Exploring Alternative Materials for Improved Sustainability in Industrial Doors

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MASTER THESIS

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Entrance Systems

Exploring Alternative Materials for Improved Sustainability in Industrial Doors

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Abstract

This thesis explores the possibility of redesigning ASSA ABLOY's industrial door in order to improve sustainability through the use of new materials.

The first step of the process involved investigating different parts contained within the door, in order to decide which part of the door should be redesigned. Because of its high environmental impact as well as opportunities for improvement, it was concluded here that the *Panel Sections* consisting of a layer of insulation surrounded by a surface layer of metal would be selected for redesign.

The next step was to investigate new potential materials for both the insulation layer and the outer surface layer. Material data was gathered through a literature study. The data was used to simulate and calculate the stress, deformation, and thermal insulation properties of various materials. Through these tests, materials were systematically eliminated.

Finally, concepts were generated by combining different materials for the surface layer and the insulation layer. The thickness of the surface material was then optimized depending on the materials used for each concept. The mass, carbon emissions, and cost of the final concepts were assessed to determine the feasibility of the suggestions.

The research identified that Concepts B0 (bamboo and expanded polystyrene), B5 (bamboo and polyurethane) and B7 (bamboo and hemp) demonstrated significant reductions in carbon footprint compared to the original panels. However, these alternatives showed slightly lower performance in thermal insulation. Despite this, the concepts are viable solutions due to their decent costs and great sustainability benefits.

The findings suggest that implementing these concepts could significantly reduce industrial waste and carbon emissions. However, more accurate data and further testing are needed to confirm the performance of the materials suggested. Future research should explore increasing panel thickness to improve thermal insulation properties.

Sammanfattning

Detta examensarbete utforskar möjligheten att omkonstruera ASSA ABLOY:s industriella dörr för att förbättra hållbarheten genom användning av nya material.

Den första delen av processen inkluderade att undersöka olika delar av dörren för att avgöra vilken del som skulle omkonstrueras. På grund av dess höga miljöpåverkan samt möjligheter till förbättringar, drogs slutsatsen att "panelsektionerna", bestående av ett isoleringslager omgivet av ett yttre lager av metall, skulle väljas för omkonstruktion.

Nästa steg var att undersöka nya potentiella material för både isoleringslagret och yttre lagret. Materialdata samlades in genom en litteraturstudie. Dessa data användes för att simulera och beräkna olika materials belastning, deformation och värmeisolerande egenskaper. Genom dessa tester eliminerades material systematiskt.

Slutligen genererades koncept genom att kombinera olika material för yttre lagret och isoleringslagret. Tjockleken på ytmaterialet optimerades beroende på vilka material som användes för varje koncept. Massan, koldioxidutsläppen och kostnaden för de slutliga koncepten utvärderades för att avgöra förslagets genomförbarhet.

Undersökningen identifierade att koncepten B0 (bambu och expanderad polystyren), B5 (bambu och polyuretan), och B7 (bambu och hampa) visade betydande minskningar i koldioxidavtryck jämfört med de ursprungliga panelerna. Dessa alternativ visade dock något lägre prestanda i värmeisolering. Trots detta är koncepten genomförbara lösningar på grund av deras rimliga kostnader och stora hållbarhetsfördelar.

Resultaten tyder på att implementering av koncepten kan minska industriellt avfall och koldioxidutsläpp avsevärt. Dock behövs mer exakt data och ytterligare tester för att bekräfta de föreslagna materialens prestanda. Framtida forskning bör undersöka möjligheten att öka panelens tjocklek för att förbättra de värmeisolerande egenskaperna.

Acknowledgements

We would like to express our deepest gratitude to everyone who has supported us on our journey to complete this Master's thesis. It would not have been possible without all the support and valuable insights we have received, both from the employees at ASSA ABLOY Entrance Systems and employees at the Faculty of Engineering at Lund University.

A special thanks to ASSA ABLOY employees Elin Elfström, Jesper Gullin and in particular our supervisor Anders Löfgren, who have been of great assistance throughout the project and helped us back on track several times. In addition, we want to thank all other employees who were willing to put their time aside joining us for interviews and discussions to aid us in our project.

We would also like to thank our supervisor at the Faculty of Engineering at Lund University, Damien Motte, for his input and support on the project. Finally, a thank you to our examiner Jože Tavčar for his feedback and contribution to this Master's Thesis.

Abbreviations and Variables

Abbreviations

ABS - Acrylonitrile Butadiene Styrene
BOM - Bill of Materials
CAD - Computer-Aided Design
DAD - Double-Glazed ”Scratch Resistant” Acrylic, Double Sealed
EPDM - Ethylene Propylene Diene Elastomer
EPS - Expanded Polystyrene
FEA - Finite Element Analysis
FEM - Finite Element Method
GWP - Global Warming Potential
HIPS - Polystyrene High Impact
IIR - Isobutylene Isoprene Rubber (Butyl Rubber)
LD - Low Density
PA - Polyamide
PC - Polycarbonate
POM - Polyoxymethylene (Acetal)
PP - Polypropylene
PUR - Polyurethane
SAN - Styrene Acrylonitrile
TPS - Starch-Based Thermoplastics
VLD - Very Low Density

Mathematical Variables

A - Area
b - Base length
d - Distance from centroid to centroid of shapes
E - Modulus of elasticity
h - Height
I - Moment of inertia
L - Length
q - Load intensity
v - Deflection

Contents

1 Introduction

1.1 Background

This master thesis project is conducted in collaboration with the Department of Design Sciences at the Faculty of Engineering LTH, Lund University, and the company ASSA ABLOY Entrance Systems. The goal of the project is to find ways of reducing the total amount of carbon emissions from industrial doors by redesigning parts of the door with more sustainable materials.

1.1.1 ASSA ABLOY

ASSA ABLOY is a global company that specializes in access solutions. ASSA ABLOY Entrance Systems is a division within ASSA ABLOY which focuses on entrance systems suitable for all areas. The division is in its turn divided into four different departments. The department this project is in collaboration with is the Business Segment Industrial, focused on industrial customers, such as doors for factories and warehouses.

1.1.2 Product Background

The industrial overhead sectional doors offered by ASSA ABLOY Entrance Systems are available in different configurations. The door itself is built up by different sections. These sections can be either panels with the thickness 42 or 82 mm, or frames. The material of the door leaf can be steel or aluminium. Door and windows are also available options. The operating system can also be configured. See Figure 1.1 for some examples of the different configurations.

Figure 1.1: A variety of ASSA ABLOY's overhead sectional doors [10].

