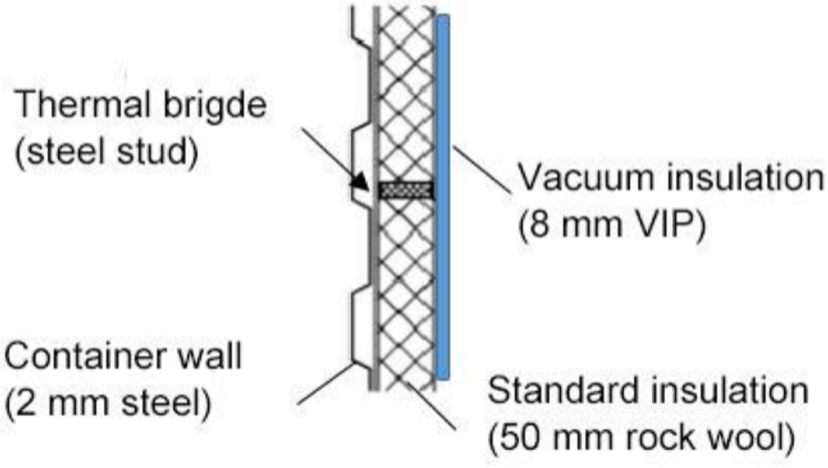


Figure 10: Wall cross section (Kristiansen et al. 2020)

1.3.7 Construction Assumptions

In order to make cost and effort estimates of different construction approaches, one must review the common construction processes of SCs summarized below. Dependant on the amount of prefabrication expertise, building process steps like installing windows & insulation can advantageously occur earlier and off-site. The transformation time and cost for converting an SC into a habitable container relies heavily on the size of the project and chosen modifications. Industrial scale has a mass production advantage, but only offers limited modifications. On the other hand, expensive and small scale custom work for specific scenarios can yield better long term performance. Material choices also significantly impact cost and effort.

I **Permitting & prerequisites**: Completing the necessary construction documentation and submitting them to a building authority for permitting. Submitting the documentation to a construction company and required sub-contractors for pricing and engineering of the container modules. Place purchase order.

II **Building process**: Begin site work including excavation for foundation, utilities, storm water management etc. Construct suitable foundation for the site.

  i *Container modifications* - No matter the type of modification to be used, it is always recommended to consult a architect or a structural engineer. Steel welding, cutting, and framing are the main parts of SC construction which should be prefabricated off-site prior to setting the containers or starting interior fitting.

ii *Install windows and doors* - Set windows and doors into the pre-cut openings framed by steel sections. This process can be done on or off site.

iii *Install interior framing, insulation, heating, plumbing, and electrical fixtures* - Construct the envelope components with chosen insulation and wood framing. Run metal hat channels along the walls and vertical beams for wiring and further installations. This process can be done on or off site.

iv *Securing containers to the foundation and one another* - Upon arrival on site the SCs are crane-lifted onto the foundation one by one, hooked in place and welded to steel plates embedded within the foundation. The inherent corner locking mechanism of SCs is enough to structurally support small to medium developments, for larger structures additional steel framing is recommended.

III **Finalization & inspection**: Inspect foundation, plumbing, electrical, architectural, and fire regulations throughout build with contractor & building official. Create final defects check list for contractor. Final inspection with a building official to certify occupancy.

1.3.8 Reference Projects

To illustrate the extensive possibilities of using SCs for construction, a set of exemplary projects across the world have been collected. Figure 11 shows a project in Germany where 68 modified SCs were placed inside an old swine market hall to completely redesign its purpose towards that of a creative quarter. Figure 12 showcases the expertise that companies such as ELA container have acquired over the years, creating a floating info center that also acts as advertisement. Figure 13 highlights the climate versatility of SC constructions whilst Figure 14 shows their applicability for developing nations. Finally, Figure 15 shows how SCs can even be utilized in dense city scapes and combined with other construction elements to create industrial/modern architecture.

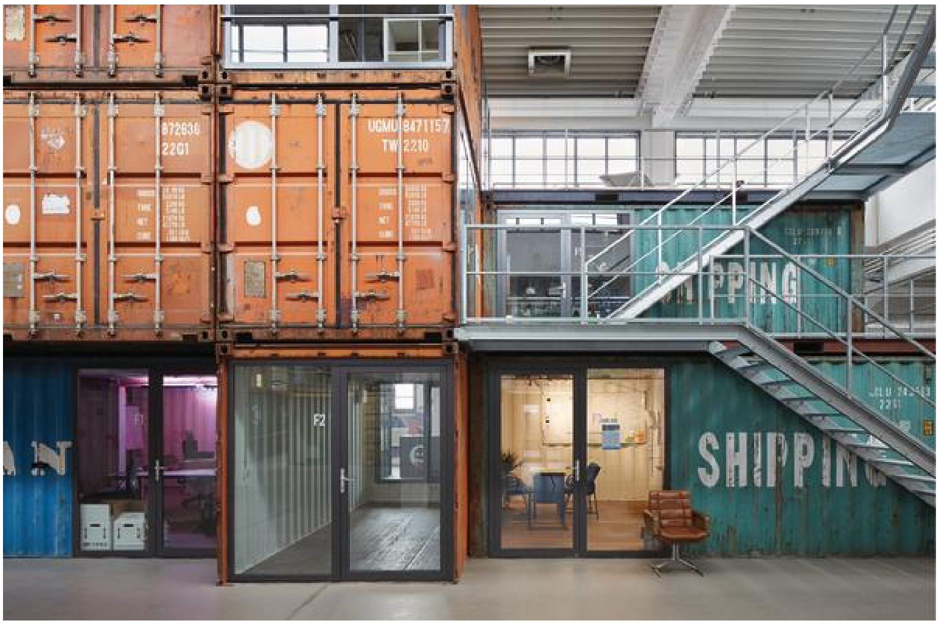


Figure 11: ‘Gründerzentrum’ in Karlsruhe, Germany. 68 modified end of life SCs within the old market hall offer affordable space for arts, design, theatre, literature, and journalism. (Deutsche Bauzeitung 2014)

Figure 12: Offices on water in Groningen, the Netherlands. 32 modified SCs with wood cladding, a 140 panel PV system, and mobile design by ELA container. (Deutsche Bauzeitung 2017)

Figure 13: Quadrum Ski Hotel in Gudariu, Georgia. Constructed in 2017 at 2200m above sea level. (Berbesz and Szefer 2018)

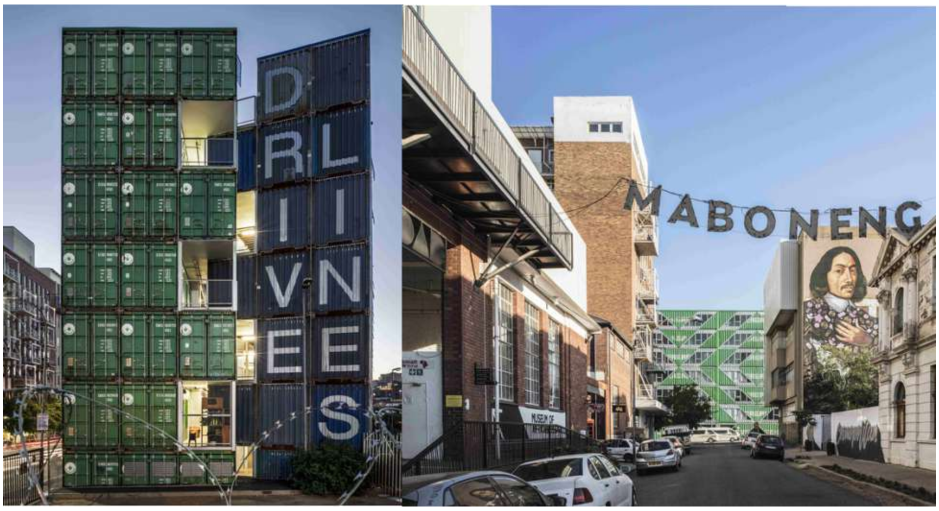


Figure 14: 'Driveless Studios' in Johannesburg, South Africa. A multifamily development constructed in 2017 with 140 SCs to create 100 studios 40-60m^2 each by Lot-ek. (Wiegel 2019)

Figure 15: Office & residential building in Barcelona, Spain. Constructed from 48 modified SCs in the narrow, uneven and historic gothic quarter of the city. (Zettel 2020)

2 Methodology

2.1 Overview

The research began with an extensive study of the published literature related to SC constructions throughout the world. A specific focus was given to sources which showed existing envelope and detail constructions of walls, floors, and roofs as well as the connections to other containers in reference to their thermal performance. Further research was carried out on the sustainability of SC based buildings and the backdrop of world trends such as population projections and climate change. Most material used was published within the last 5 years in respected scientific journals, presented at conferences, or reported by trusted institutions. This is partially because the field is still relatively fresh and the data has not yet made its way into hardcover format, but also due to some topics in the field such as life cycle analysis still remaining in healthy discussion without true consensus.

The research yielded enough information for a preliminary analysis to be carried out, evaluating which SC envelope and detail constructions should be subjected to further analysis. Three types of interior and exterior insulation constructions were chosen, based on their ease of construction, financial viability, sustainability, frequency of deployment, fire safety, as well as stated thermal performance. Confined within these were enough options to create solutions for greatly varying climates. The ideas emergent from the literature were slightly modified to create base case envelope components and detail constructions for analysis which were iteratively improved upon. The general work flow consisted of construction selection, model generation, performance evaluation, an iterative feedback loop to model optimization, and creation of a final construction design.

The optimization process after the first thermal performance evaluations allowed for further improvements such as adjusting the thickness or application areas of insulation to be undertaken in an iterative manner. New U-value calculations and numeric thermal bridge simulations were performed until all envelope components and detail constructions satisfied the given climate conditions. Throughout this iterative improvement phase the research questions were evaluated. After thorough optimization, the final results were presented in BIM format for the viable envelope components and detail constructions, distinguished by their differing locations in the construction and insulation approaches. Their relative thermal performances were compared, but also their construction complexity and efficiency discussed.

2.2 Detail Evaluation

The chosen SC envelope components and detail constructions were evaluated primarily based on numerical thermal bridge simulations. These were created using AnTherm software (Kornicki Dienstleistungen in EDV und IT 2021) to solve the complex differentials governing the heat flows and temperature distributions in a 3D environment. The main outputs are 3D false color images showing the surface temperatures, temperature distributions and heat flows inside and across the constructions. Additionally, key performance indicators, such as the temperature factor (f_{Rsi}) and minimum interior surface temperature can be obtained from the simulation efforts. These are used to assess the thermal bridging and condensation behavior of the given detail constructions and guide iterative improvement efforts. To represent different climates within the simulations, varying outer temperature boundaries are applied ranging from zero to minus twenty degrees Celsius. As a secondary evaluation metric, U-value calculations of the different detail constructions have been carried out utilizing a spreadsheet-based tool (Mahdavi and Pont 2013).