1.1.3 Problem Background

Global warming is perhaps the greatest threat humanity is facing within the immediate future. By 2017, human-induced global warming totaled to around 1°C since the first accurate measurements were made around the late 1800s. [36]

In order to contribute to minimizing global warming, ASSA ABLOY have committed to "Science-Based Targets". These targets serve as guides for companies to make changes that will contribute to limiting global warming to 1.5°C above pre-industrial levels according to the Paris Agreement. [57]

Specifically for ASSA ABLOY, following the science based targets means that they need to halve absolute emissions from 2020 to 2030, and reach net-zero no later than 2050 [8]. In order to reach this goal, major changes need to be made to their products.

The most important area that these changes need to be made are within the material usage of the current products, as this is the factor which significantly contributes the most emissions according to ASSA ABLOY. For the materials, ASSA ABLOY have already looked into reducing the amount of material used in their products, as well as switching the more sustainable types of the same materials. In order to see greater impacts, however, they are now interested in the potential of instead completely switching out materials to new more sustainable materials instead.

1.2 Project Description

This project will focus on one of the company's overhead sectional doors which consists of four area parts; door leaf, track set, balancing system, and operating system, see Figure 1.2. These primary areas in its turn are built up by smaller parts. The goal is to develop a more sustainable industrial door by switching materials in one such part of the door, where it is considered most effective but also feasible. This part will then be redesigned to fulfill the criteria, with the new materials in mind.

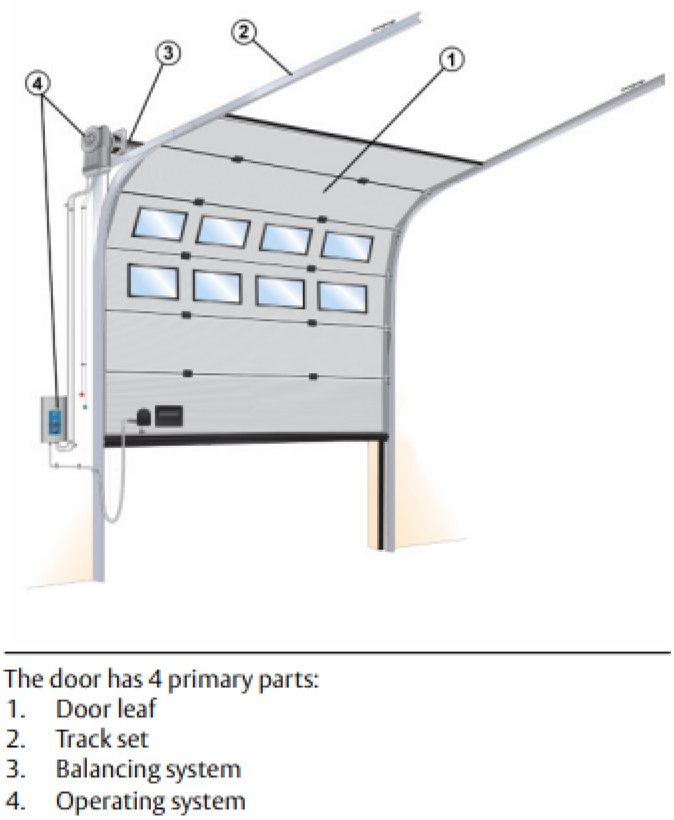


Figure 1.2: Overhead sectional door with window sections [9].

1.2.1 Goals and Research Questions

The aim of this report is to provide insight into the environmental impact of the material usage for the overhead sectional door. This project further aims to provide suggestions on possible concepts which will reduce the impact on the environment, compared to current designs. The cost, performance, and feasibility have to be considered. Following research questions are to be answered:

- For which part of the industrial door will a change in material have the biggest impact on sustainability?
- What materials would be most suitable for the part, in order to improve sustainability while maintaining sufficient performance?
- How can the design be optimized for the new materials?
- How much can the total emissions be reduced with a new design compared to the existing product?

1.2.2 Delimitations

In addition to the limitation of focusing on one specific part within one specific door model, there are several other limitations on the project, mainly due to the master thesis project being limited to 20 weeks. The project concludes after the concept development stage, with no time for physical prototypes and tests. Concept development of adjacent parts from the one specified will not be considered. In addition, the main focus of the concept generation will be to find and decide on new suitable materials, as opposed to working on new physical designs, since the materials themselves were identified as the main emission contributors, with the most room for improvement.

2 Methodology

2.1 Adopted Product Development Process

The product development process used in this project consists of four stages:

1. Planning Phase
2. Part Selection
3. Material Selection
4. Concept Development

2.1.1 Planning Phase

The planning phase involved establishing a mission statement to clearly define the project's goals and objectives. This phase also included creating a detailed time plan to ensure that all tasks were scheduled and milestones were set. This provided a structured framework for the project and helped in managing time effectively.

2.1.2 Part Selection

In the second phase, the various parts within the specified door were investigated in order to decide on which part to redesign. The focus was on selecting the part within the industrial door with the highest potential for sustainability improvement while being feasible to change. This phase involved conducting an emission analysis of the different parts of the door to identify which components contributed most to the overall emissions.

2.1.3 Material Selection

The third phase in the process is material selection. This phase is divided into several key steps.

As an initial step, before going into the material investigation, a product specification was set up in order to get an understanding over what the concepts would need to fulfill. This was used as a base for evaluating the different materials in the following steps.

The next step involved finding a set of initial potential materials to evaluate. This was done by first conducting a literature study to gather a list of suitable materials. A scoring method was then used to evaluate the different materials as objectively as possible based on several different types of criteria. Several materials were then selected for further testing.

The final step of this phase is material testing. The selected materials were tested through calculations and simulations to further determine their performances and, if necessary, eliminated.

2.1.4 Concept Development

In the fourth phase, the focus shifted to developing and evaluating product concepts.

The first step in this phase is concept generation. During this step, concepts are generated with a concept combination table to systematically explore potential solutions.

Then the generated concepts are tested using calculations and simulations, and evaluated using criteria such as performance, cost, and sustainability. After this, a few concepts are selected as final concepts based on evaluations from previous testing.

Finally, this phase concludes with a detailed comparison of the selected concepts, discussing their advantages and disadvantages. This included evaluating their potential impact on sustainability, performance, and cost-effectiveness. The discussion is aimed to highlight the strengths and weaknesses of each concept, providing a basis for making informed decisions on the best options for implementation.

2.2 Thesis Layout

This thesis is organized into several key sections, each serving a specific purpose to ensure a comprehensive presentation of the research on alternative materials for industrial doors to reduce emissions. The following is an overview of the report's structure:

Part Selection
This section presents emission analyses of various parts of the industrial door and identifies the part that will have the highest impact on sustainability, for redesign. It includes charts to illustrate the data and provides a detailed description of the chosen part.

Product Specifications
This section introduces the established product specifications for the selected part, detailing the requirements and criteria that guided the redesign process.

Material Selection
Divided into two subsections, one for the surface material and one for the insulation material, this section presents findings from the literature review. It includes tables with performance scores and a weighted score matrix to evaluate the materials.

Material Testing
Similar to the previous section, material testing is also divided into surface and insulation material subsections. It includes results from hand calculations, mechanical simulations, and thermal simulations, with figures and tables illustrating the findings. A final material rating is also provided.

Concept Generation
This section describes the process of generating different concepts for the redesign, introducing the different concepts.

Concept Testing
In this section, the results and scores of the generated concepts are presented. It concludes with an introduction of the final concepts selected.

Final Concepts
This section thoroughly presents the final concepts and compares them to the current panels. Charts are included to illustrate the performance and advantages of the new designs.

Conclusion
The conclusion summarizes the key findings and highlights the study's contributions to the field. It also provides practical recommendations based on the research outcomes.

Bibliography
This section contains a list of all sources used in the thesis, presented in alphabetical order.

Appendix
This section contains several appendices with more detailed information about certain aspects mentioned in the thesis. They are referred to in the sections where they are relevant.

3 Part Selection

As previously stated, the purpose of this project was to redesign the industrial door in order to make it more sustainable. However, since the door is a very complex product containing hundreds of components on different levels, it was decided that one part of the door should be singled out for redevelopment. In order to decide which part to focus on, the team started a process of analyzing the different parts within the door in order to find the one with the greatest potential for increased sustainability without negatively impacting the performance of the door as a whole.

3.1 Component List Assessment

The first step of the part selection process was to eliminate all of the parts that could be directly excluded from the analysis due to their obvious low impact. Following this, information regarding the weights and materials needed for the emission analysis were gathered for these parts.

To perform this analysis, a document including an interactive bill of materials (BOM) of all of the components included in the overhead sectional door with the dimension 3600x3600 mm, was provided by the R&D manager of ASSA ABLOY Entrance Systems. This list showed that the door was divided into five major areas, these being:

1. Door Leaf
2. Tracks
3. Balancing
4. Operation
5. Packaging

See Figure 1.2 for the first four areas. Each of these areas contained several different parts (in total 54 parts), which in turn were built up of several different components (up to 20 for a single part). Information about the material and weight of all components can be found in the list. It was decided that we should focus on one of the 54 parts with its components included for the redesign.

Out of the five areas shown above, the last two were decided to be excluded from the analysis. The Operation area was not included as this mostly contained electronic parts which was outside the scope of the team's project within mechanical engineering. The Packaging area was excluded as this had a very low total environmental impact.

This left the first three areas: Door Leaf, Tracks, and Balancing to be analyzed in order to find a suitable part under one of these. As a first step, a quick assessment was made to exclude a large number of parts that would have a negligible impact due to their low weights (< 7 kg) and materials used. This left eight potential parts from two of the three areas, as shown in Table 3.1 below:

Table 3.1: The eight parts selected for analysis, and their corresponding areas they belong to.

Area	Part
Door Leaf	Panel Section
	Truss
	Insulated Frame Section
	Infill Double-Glazed "Scratch Resistant" Acrylic, Double Sealed (DAD)
	Bottom Section Assembly
	Rollers and Roller Brackets
Tracks	Wall-Angle + V-Track
	H-Track + C-Profile

The document with the BOM contained certain parameters that could be configured in order to change what door setup the BOM would display. As the components would change and have different effects on the emissions depending on the configuration, a few different configurations were set up and compared. Their parameter values can be seen in Table 3.2. The configurations set up are exemplified by the doors depicted in Figure 3.1.

Table 3.2: First BOM door parameter setup for emission calculations.

Parameter	Setup 1	Setup 2	Setup 3	Setup 4
Section thickness	42 mm	42 mm	42 mm	42 mm
Panel sheet material	Steel	Aluminium	Steel	Aluminium
Number of trussed sections	2	2	2	2
Number of frame sections	0	0	4	4
Type of frame sections	Insulated	Insulated	Insulated	Insulated

Figure 3.1: Left: Door configuration with only Panel Sections in either steel or aluminium. Right: Door configuration with four Insulated Frame Sections and Panel Sections in either steel or aluminium.

The components and material distributions within these four configurations can be seen in Appendix A. The weights for each material displayed there were used to calculate emissions in the next section.

3.2 Emission Calculations

In this section, carbon emissions and energy usage of the eight parts for the four different configurations were computed so that comparisons could be made to see which part had the greatest environmental impact. The amount of material contained in each part is presented in Appendix A. The computation was done with both Ansys Granta (in section 3.2.1) and on a provided calculation tool, the Compass Calculator (in section 3.2.2), from ASSA ABLOY.

Ansys Granta is a software that provides access to a range of different materials property data as well as a lifecycle analysis tool. The material emission data used for the calculations was pre-determined for each material based on Ansys' own database.

The Compass Calculator is a calculation tool with many predefined materials and corresponding values on the global warming potential (GWP). All of the main materials had numbers for GWP provided by ASSA ABLOY. For materials not predefined, users have the option to manually input the GWP value. Component materials, weights, as well as certain processing methods and origin countries were retrieved from the BOM mentioned previously.

The reasoning for using both of these tools to calculate emission was mainly to ensure that the results would be as accurate as possible, since it was difficult to verify how reliable the numbers were for any of these tools. Therefore, if both tools would provide similar results, despite using different sources for their numbers, this would help indicate that none of the numbers were completely off. Additionally, the two tools provided some differing features, such as Ansys Granta having the addition of energy use calculation, while the Compass Calculator was more integrated with the different configurations of ASSA ABLOY's products.

3.2.1 Calculations on Carbon Footprint with Ansys Granta

Using Ansys Granta, the "Eco Audit" tool was used to conduct a lifecycle analysis for each of the parts so that they could all be compared. This analysis calculated the total energy use and carbon emissions produced during the lifetime of each part, as a result of the material, manufacturing processes, transport, use and disposal. The results from using these tools will present the distribution of emissions from each of the eight selected parts, tested on the four selected configurations.

The emissions from all of the parts were then compared side by side in the figures below in order to see which parts contributed the most. This process was then repeated for different configurations of the door.