2.2.1 AnTherm

According to antherm.at (Ant 2021) “AnTherm (Analysis of Thermal behavior of Building Constructions with Heat Bridges) is a powerful program used for heat flow calculation in building construction elements - the thermal heat bridges and vapor bridges.” It can reliably calculate the temperature, heat flows and vapor diffusion streams within arbitrary detail constructions whilst meeting the qualifications of current standards for evaluating thermal performance. AnTherm conforms to all respective criteria specified within “Thermal bridges in building construction — Heat flows and surface temperatures — Detailed calculations” (ISO 10211:2017) and “Thermal performance of windows, doors and shutters — Calculation of thermal transmittance — Part 2: Numerical method for frames” (ISO 10077-2:2017). It thus qualifies as a “two- and three-dimensional steady-state high precision method” as well as a “standard method for calculation of heat flow through frames of windows, doors and shutters.”

2.2.2 Input Settings

Thermal conductivity of materials

Thermal conductivity is a material property that describes the flow of heat through a material due to the heat transport mechanism of thermal conduction. The thermal conductivity of the materials used within the respective building detail construction is thereby a definite requirement to preform numerical thermal bridge simulations for simple, stationary calculations of heat flux and temperature distributions. The thermal conductivity values used throughout the simulations are shown in Table 2. These are based on empirical values and corresponding normative documents (ie. ÖNORM B 8110-7:2013, ÖNORM B 8110-8:2017, and DIN 4108-4:2020), but may vary depending on the manufacturer. It should be noted that thermal conductivity is strongly dependent on the moisture penetration of a material, as water has higher thermal conductivity and thereby ruins the insulation behaviour of the construction. Immoderate surface condensation would also yield higher thermal conductivities and should be avoided. Throughout the simulations a dry condition in which no excessive moisture content occurs was assumed.

Table 2: Material thermal conductivity according to normative documents and literature (Bowley and Mukhopadhyaya 2019, Elrayies 2017, Schiavoni et al. 2016, Shen and Zhang 2019)

Material	Thermal conductivity ($Wm^{-1}K^{-1}$)
CorTEN steel	42.7
Wood framing	0.12
Wood rainscreen	0.15
Gypsum board	0.18
Fireline board	0.24
Epoxy on plywood	0.14
Mineral Wool	0.035
Polyurethane foam	0.025
VIP	0.008

Climate conditions

For all climates the indoor air conditions were assumed to be 20°C, in accordance with ÖNORM B 8110-2:2020. This standard sets the outdoor air conditions to be used for the condensation analysis as the differing monthly mean temperatures for opaque building components or building components with a corresponding storage mass. Alternatively the standard suggests using the average daily lows instead of the monthly mean for building components with low storage efficiency. This work assumes the outdoor climate to be generic and therefore represents different climates within the simulations by applying respective outdoor air conditions of 0, -10, and -20°C. These are extreme values that constructions must endure to adequately perform in all climates presented in the Köppen climate classification (Beck et al. 2018).

Heat transfer resistances at detail surfaces

Convective-radiative heat transport takes place at the transitions from opaque materials to air spaces. To include this heat transport behaviour in U-value calculations or thermal bridge simulations, which are primarily based on thermal conduction, heat transfer resistances (R_s) are given as approximations of the effects in many normative documents. The calculations within this thesis are based on the conventional heat transfer resistances according to ISO 6946:2017 as shown in Table 3 below. Heat transfer resistance values are also mentioned in other standards such as DIN 4108-2:2013 which recommends that an R_{si} of 0.25 m^2KW^{-1} should be used within areas of thermal bridging.

Table 3: Conventional heat transfer resistances (ISO 6946:2017)

Heat transfer resistance (m^2KW^{-1})	Direction of heat flow		
	up	horizontal	down
R_{si}	0.1	0.13	0.17
R_{se}	0.04	0.04	0.04

Grid determination

For the numerical calculation in AnTherm the element structure of the construction model must be resolved into a grid. The smallest cell size of the grid has to be specified for this purpose such that the grid may be divided in a manner with corresponds to the construction under study. For subdivision of the grid, a reproducible and well-defined method should be used. The corrugated steel panel with a thickness of 1.8mm is the determining factor for the smallest cell size of the grid.

2.2.3 Key Performance Indicators

In addition to other outputs of the thermal bridge simulations, such as false color images and temperature distributions of the simulated constructions, the following three indicators are explicitly considered and used as evaluation criterion:

Temperature Factor

ISO 13788:2012 describes the temperature factor (f_{Rsi}) for interior surfaces as the difference between the interior surface and the exterior air temperatures, divided by the difference between the interior air and the exterior air temperatures. The formula for this is presented below. Here f_{Rsi} denotes the temperature factor for the interior surface (dimensionless between 0 and

1), $\theta_{si,min}$ the minimum interior surface temperature (°C), θ_e the exterior air temperature (°C), and θ_i the interior air temperature (°C). For the purpose of this thesis, the critical threshold for f_{Rsi} values of construction variants to exceed in order to prevent mold growth, according to ÖNORM B 8110-2:2020, is **0.71**. Additionally it is recommendable that the f_{Rsi} values are greater than 0.88 to avoid material-specific corrosion processes.

$$f_{Rsi} = \frac{\theta_{si,min} - \theta_e}{\theta_i - \theta_e} \tag{1}$$

Minimum interior surface temperature

The temperature factor already takes into account the minimum surface temperature of the warm interior $\theta_{si,min}$. Alongside this absolute temperature value, the location is also of great importance as this point of the detail construction will be most susceptible to mold growth and condensation. These points will be highlighted by the thermal simulation and require optimization with constructive measures to prevent damage from the hygrothermal effect and alleviate the condensation risks.

Thermal transmittance of detail construction

Within the context of this thesis, thermal performance of different SC detail constructions is evaluated with the main focus on thermal bridges. However, in the broader field of building construction a coarser scale is the standard. This is evident for purposes such as the preparation of energy certificates, where the characteristic indicators from thermal bridge simulations are hardly used. Instead they rely on the heat transfer coefficient which is a frequently used performance value for envelope components and commonly known as the U-value. The U-values of homogeneous and inhomogeneous opaque constructions are calculated in accordance with ISO 6946:2017. The principal statements of ISO 6946 apply the following Formula 2 for calculating the U-value by simplified method. Herein U is the thermal transmittance in $Wm^{-2}K^{-1}$ and R_{tot} is the total thermal resistance, which is the sum of thermal resistances of the construction layers as calculated by the fraction of their thickness to thermal conductivity. The detailed calculation method of thermal transmittance is given in ISO 10211:2017. The delta between thermal transmittances of homogeneous and inhomogeneous constructions may also be used to estimate thermal bridges.

$$U = \frac{1}{R_{tot}} \tag{2}$$

3 Results

3.1 Base Cases

The starting point for SC constructions is commonly the base steel container which has been discarded from freight usage. This has no insulation or modifications of any kind and most likely shows some light wear and tear, thereby base steel containers are generally not suited for habitation. To be useful for military activities or disaster relief, all envelope components are minimally insulated with polyurethane foam. The base steel container and militarily modified constructions were modeled in AnTherm as shown in Figure 16. These are considered the base cases to be improved upon and serve as reference points for performance comparisons. The constructions are essentially the same for wall, roof, and floor just with different heat flow directions and interior finishes. The respective U-values are 6 and 1 $W \cdot m^{-2} \cdot K^{-1}$ for base steel container and military modification variant respectively.

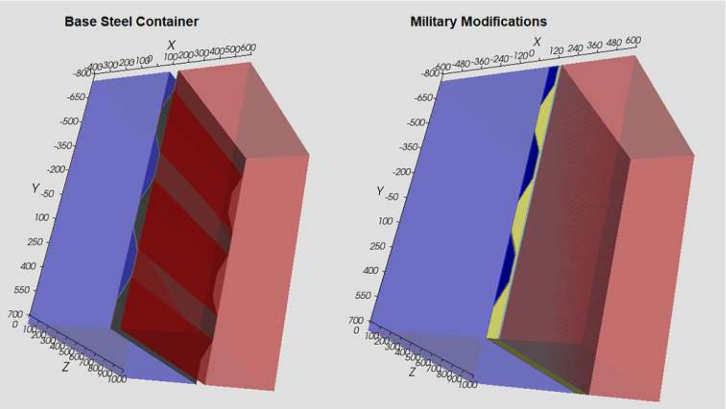


Figure 16: Base case 3D AnTherm wall construction views with spaces

These constructions were simulated according to the input settings of Section 2.2.2. The 3D temperature distributions with isolines at θ_e of -10°C are shown in Figures 17 and 18. As expected the minimum interior surface temperature of the base steel container is critically low at -3.20°C, yielding a temperature factor of only 0.23. The military modification construction does not fare much better with a minimum interior surface temperature of 6.47°C. The temperature factor of this construction is 0.55 which is also below the required threshold of 0.71. Overall, these constructions show very poor thermal performance, but provide first insights about the necessary improvements to be made.

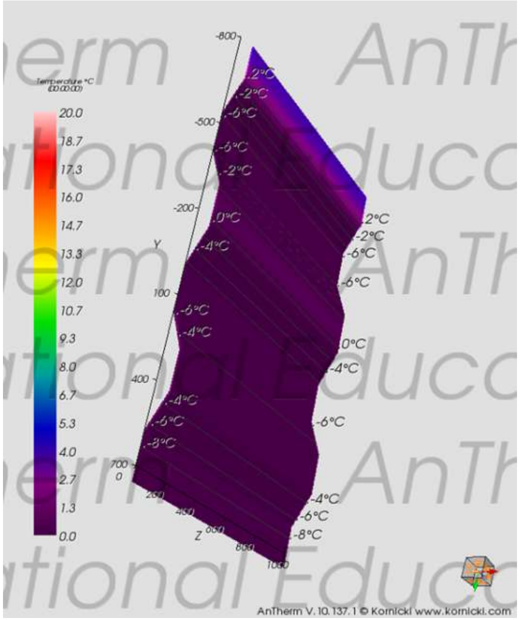


Figure 17: Base steel container wall construction 3D temperature distribution with isolines

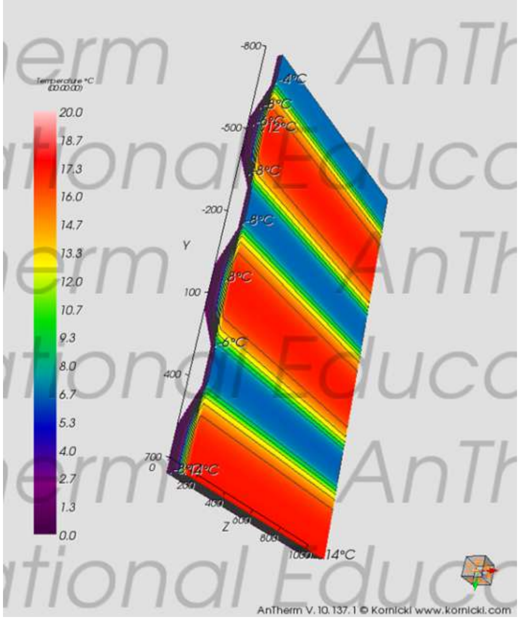


Figure 18: Military modifications wall construction 3D temperature distribution with isolines

3.2 Preliminary Evaluation

The viable wall envelope component and detail constructions inspired by literature are assembled with mineral wool, polyurethane foam, and VIPs as insulation layers. These are initially considered both as inside and outside variants as shown in Table 4 and Figure 19. Interior and exterior finishes are simple gypsum or fireline boards and wooden rainscreens or corrugated steel panels respectively. The framing for the insulation layers are made of light wood as they are non-load-bearing and connected to the steel panel and finish with metal studs. The constructions using VIPs are slightly thinner than the others since this material has incredibly low thermal conductivity, as is evident by the lowest thermal transmittances. The EXT 3 variant performs best in terms of thermal transmittance, it is however the most complex construction presented here, already utilizing a mixture of insulators. The more affordable variants utilizing mineral wool and polyurethane as insulators also perform reasonably well, even the abundant mineral wool constructions showcase a thermal transmittance below 0.4 $Wm^{-2}K^{-1}$. Considering habitable space implications, the internally insulated constructions, pose a slight disadvantage as they occupy more interior space. This is in the range of 5-10cm thickness per envelope component, which sums to almost 3 square meters given a single 40ft container where all walls are modified as such.