Configuration 1: Steel Panel with 0 Frame Sections

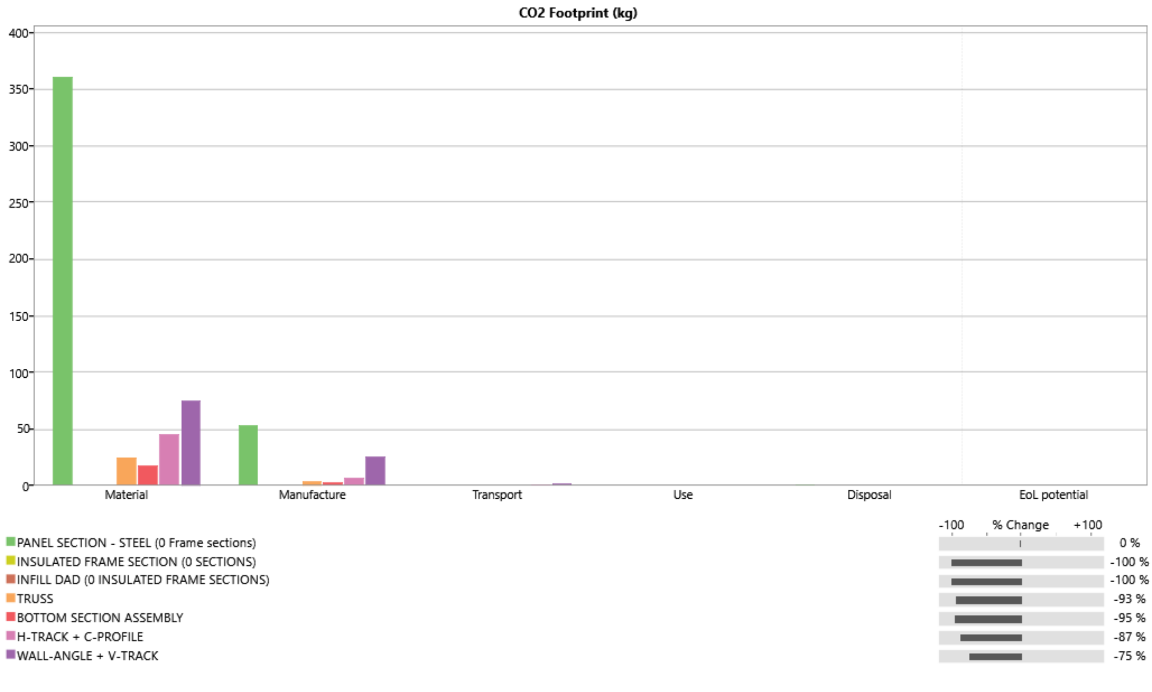


Figure 3.2: Carbon emissions for the shown components for a door configuration with Steel Panels and 0 Frame Sections.

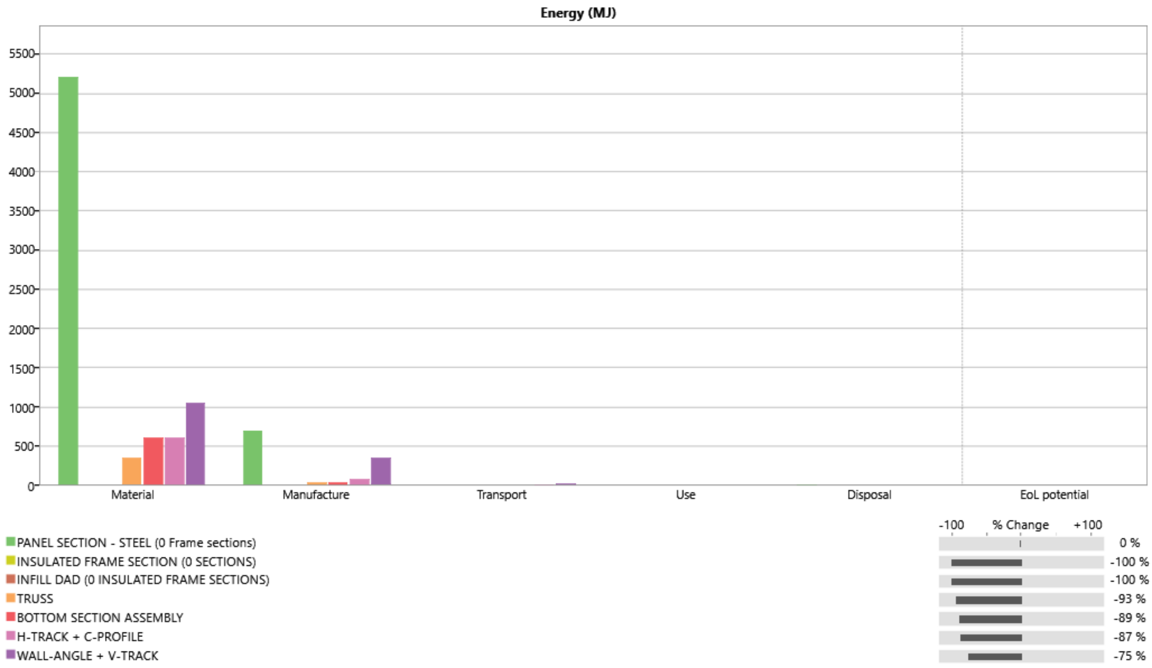


Figure 3.3: Energy usage for the shown components for a door configuration with Steel Panels and 0 Frame Sections.

Configuration 2: Aluminium Panel with 0 Frame Sections

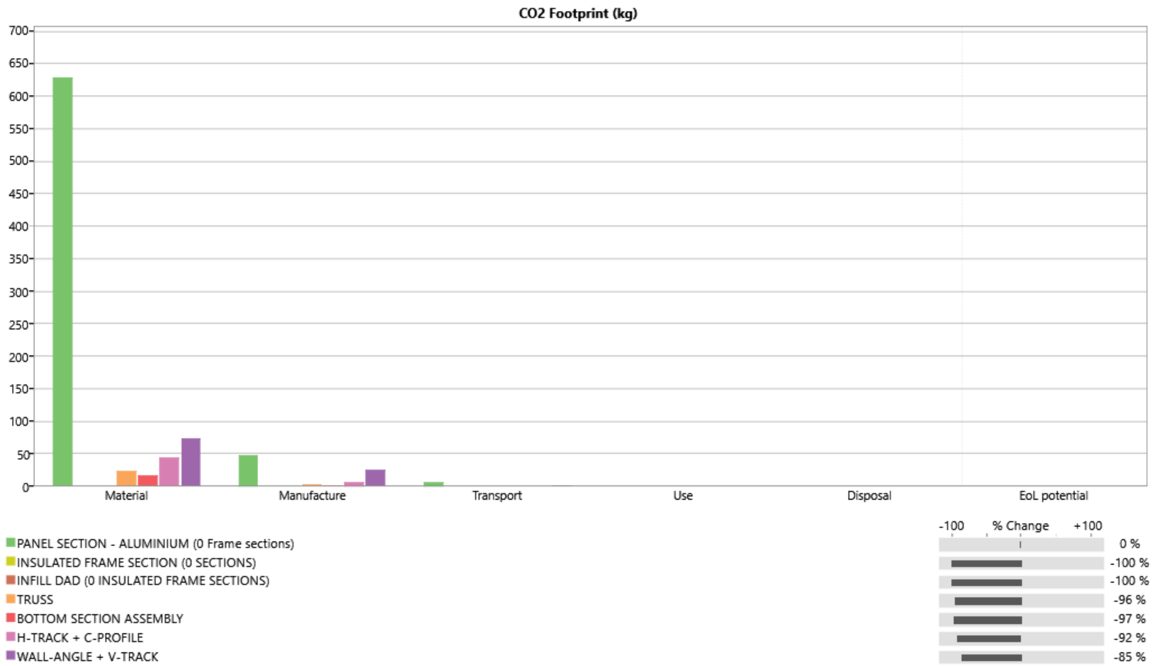


Figure 3.4: Carbon emissions for the shown components for a door configuration with Aluminium Panels and 0 Frame Sections.

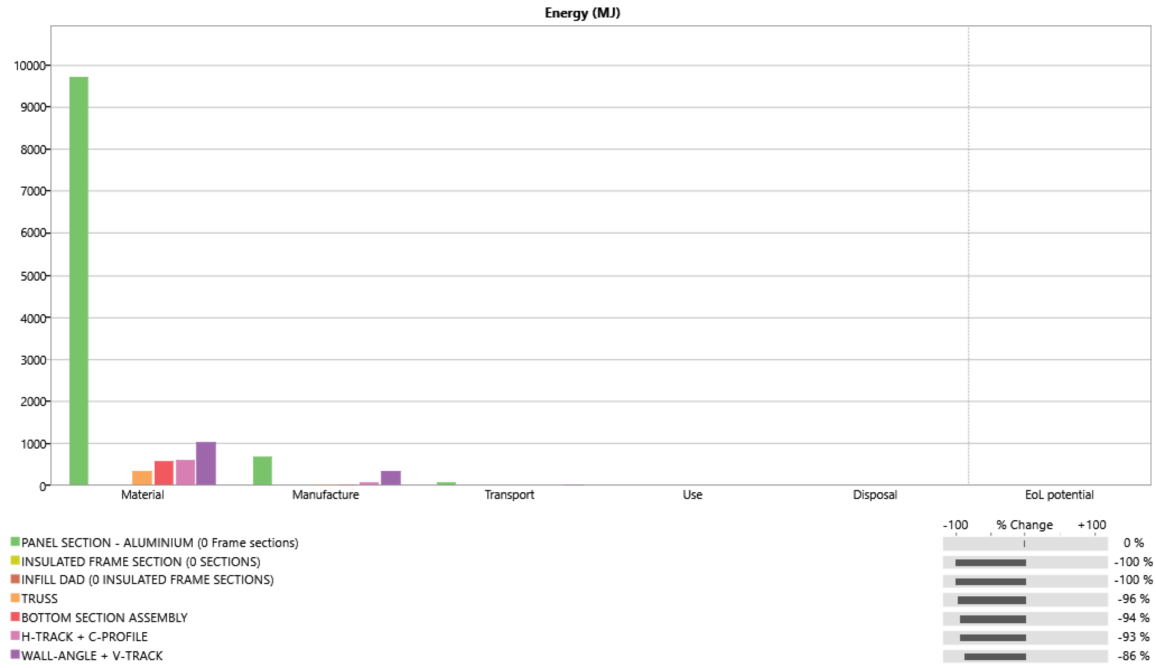


Figure 3.5: Energy usage for the shown components for a door configuration with Aluminium Panels and 0 Frame Sections.

Configuration 3: Steel Panel with 4 Frame Sections

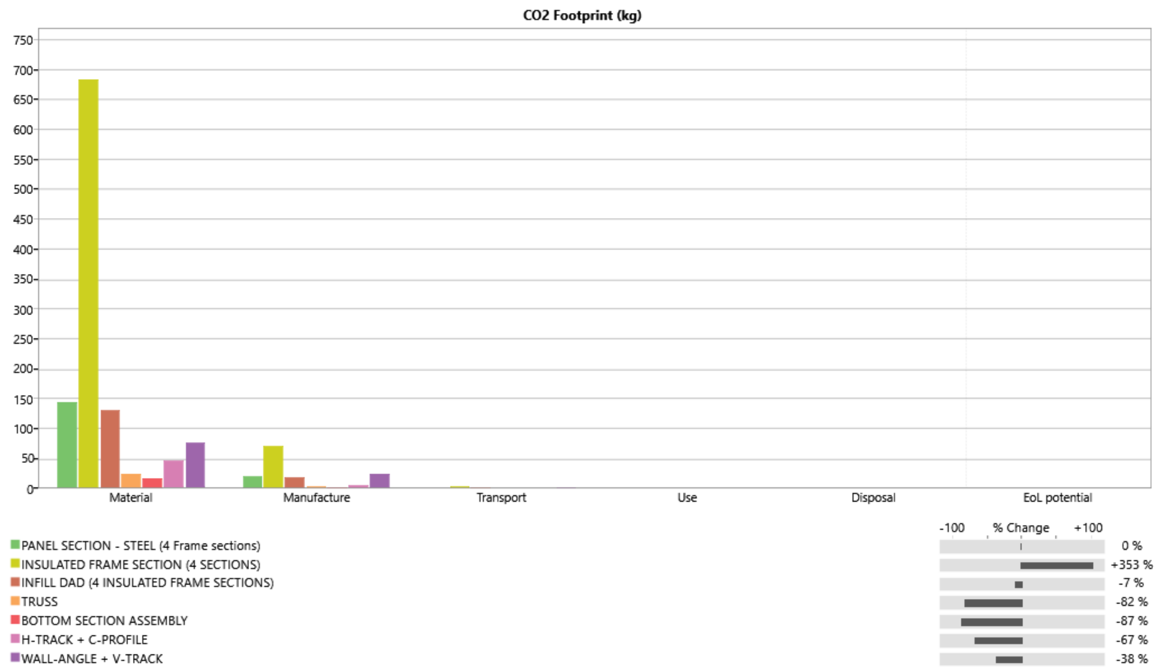


Figure 3.6: Carbon emissions for the shown components for a door configuration with Steel Panels and 4 Insulated Frame Sections.