Table 4: Initial wall constructions and thermal transmittance

Type	Wall Construction	U-Value ($Wm^{-2}K^{-1}$)
Wall Int 1	2 layers 12.5mm fireline board, 9mm plywood, 80mm mineral wool with wood framing, 1.8mm corrugated steel panel	0.38
Wall Int 2	25mm gypsum board, 80mm polyurethane spray foam with wood framing, 1.8mm corrugated steel panel	0.34
Wall Int 3	25mm gypsum board, 50mm VIP with wood framing, 1.8mm corrugated steel panel	0.28
Wall Ext 1	25mm gypsum board with metal studs, 1.8mm corrugated steel panel, 80mm mineral wool with wood framing, 30mm wood rainscreen	0.36
Wall Ext 2	25mm gypsum board with metal studs, 1.8mm corrugated steel panel, 80mm polyurethane spray foam with wood framing, 30mm wood rainscreen	0.32
Wall Ext 3	25mm gypsum board with metal studs, 1.8mm corrugated steel panel with 20mm polyurethane spray foam, 40mm VIP with wood framing, 30mm wood rainscreen	0.25

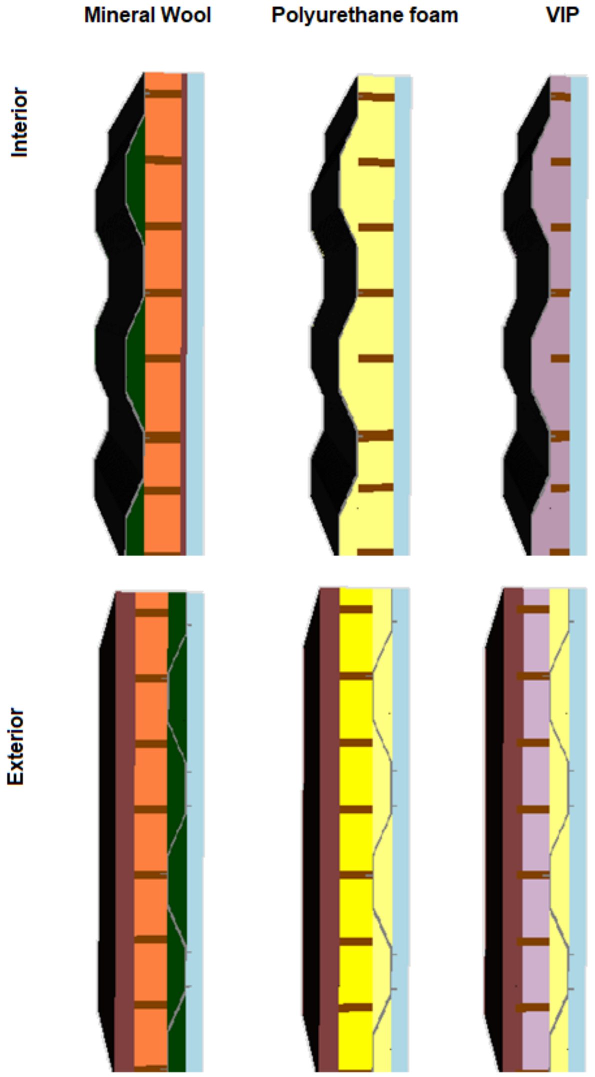


Figure 19: 3D AnTherm wall construction views according to Table 4

The results of the AnTherm wall construction simulations regarding the temperature factor and minimum surface temperature are shown in Table 5. The 3D temperature distributions with isolines at θ_e of $-10°C$ are shown in Figures 20 to 22. All constructions satisfy the condition of having a temperature factor above 0.71. The INT 3 (VIP) variant showcases the lowest minimum surface temperatures and thereby also the lowest temperature factor. Its thin construction of steel, wood, and gypsum at the internally corrugated panel creates a thermal bridge along it. The pattern is distinctly visible in the internally insulated variant with VIPs, but also present to a smaller extent in the other constructions. The minimum surface temperatures of all constructions is located across the internally corrugated panel where metal studs are utilized, creating the pattern of uneven temperature distributions along the gypsum surfaces. This is least pronounced in the constructions with polyurethane foam, particularly EXT 3 which utilizes both VIP and polyurethane foam as insulation, yielding it the best performance. The EXT 1 construction with mineral wool performed below expectation compared to its INT 1 counterpart.

Table 5: Initial AnTherm Results

Type	Temperature factor f_{Rsi}	Minimum Surface Temperature at θ_e 0°C	-10°C	-20°C
Wall Int 1	0.92	18.34	17.51	16.68
Wall Int 2	0.92	18.38	17.57	16.76
Wall Int 3	0.89	17.88	16.82	15.77
Wall Ext 1	0.90	17.97	16.96	15.95
Wall Ext 2	0.91	18.17	17.25	16.33
Wall Ext 3	0.93	18.53	17.80	17.07

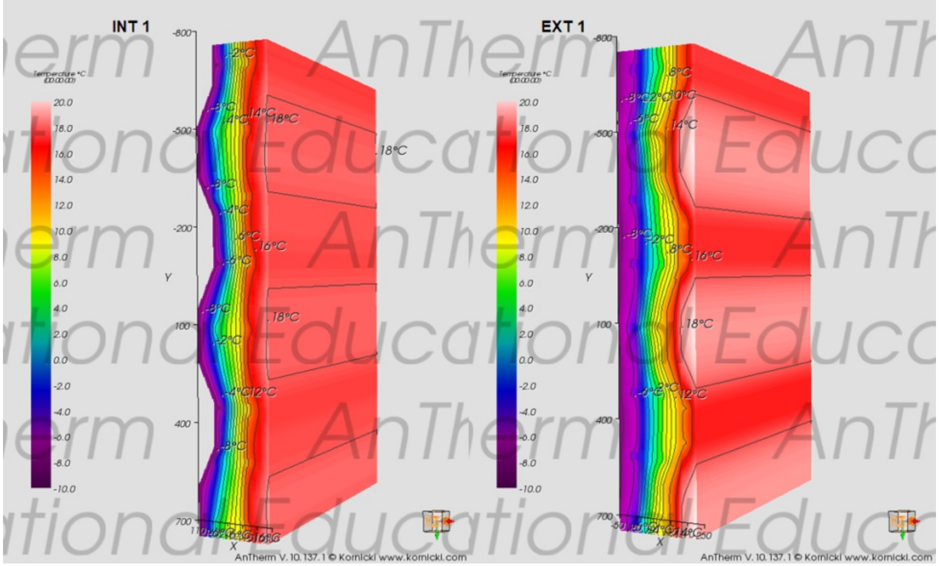


Figure 20: Mineral wool wall construction 3D temperature distributions with isolines

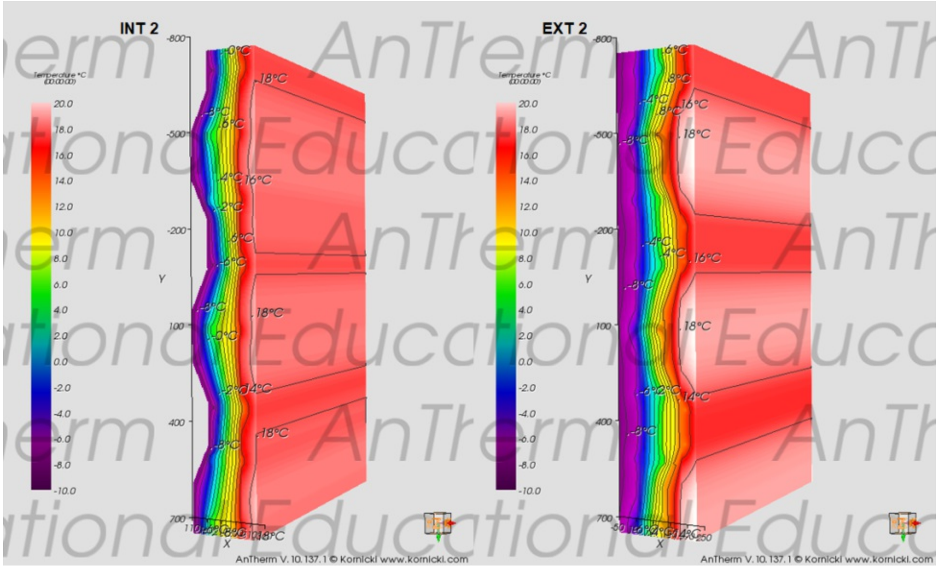


Figure 21: Polyurethane foam wall construction 3D temperature distributions with isolines

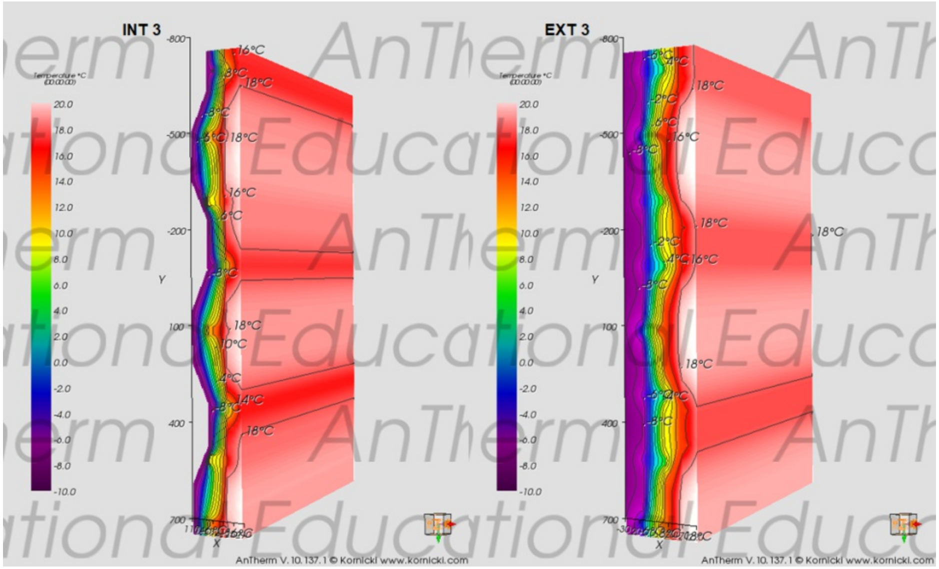


Figure 22: VIP wall construction 3D temperature distributions with isolines

3.3 Wall Constructions

The first iterative improvement to take place is the use of a broader mixture of the insulation materials. This is particularly true for polyurethane foam which is now present in all but one of the constructions shown in Table 6 and Figure 23. For interior constructions it is the last layer before the outer corrugated steel panel and for exterior variants it is wrapped around both sides of the panel. Another improvement to occur for all constructions is the switch from metal to wooden studs to create pure timber framing environments with all load being carried by the steel panel. Overall these improvements yielded about a 10% decrease in the constructions' thermal transmittance, compared to their previous iterations of Table 4, at the cost of slightly increased construction complexity. The INT 6 construction does not utilize polyurethane foam like the INT 5 construction, but instead thicker mineral wool and thinner VIP to make it more affordable.

Table 6: Improved wall constructions and thermal transmittance

Type	Wall Construction	U-Value ($Wm^{-2}K^{-1}$)
Wall Int 4	2 layers 12.5mm fireline board, 9mm plywood, 50mm mineral wool with wood framing, 25mm polyurethane spray foam, 1.8mm corrugated steel panel	0.35
Wall Int 5	25mm gypsum board, 40mm VIP with wood framing, 25mm polyurethane spray foam, 1.8mm corrugated steel panel	0.25
Wall Int 6	25mm gypsum board, 20mm VIP, 50mm mineral wool with wood framing, 1.8mm corrugated steel panel	0.27
Wall Ext 4	25mm gypsum board with wood studs, 30mm polyurethane spray foam around 1.8mm corrugated steel panel, 50mm mineral wool with wood framing, 30mm wood rainscreen	0.32
Wall Ext 5	25mm gypsum board with wood studs, 30mm polyurethane spray foam around 1.8mm corrugated steel panel, 40mm VIP with wood framing, 30mm wood rainscreen	0.23

With the AnTherm models adapted according to the improvements above, another set of simulations was carried out to find the temperature factors and minimum surface temperatures as shown in Table 7. The 3D temperature distributions with isolines at θ_e of -10°C are shown in Figures 24 and 25. The temperature factors of all constructions satisfy the condition of being above 0.71, with an improved 0.90 instead of 0.89 minimum of the set when compared to Table 5. Both internally and externally insulated construction variants with polyurethane foam and VIPs perform better than the EXT 3 construction previously. They may even be suited for climates which reach -20°C extremes. The constructions with polyurethane foam and mineral wool perform marginally worse and the construction with VIPs and mineral wool

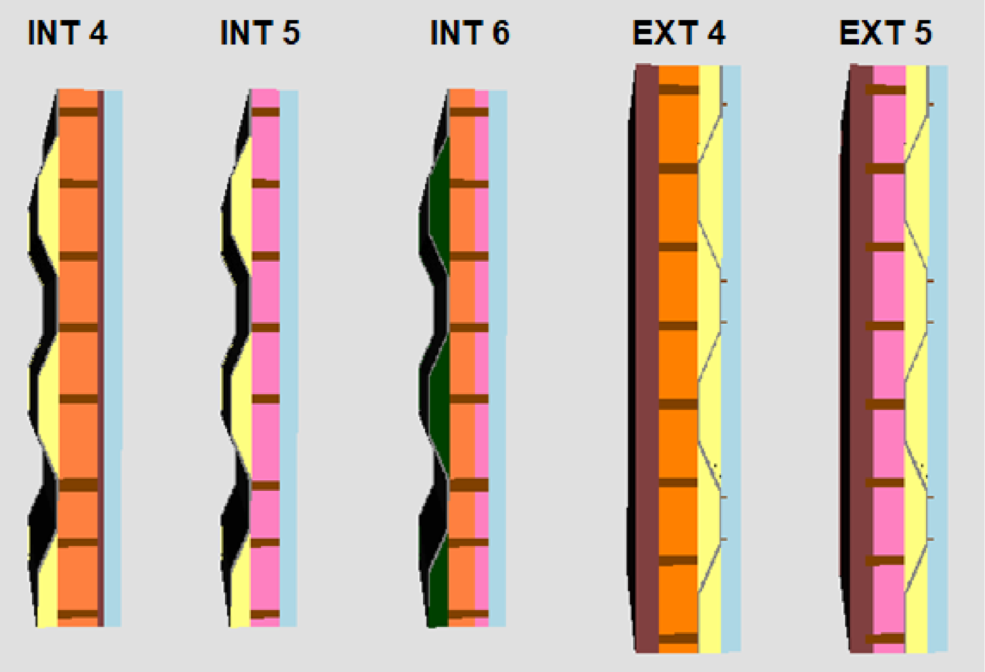


Figure 23: 3D AnTherm improved wall construction views according to Table 6

performs the poorest, but still enough to satisfy climate extremes down to -10°C. The pattern of uneven temperature distributions along the gypsum surfaces has been greatly improved for the internally insulated constructions except INT 5, but remains very visible in the externally insulated constructions. A possible way to alleviate this situation would be to place another insulation layer between the internally corrugated part of the steel panel and the interior finish.

Table 7: Improved AnTherm Results

Type	Temperature factor f_{Rsi}	Minimum Surface Temperature at θ_e 0°C	-10°C	-20°C
Wall Int 4	0.92	18.30	17.45	16.60
Wall Int 5	0.93	18.59	17.89	17.19
Wall Int 6	0.90	17.99	16.98	15.98
Wall Ext 4	0.90	18.02	17.03	16.04
Wall Ext 5	0.93	18.63	17.95	17.27

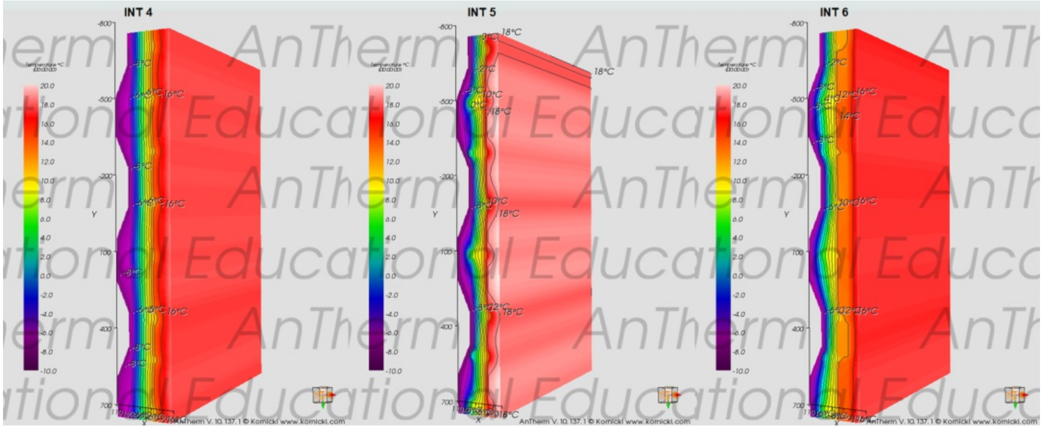


Figure 24: Improved internally insulated wall construction 3D temperature distributions with isolines

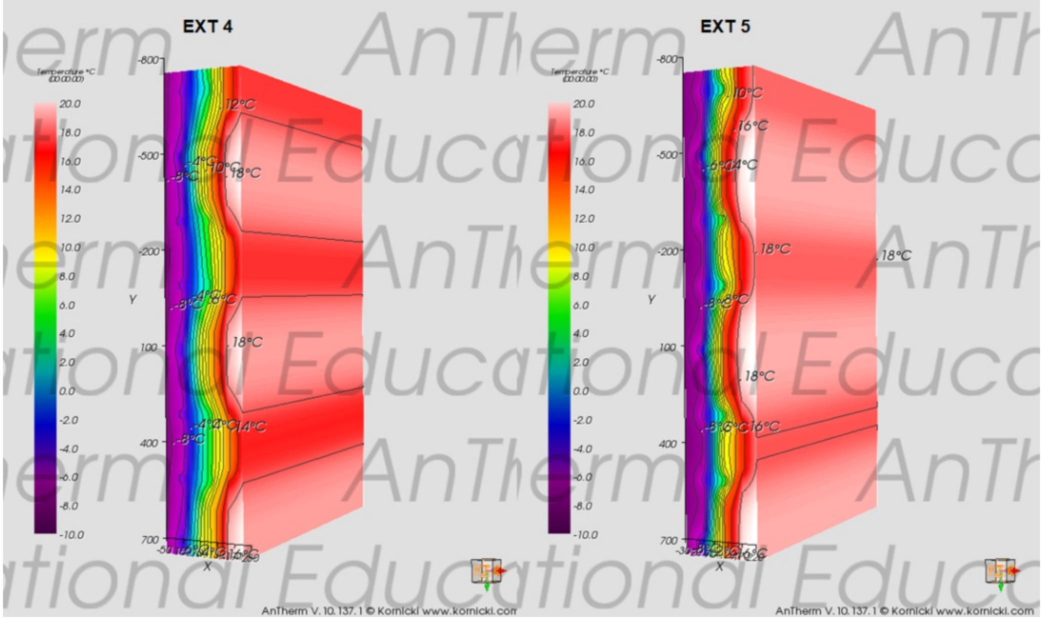


Figure 25: Improved externally insulated wall construction 3D temperature distributions with isolines

3.4 Roof and Floor Constructions

Considering the thermal perimeter of most modern constructions, the roof and ground floor only make up a small percentage of the total outer envelope component area as the largest contribution is made by the walls. Therefore roof and floor constructions are examined more simply in this section with the constructions presented in Table 8 as well as Figures 26 and 27 for roof and floor constructions respectively. The insulation approaches are the same for roof and floor construction, but have the opposite heat flows applied and different steel structures. The interior finish for the roof construction is a gypsum board while the floor has a layer of epoxy on plywood. The insulation was chosen based on the previous evaluations from which combinations of polyurethane foam and mineral wool or VIPs emerged. For the external constructions the polyurethane foam is wrapped around the steel panel. These constructions yield great variance in thermal transmittance whilst providing both affordable and high performance options.