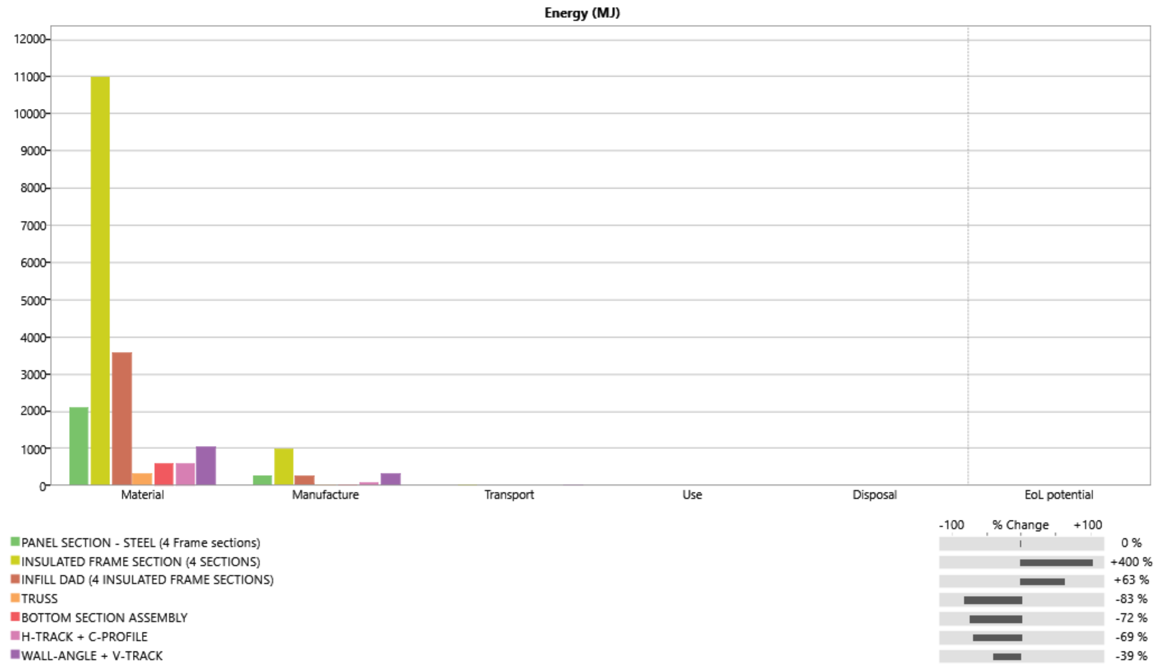


Figure 3.7: Energy usage for the shown components for a door configuration with Steel Panels and 4 Insulated Frame Sections.

Configuration 4: Aluminium Panel with 4 Frame Sections

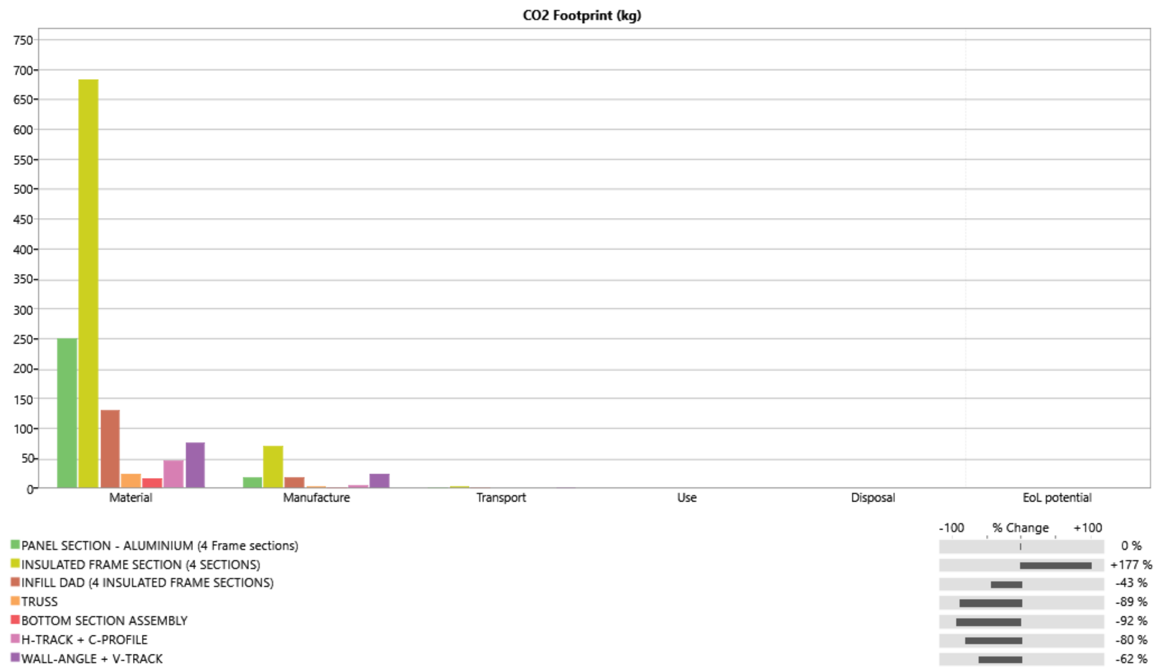


Figure 3.8: Carbon emissions for the shown components for a door configuration with Aluminium Panels and 4 Insulated Frame Sections.

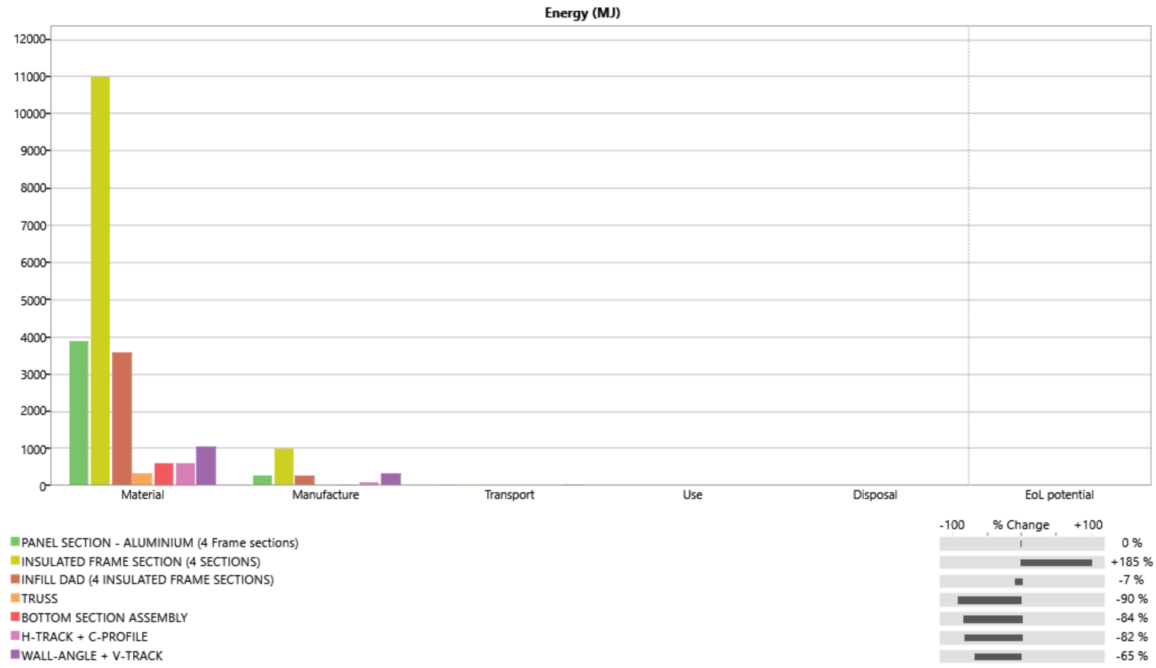


Figure 3.9: Energy usage for the shown components for a door configuration with Aluminium Panels and 4 Insulated Frame Sections.