Table 8: Roof/floor constructions and thermal transmittance

Type	Roof & Floor Construction	U-Value ($Wm^{-2}K^{-1}$)
Roof/Floor Int 1	25mm interior finish, 50mm mineral wool with wood framing, 30mm polyurethane spray foam, 1.8mm outer steel panel	0.34
Roof/Floor Int 2	25mm interior finish, 40mm VIP with wood framing, 25mm polyurethane spray foam, 1.8mm outer steel panel	0.16
Roof/Floor Ext 1	25mm interior finish, 30mm polyurethane spray foam around 1.8mm steel panel, 50mm mineral wool with wood framing, 30mm wood rainscreen	0.32
Roof/Floor Ext 2	25mm interior finish, 30mm polyurethane spray foam around 1.8mm steel panel, 40mm VIP with wood framing, 30mm wood rainscreen	0.23

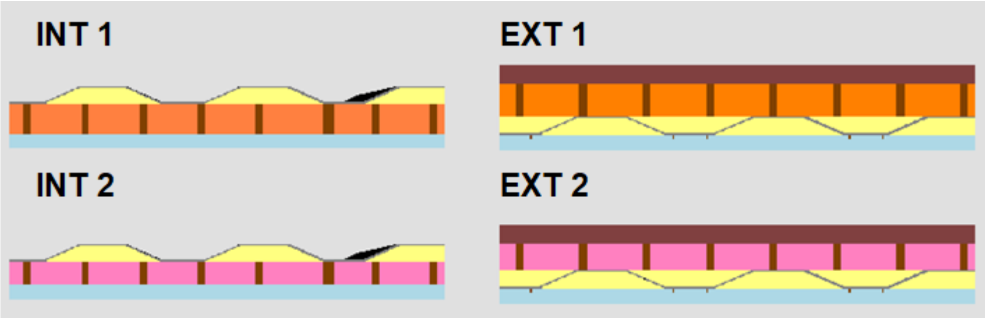


Figure 26: AnTherm roof construction views according to Table 8

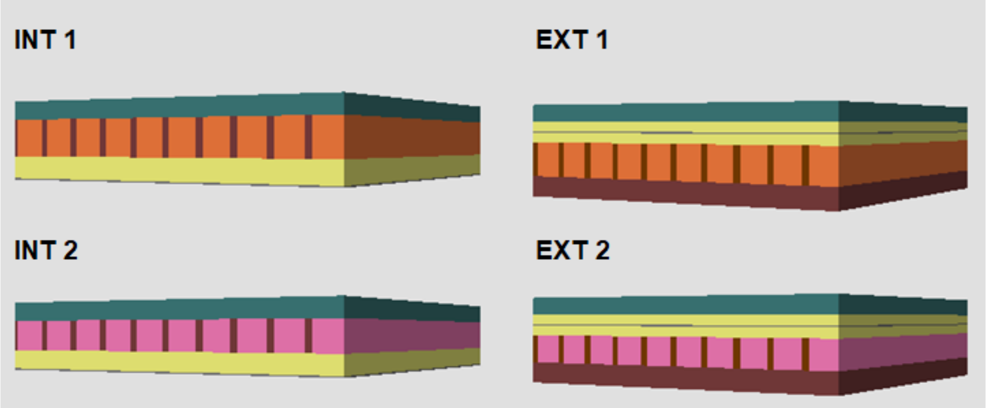


Figure 27: AnTherm floor construction views according to Table 8

The roof and floor constructions were modelled in AnTherm and their thermodynamic behaviour simulated to find the temperature factors and minimum surface temperatures as shown in Table 9. The 3D temperature distributions with isolines at θ_e of -10°C are shown in Figures 28 to 31. The roof and floor constructions are essentially mirror images of each other with different interior finishes and behave very similarly, however the floors perform significantly better in terms of temperature factor and minimum surface temperature. This stems from the difference in heat transfer resistances between upward and downward directions of heat flow (see Table 3), but also the difference in steel structures. Overall these constructions show great performance as even the lowest temperature factor is 0.90 and minimum surface temperature generally above 17 °C at θ_e of -10°C. This suggests the constructions, particularly the floors, could be viable with thinner insulation layers too. Furthermore the externally insulated variants perform marginally better than the internal variants without causing internal space implications. The temperature distributions of the roof constructions showcase the same uneven pattern of surface temperatures as for the wall constructions previously. This is not the case for the floor constructions, although might occur when including the steel cross members and ground within a more complex simulation. The INT and EXT 2 floor construction temperature distributions display the wood framing as another area of potential improvement.

Table 9: Roof and floor AnTherm Results

Type	Temperature factor	Minimum Surface Temperature at θ_e		
	f_{Rsi}	0°C	-10°C	-20°C
Roof Int 1	0.91	18.12	17.17	16.23
Floor Int 1	0.96	19.30	18.95	18.60
Roof Int 2	0.92	18.38	17.57	16.76
Floor Int 2	0.97	19.41	19.12	18.82
Roof Ext 1	0.90	18.02	17.03	16.04
Floor Ext 1	0.97	19.35	19.02	18.70
Roof Ext 2	0.93	18.63	17.94	17.25
Floor Ext 2	0.97	19.48	19.22	18.96

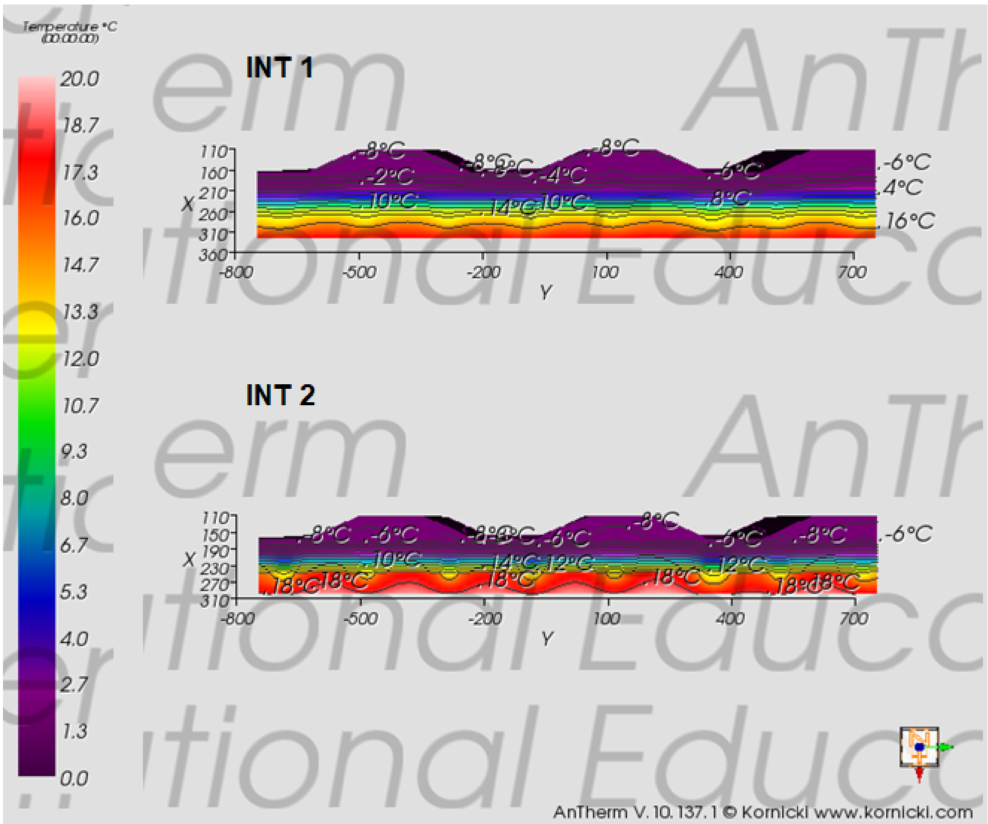


Figure 28: Internally insulated roof construction temperature distributions with isolines

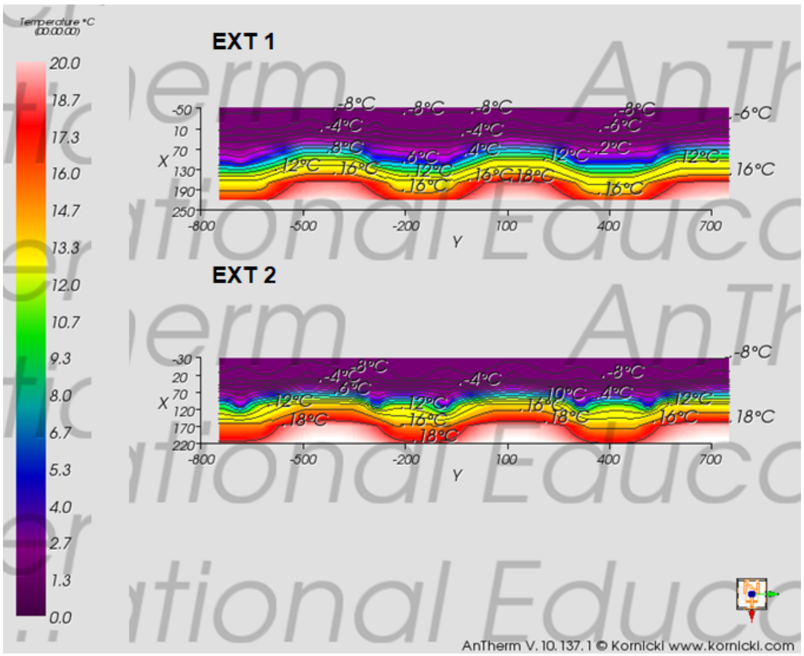


Figure 29: Externally insulated roof construction temperature distributions with isolines

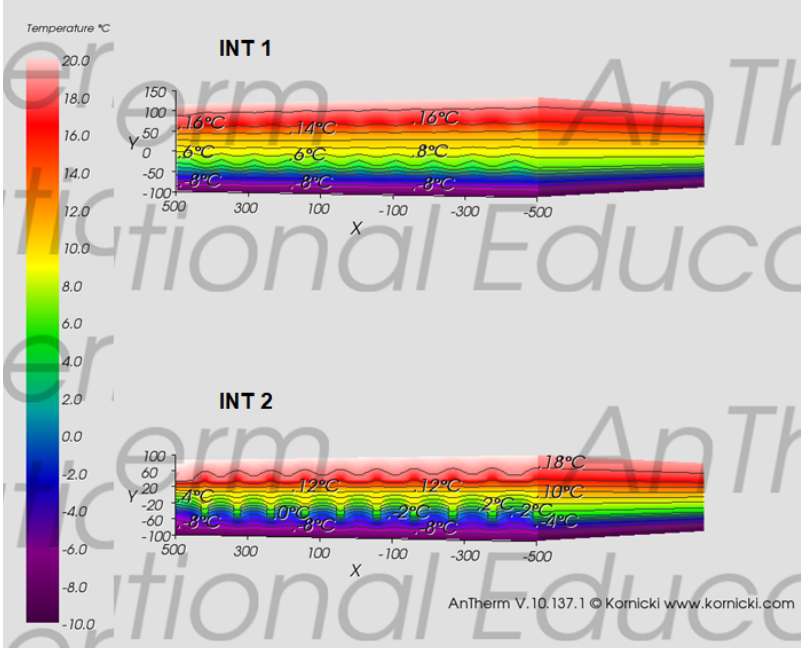


Figure 30: Internally insulated floor construction temperature distributions with isolines

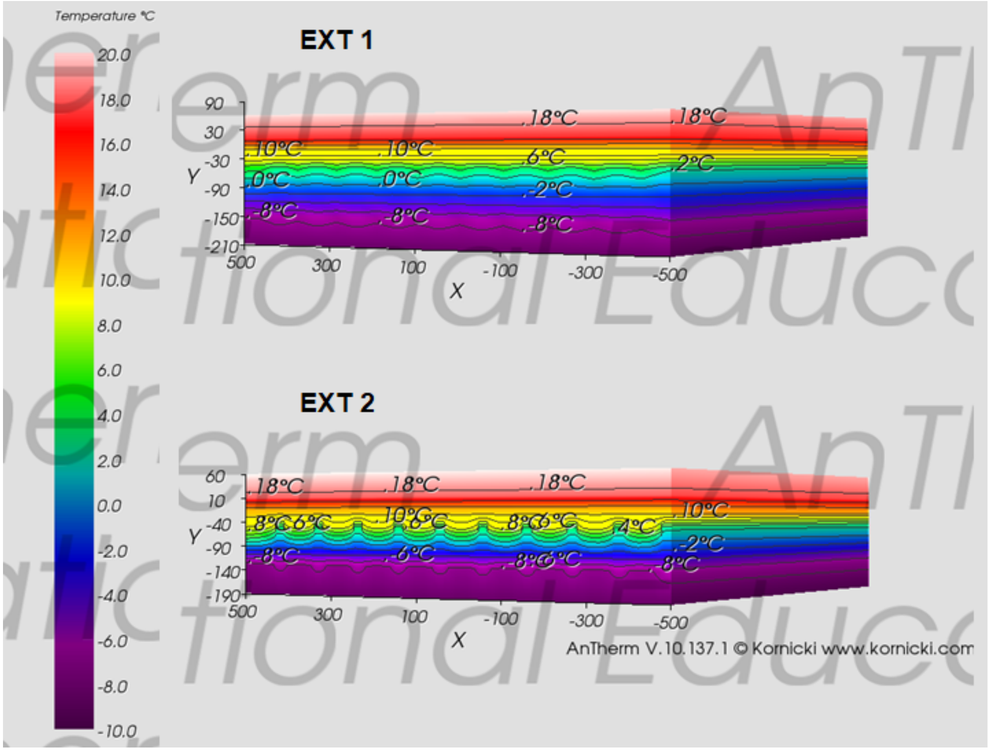


Figure 31: Externally insulated floor construction temperature distributions with isolines

3.5 Corner Constructions

Thermal bridges are most likely to occur at the corners of modified SC constructions as there is thicker steel framing and a complex geometry. Here the corrugated steel sheets of the envelope components are continuously welded to the 6mm corner posts and 4.5mm side rails of pressed steel. Therefore several wall-wall and wall-roof constructions are examined in this section as summarized in Table 6. These are largely based on the constructions presented previously in Sections 3.3 and 3.4. Wall-floor constructions were excluded due to the floor constructions' overwhelming performance previously and highest heat transfer resistance. This is also based on the assumption that if a roof with similar construction performs well, the floor would perform even better, deeming further simulation less efficient as opposed to exploring wall-roof constructions.

Optimizations compared to the previous constructions have been made by changing the design of the wood framing. The roof constructions all utilize a thinner combination of polyurethane foam and VIP insulation. As expected due to the increased amount of steel and thinner insulation, the thermal transmittance of these constructions is marginally worse than of those presented in the previous sections. This however should not have a broad effect on the average U-value of a SC construction as the ratio of effective corner area with respect to the overall outside envelope area is generally negligible. The thermal transmittance of the constructions presented here is therefore only specific to the vicinity of the corner and only partially representative for the envelope components involved.

Table 10: Corner constructions and thermal transmittance

Type	Corner Construction	U-Value ($Wm^{-2}K^{-1}$)
Wall-Wall Int 1	20mm fireline board, 9mm plywood, 50mm mineral wool with wood framing, 25mm polyurethane foam, 6mm pressed steel	0.37
Wall-Wall Int 2	20mm gypsum board, 40mm VIP with wood framing, 25mm polyurethane foam, 6mm pressed steel	0.26
Wall-Wall Ext 1	20mm gypsum board with wood studs, 30mm polyurethane foam, 6mm pressed steel, 50mm mineral wool with wood framing, 25mm wood rainscreen	0.33
Wall-Wall Ext 2	20mm gypsum board with wood studs, 30mm polyurethane foam, 6mm pressed steel, 40mm VIP with wood framing, 25mm wood rainscreen	0.24
Wall-Roof Int	20mm gypsum board, 30mm VIP with wood framing, 25mm polyurethane foam, 4.5mm pressed steel	0.21
Wall-Roof Ext	20mm gypsum board, 30mm polyurethane foam around 4.5mm pressed steel, 30mm VIP with wood framing, 25mm wood rainscreen	0.27

The wall-wall corner construction models in AnTherm are shown in Figure 32. These were simulated to find the temperature factors and minimum surface temperatures as presented in Table 11. The 3D temperature distributions with isolines at θ_e of -10°C are shown in Figure 33. The internally insulated corner variants perform slightly worse than their individual wall components, but well within acceptable limits given the increased amount of steel of the corner posts. The externally insulated variants however, perform below the requirements set for the temperature factor of 0.71 and yield minimum surface temperatures far below satisfactory levels. These are to be additionally improved by moving the internal corner point further from the corner post.

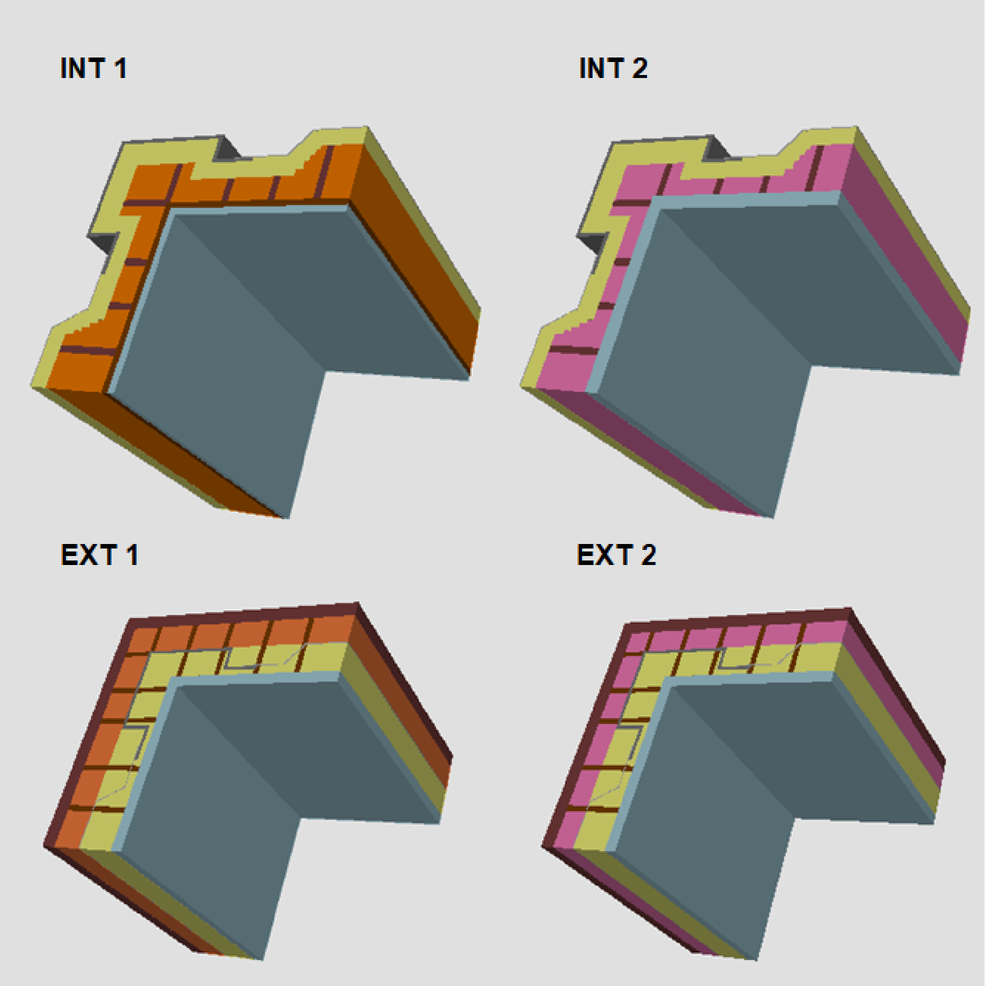


Figure 32: 3D AnTherm wall-wall corner construction views according to Table 10

Table 11: Wall-Wall AnTherm Results

Type	Temperature factor f_{Rsi}	Minimum Surface Temperature at θ_e 0°C	-10°C	-20°C
Wall-Wall Int 1	0.88	17.54	16.30	15.07
Wall-Wall Int 2	0.91	18.12	17.18	16.24
Wall-Wall Ext 1	0.64	12.81	9.22	5.63
Wall-Wall Ext 2	0.67	13.32	9.98	6.64