3.2.2 Calculations on Carbon Footprint with Compass Calculator

The Compass Calculator was used to conduct the carbon footprint for each of the parts in different configurations. The GWP values provided by the Compass Calculator are only for the production of the material itself because the emissions from transport and processing are relatively small in comparison. The GWP values are presented in Table 3.3. Information on a few of the materials in the potential parts of the industrial door is not provided in the Compass Calculator. Other sources were used to fill in the information gap. The values from these sources are presented in the same table.

Table 3.3: GWP value of materials in potential parts of the industrial door.

Material type	GWP [kgCO_2eq/kg]
Acrylonitrile Butadiene Styrene (ABS)	3.0424
Aluminium	9.6588
Ethylene Propylene Diene Elastomer (EPDM)	1.8751
Polyisobutylene	5.77 [27]
Polyamide (PA)	8.1002
Polycarbonate (PC)	3.9561
Polypropylene (PP)	2.1912
Polystyrene high impact (HIPS)	3.5906
Polyurethane (PUR)	5.2876
Siloxane	9.9 [17]
Steel	2.2328
Styrene Acrylonitrile (SAN)	3.5 [44]

With the GWP values from Table 3.3 and the amount of each material in different parts from Table A.1 - A.4, the emission was calculated for each configuration and presented below.

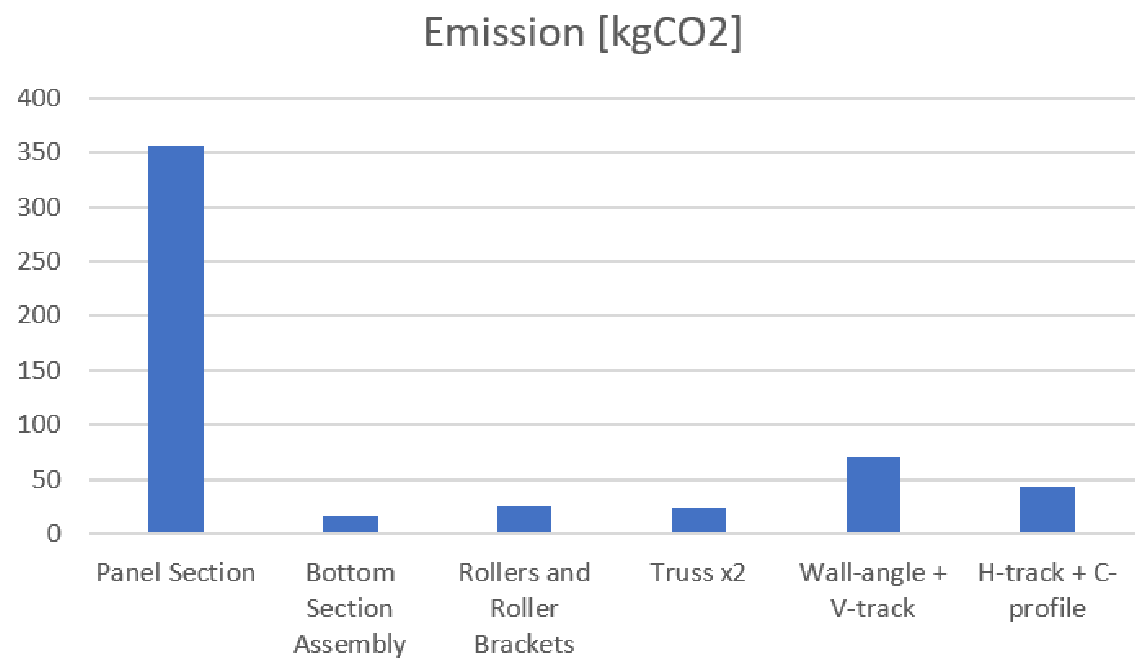


Figure 3.10: Carbon emissions for the shown components for Configuration 1 (Steel Panel with 0 Frame Section).

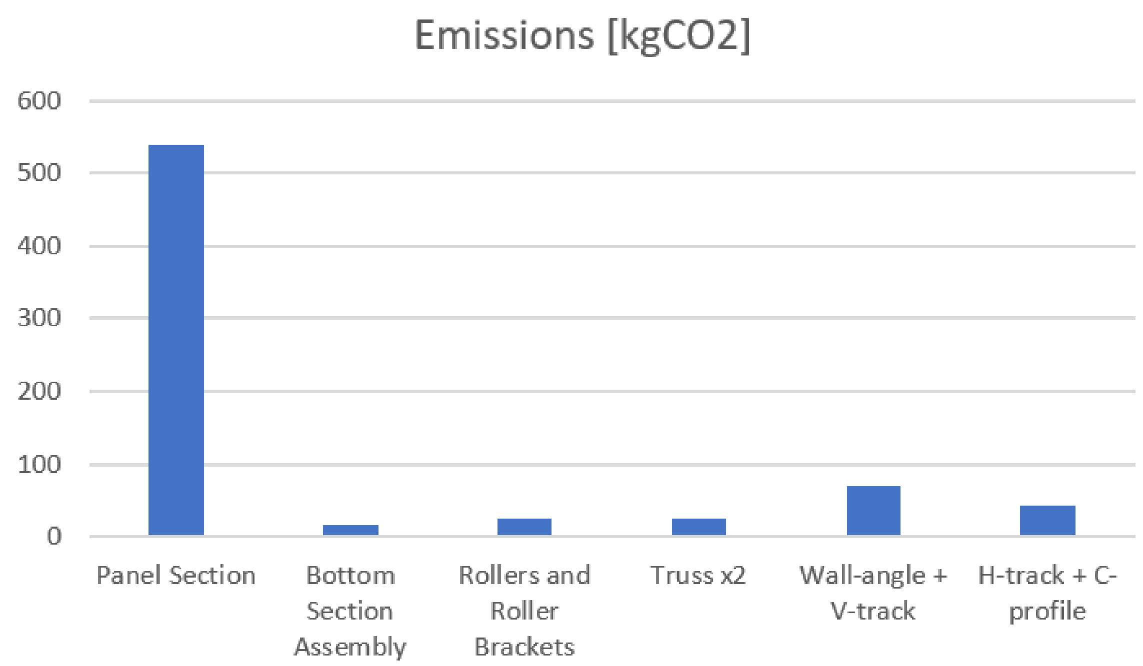


Figure 3.11: Carbon emissions for the shown components for Configuration 2 (Aluminum Panel with 0 Frame Section).