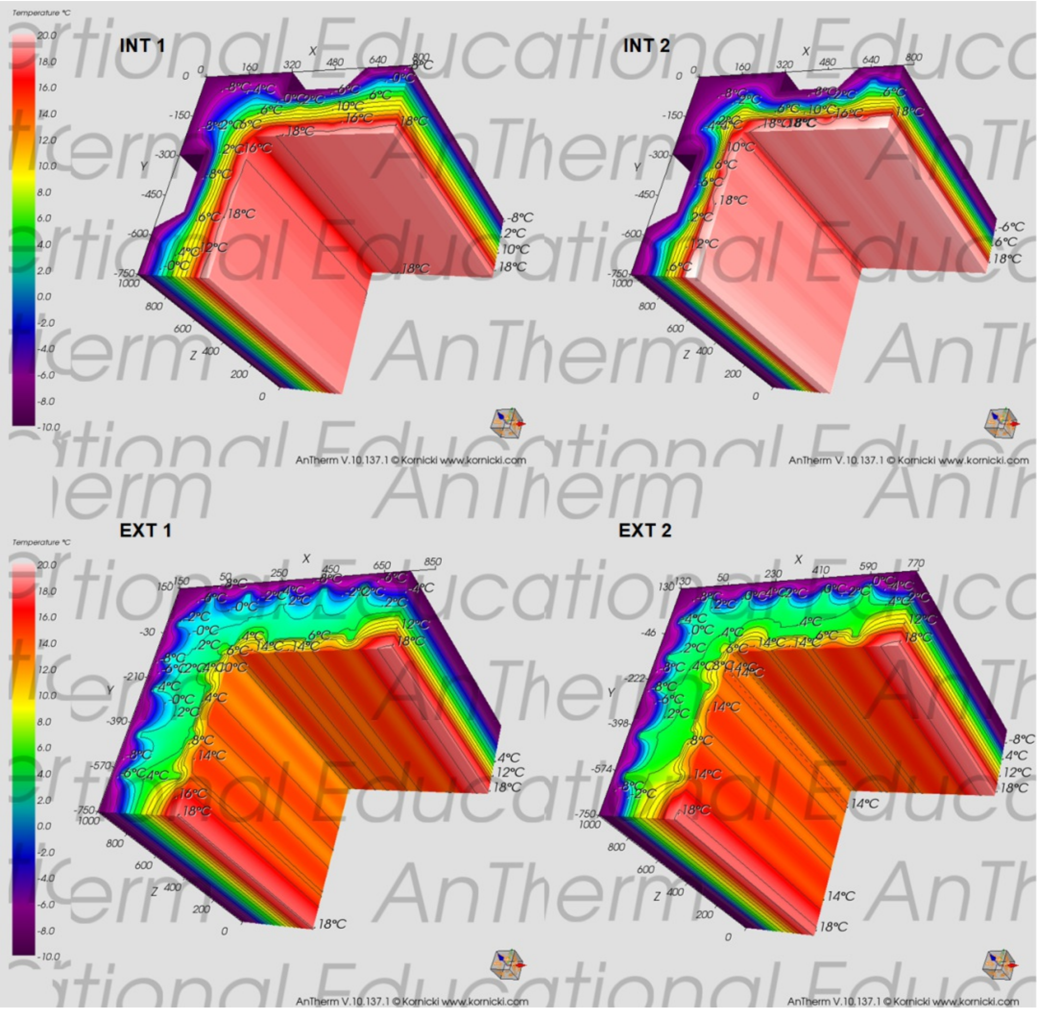


Figure 33: Wall-wall corner construction 3D temperature distributions with isolines

The improved externally insulated wall-wall corner construction 3D views in AnTherm are shown in Figure 34 and the simulated temperature distributions with isolines at θ_e of -10°C in Figure 35. The construction change of bringing the corner inward increased the complexity of the construction slightly whilst greatly improving the temperature factors to 0.71 and 0.73 for mineral wool and VIP constructions respectively. This also improves the minimum internal surface temperatures to a modest 11-12°C range given θ_e of -10°C.

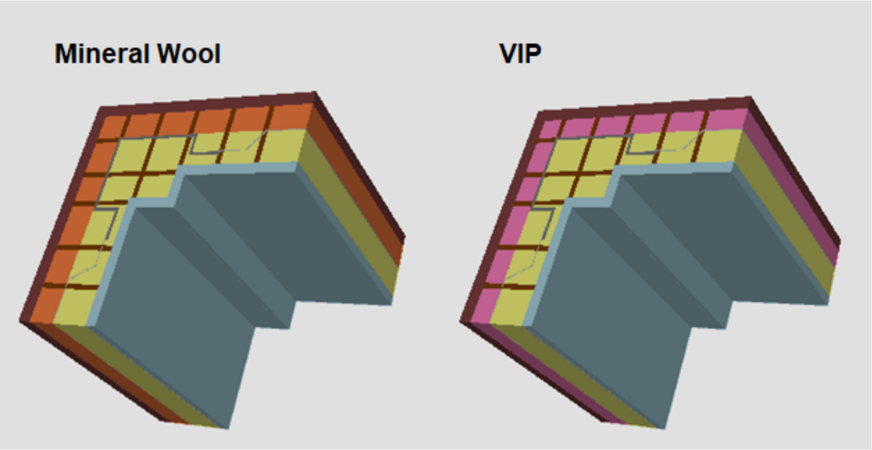


Figure 34: 3D AnTherm improved externally insulated wall-wall corner construction views

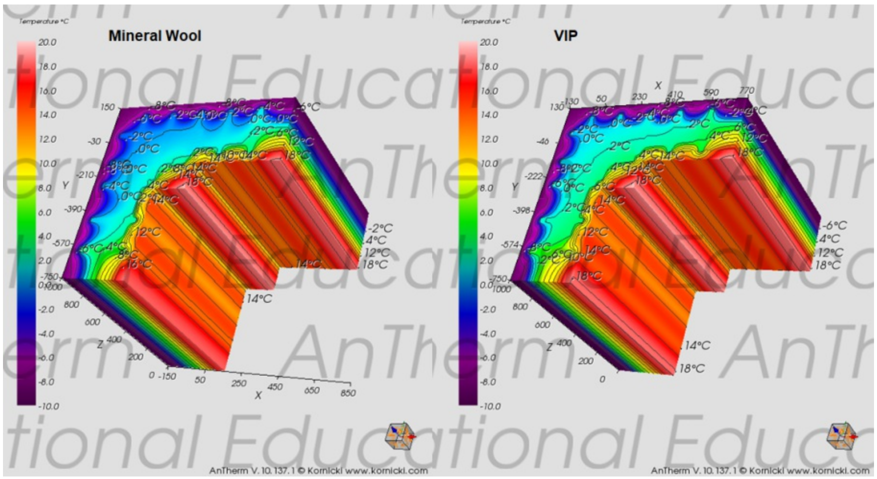


Figure 35: Improved externally insulated wall-wall corner construction 3D temperature distributions with isolines

The wall-roof corner construction models in AnTherm are shown in Figure 36. The simulation results for the temperature factors and minimum surface temperatures are presented in Table 12. Different views of the 3D temperature distributions with isolines at θ_e of -10°C are shown in Figures 37 and 38. As seen with the wall-wall constructions, the wall-roof constructions also perform slightly worse than their individual envelope components in terms of temperature factor and minimum surface temperature. These indicators are however well above the requirements and the introduction of the side rail to the construction has had less impact than the corner post for wall-wall constructions. To further improve the thermal performance of the wall-roof INT construction for colder climates, the insulation would have to be thicker at the cost of valuable internal ceiling height.

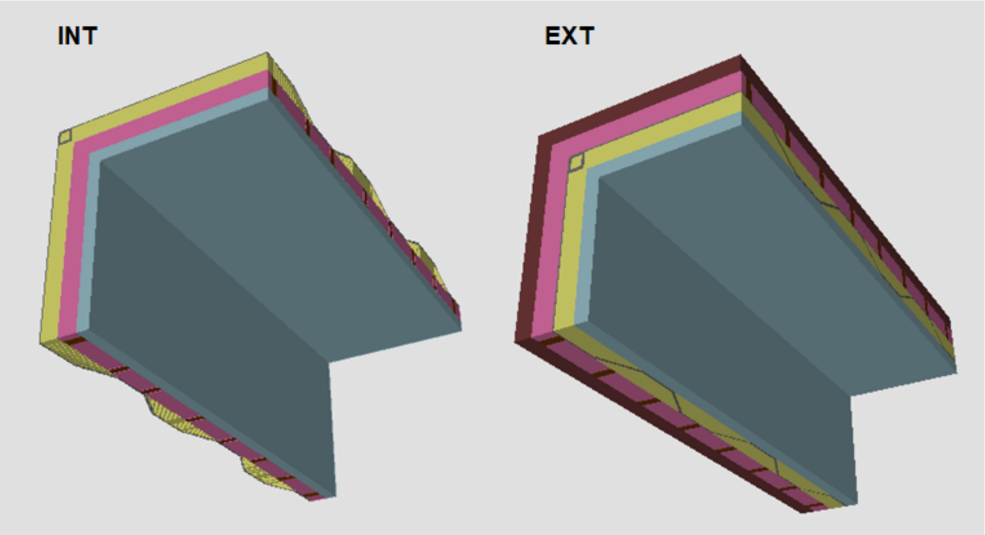


Figure 36: 3D AnTherm wall-roof corner construction views according to Table 10

Table 12: Wall-Roof AnTherm Results

Type	Temperature factor f_{Rsi}	Minimum Surface Temperature at θ_e 0°C	-10°C	-20°C
Wall-Roof Int	0.81	16.22	14.34	12.45
Wall-Roof Ext	0.86	17.11	15.67	14.22

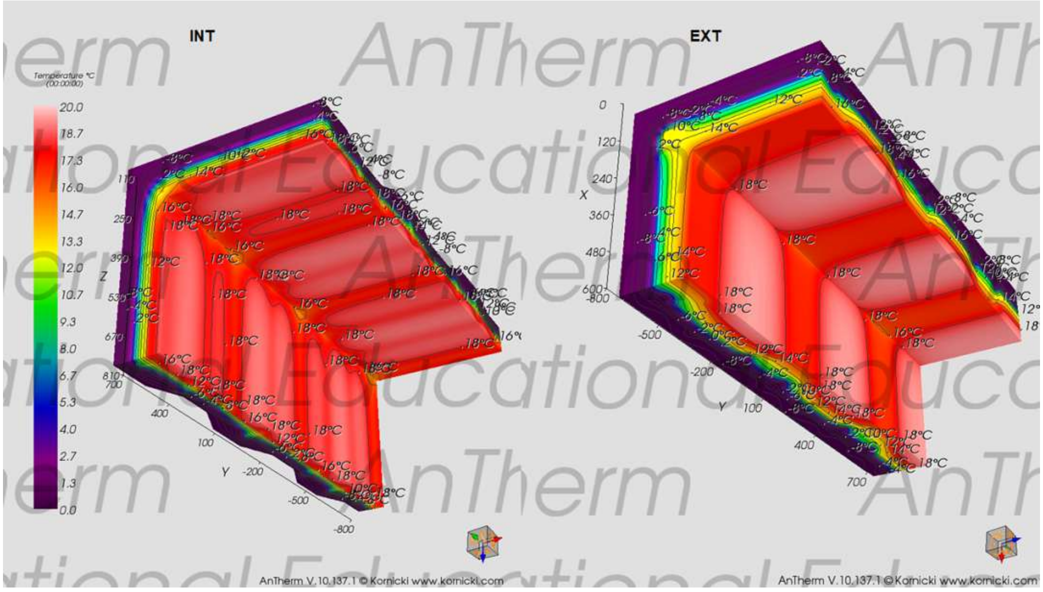


Figure 37: Wall-roof corner construction 3D temperature distributions with isolines

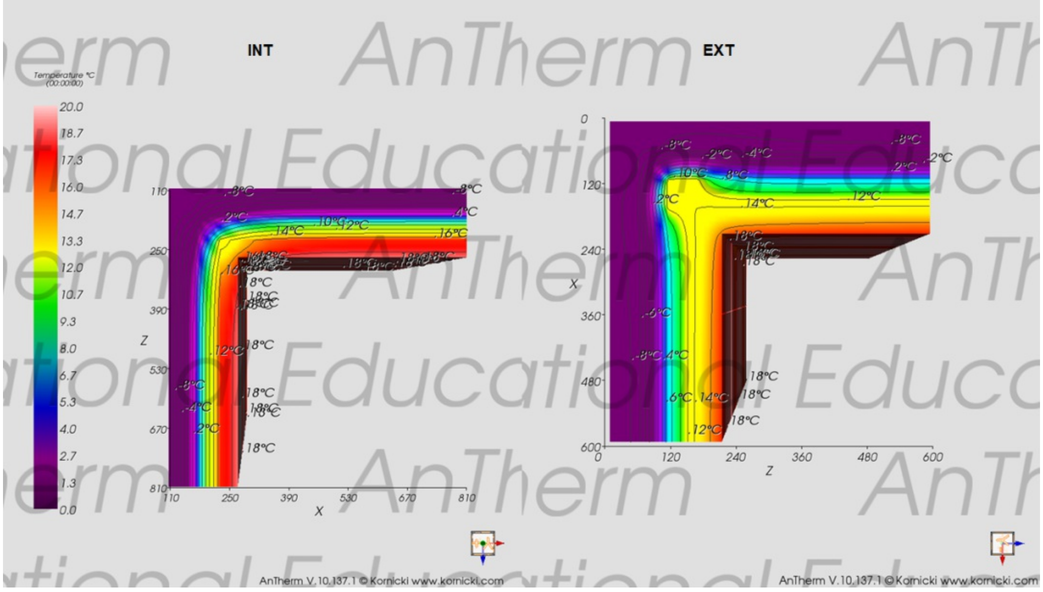


Figure 38: Wall-roof corner construction 3D temperature distributions with isolines sectional view

4 Discussion

The thermal performance evaluations of different iterations of detail constructions have shown great progress compared to their base case representations of discarded SCs without insulation or simple military modifications. The thermal transmittance of all optimized SC envelope constructions, excluding the more complex corner constructions where this indicator is less reliable, was improved to below 0.35 $W \cdot m^{-2} \cdot K^{-1}$. The temperature factors consistently satisfied the threshold requirement of 0.71 and minimum interior surface temperatures were generally above 16°C given θ_e at -10°C suggesting no mold growth or condensation risks. The characteristic structures of SCs such as the corrugated steel panel, corner post, and side rail directly translated to the 3D temperature distributions due to their high thermal conductivity. Particularly constructions with corrugated steel panels showed uneven temperature distribution patterns on their respective interior finishes. These issues were alleviated by adding more insulation or redesigning the construction in such a manner that interior finishes always had a layer of insulation between them and any steel component.

The wall constructions were designed with three clear insulation material choices in mind: mineral wool, polyurethane foam and VIPs. These were found to have the best performance when combined, such that polyurethane foam was utilized in almost all improved constructions. Internal and external insulation designs were created with non-load bearing wood framing connected to the steel structure with initially metal, later wooden studs. The improved wall constructions showed temperature factors above 0.9 and minimum interior surface temperatures around 17°C given θ_e at -10°C. The wall constructions INT and EXT 5 with thinner VIP insulation had the lowest thermal transmittances with values below $0.25W\dot{m}^{-2} \cdot K^{-1}$ and were overall the best thermal performers, possibly suited for climates with temperature extremes down to -20°C. However, these constructions are more complex, expensive, and fragile to work with than those with mineral wool and still show some signs of uneven temperature distribution patterns across their interior finish.

The floor and roof constructions were designed based on the previous findings and simulated with opposing heat flows applied to their slightly different interior finishes and steel structures. The construction variants with combinations of polyurethane foam and mineral wool or VIPs had thermal transmittances below 0.35 or $0.25W \cdot m^{-2} \cdot K^{-1}$ respectively. The temperature factors were firmly above 0.9 and minimum interior surface temperatures above 17°C given θ_e at -10°C with suitability of the constructions including -20°C extremes. Due to the difference in heat transfer resistances and thermally advantageous steel structure, the floor constructions generally outperformed their roof counterparts. A marginal advantage of the externally insulated constructions was also observed, although this may be ascribed to the impact of wrapping polyurethane foam around the steel panel leading to a small amount of insulation actually being internal and acting as a thermal barrier before the interior finish. Furthermore it should be noted that since floor and roof constructions usually only make up a small percentage of the total outer thermal building envelope, it should be considered attractive to utilize the more affordable and simpler to construct polyurethane and mineral wool insulation combination. These constructions still perform very well and would also require less wood framing.

Since thermal bridging is most likely to occur in locations with complex geometries and highly conductive materials, the corner constructions with thick steel framing of panels welded to corner posts and side rails were of particular interest. Several wall-wall and wall-roof corner constructions were evaluated with less wood framing and thinner insulation than their previous iterations of respective single envelope components. Wall-floor constructions were excluded based on the floor constructions' previous great performance and the assumption that the wall-roof constructions' thermal performance gives the lower bound for the wall-floor constructions' performance. The wall-wall corner constructions had thermal transmittances below 0.4 and $0.26W \cdot m^{-2} \cdot K^{-1}$ when utilizing mineral wool and VIPs with polyurethane foam respectively. These values are marginally worse than those of the improved wall constructions, but carry less weight as corner constructions are dominated by thermal bridging behaviour. This was very visible in the wall-wall EXT constructions' 3D temperature distributions which had to be improved by moving the corner further inward. Thereby the temperature factors were increased above the 0.71 threshold and minimum interior surface temperatures to a around 12°C given θ_e at -10°C. The wall-wall INT constructions performed far better with temperature factors above 0.88 and minimum interior surface temperatures around 16°C. The wall-roof constructions were made only with combinations of polyurethane foam and VIPs as internal and external variants to have thermal transmittances below $0.3W \cdot m^{-2} \cdot K^{-1}$. Their temperature factors were consistently above 0.81 and minimum interior surface temperature above 14°C given θ_e at -10°C. The internal variant performed worse and could only be improved further at the cost of valuable internal ceiling height. Overall the corner constructions performed slightly worse than their respective single envelope components and, as expected due to the difference in steel thickness, the side rail had less of an impact than the corner post on thermal performances.

The detail constructions presented in the results are based on state of the art construction practices which are straight forward for prefabrication purposes on a large scale given discarded SC availability. The steel cutting, welding, and usage of heavy machinery such as cranes however demands skilled and experienced labour. This may not be equally available in the developing world where the population growth leads to most current housing crises. Likewise some variability in the availability and material properties like thermal conductivity is to be expected which would be cause for slight redesigns of the constructions. These hurdles should be overcome by the advantageous economic feasibility of SC constructions as well as the environmentally friendly upcycling of discarded freight SCs. However, to determine the constructions detailed environmental footprint it would be recommended to perform a full LCA study.

4.1 Limitations

The greatest limitation of the thesis is the fact that it is entirely simulation based. The thermal performance of the detail constructions suggested in the results have yet to be verified in the real world. Therefore it would be a worthy endeavour to build a simple SC demo-project with several of the optimized envelope constructions and validate their performances with on-site measurements of the key performance indicators and a thermal camera. Furthermore, the simulations are based on the numerical solution of heat conduction equations in which the influence of convection and thermal radiation are only estimated via single numbers for R_{si} and R_{se}. Of course the reality is more complex, in which convective-radiative heat transfers take place at the transitions between opaque materials and air spaces and directly impact the internal surface temperatures. The simulations presented in this thesis remain sufficiently useful for SC development purposes, however more complex computation fluid dynamics models which account for all heat transport mechanisms should be created in the future to reach further understanding.

Other sources of error in the AnTherm simulations might stem from the level of detail of the constructions as a greater amount of complexity in these would have increased the time for simulation significantly. A simplistic approach to panel, corner post, and side rail welding was chosen which does not fully represent the highly detailed steel structures of SCs. For instance steel cross-members were excluded from floor construction simulations as these showed little effect on the thermal performance due to their external location in the construction, but almost tripled the simulation time. Another noteworthy exclusion was the use of ceramic paint as thermal insulator for steel surfaces due to its thinness and intricate geometry on the mostly corrugated steel panels making it not worth the effort. Construction complexity limitation due to time constraints also meant that no three envelope component corner details such as wall-wall-roof or wall-wall floor constructions were modeled and simulated. Furthermore, the simulations also do not account for the thermal behaviours throughout the foundations or connection constructions. Including anchoring to cast-in-place foundation walls or point-like foundation footings as further construction variables could yield insights into the temperature changes within the foundations from steel to concrete. Finally, the constructions also do not consider the impact of electrical installations, windows, and other major construction modifications besides the insulation. Introducing models with these features would probably cause a redesign of the viable detail constructions and significantly increase the holistic comprehension of modified SC thermal performance.

5 Conclusion

Thermal bridges mostly occurred at the internally corrugated steel panel sections and between envelope components at the more steel-dense corner constructions. These could successfully be alleviated with additional insulation or redesigns of the spacing between interior finish and steel structure. A clear distinction in thermal performances between internally and externally insulated detail constructions did not become clear throughout the work. The insulation approaches covered a range of options to be suitable for varying climates in which the choice of internally or externally insulating might be determined by other parameters, such as the implication for internal volume when insulating internally or the loss of the inherent weather resistance of SCs when insulating externally. The selection of insulation materials was based on the existing SC literature and consisted of combinations of closed-cell polyurethane foam, which is very durable, has a high thermal resistance and provides extra sealing for the constructions, with layers of mineral wool or VIPs. The constructions with mineral wool generally under performed those with VIPs, but mineral wool is more affordable and easier to work with than the expensive and fragile VIPs. Therefore VIP constructions can only be recommended for colder climates in which their low thermal transmittance is required and the necessary construction expertise is present.

Overall this work presented significant iterations that contributed to the optimization of modified SC detail constructions to prove their thermal performance as adequate for climate extremes down to -10°C, with several variants appropriate for -20°C. The effects of thermal bridging throughout the modified steel structures of the SC walls, roofs, and floors have been thoroughly simulated with numerical thermal bridge simulations in AnTherm. The discovered problem zones have been addressed such that internal surface temperatures were at comfortable levels around 15-17°C given θ_e at -10°C. Temperature factors above 0.71 were consistently satisfied with optimized constructions boasting values around 0.9. The thermal transmittances were calculated to be around 0.35 and $0.25 W \cdot m^{-2} \cdot K^{-1}$ for mineral wool and VIP constructions respectively. The optimized SC detail constructions have thereby proven that they can satisfy all thermal performance requirements, in terms of thermal transmittance and thermal bridging, to possibly be considered as a sustainable low energy building alternative.

5.1 Future Research

Future research instrumental to the further development of this topic should initially be focused on creating more construction variations with greater detail and more two or three envelope component corner constructions. Additional visualizations and in depth analysis of the temperature distributions would also be recommended. Furthermore, better computational fluid dynamics models should be created to account for convective and thermal radiative heat transfers. The optimized detail constructions should then be realized as prototypes in a demo SC project to validate their simulated thermal performances with on-site measurements. Widening this project to different climate conditions could bring further insights. A rigorous financial feasibility and cost effectiveness analysis should also be carried out to determine the applicability of modified SC constructions for port regions in the developing world and possible construction knowledge gaps that have yet to be addressed. A comprehensive life cycle assessment of the SC constructions should also be performed to quantify their environmental footprints. This work also suggests that the norms regarding the building codes of SC constructions should be updated. These efforts could possibly bring significant attention and, more importantly, acceptance to the use of modified SC constructions as a solution for sustainable housing crises around the world.

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