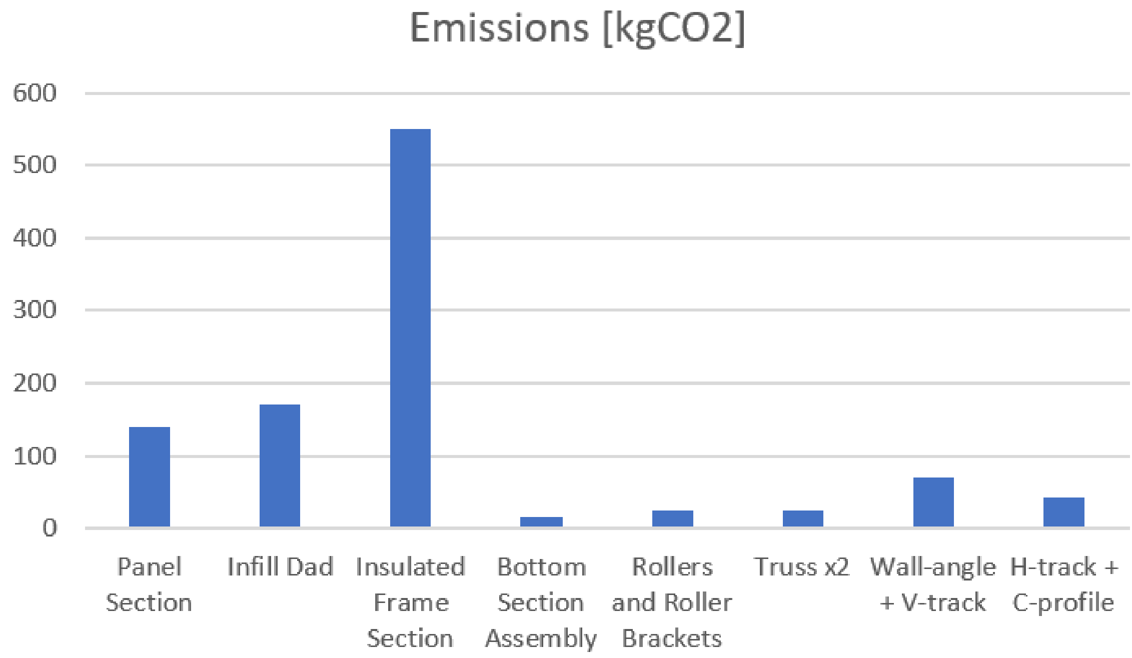


Figure 3.12: Carbon emissions for the shown components for Configuration 3 (Steel Panel with four Insulated Frame Sections).

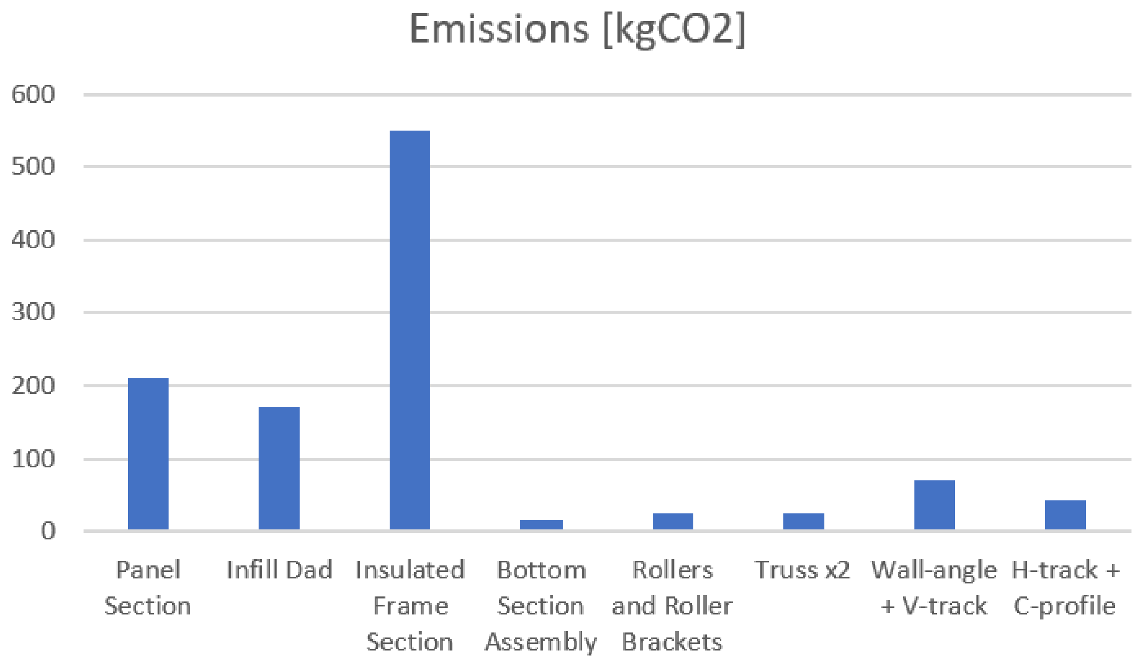


Figure 3.13: Carbon emissions for the shown components for Configuration 4 (Aluminum Panel with four Insulated Frame Sections).

3.2.3 Analysis

From the results obtained from the Compass Calculator as well as Ansys Granta, several conclusions can be drawn.

The most obvious conclusion is that the five parts: *Bottom Section Assembly*, *Rollers and Roller*

Brackets, *Truss*, *Wall-Angle + V-Track* and *H-Track + C-Profile* could directly be excluded since they contributed significantly less than the other parts in all different configurations.

For the other parts, their contributions varied depending on the configuration. For the most basic configurations, where all sections of the door were Panel Sections, the Panel Section is the part that contributes by far the most emissions compared to all of the other parts that build up the door. When these Panel Sections use aluminium they contribute significantly more emissions than they do when they are made in steel (almost twice as much).

However, in configurations using Insulated Frame Sections, the Insulated Frame Section part instead contributes by far the most emissions. Additionally, the "Infill DAD" part also contributes significant emissions in these configurations, surpassing the Panel Section in the configuration in steel, but not doing so in the aluminium configuration.

It is therefore of interest to compare a Panel Section made out of steel and one out of aluminum to an Insulated Frame Section. The Infill DAD will also be included in the comparison.

The amount of material in a single Insulated Frame Section with the dimensions 545x3600 mm and a single Infill Dad with the same dimensions are presented in Appendix A. The result is presented in Figure 3.14.

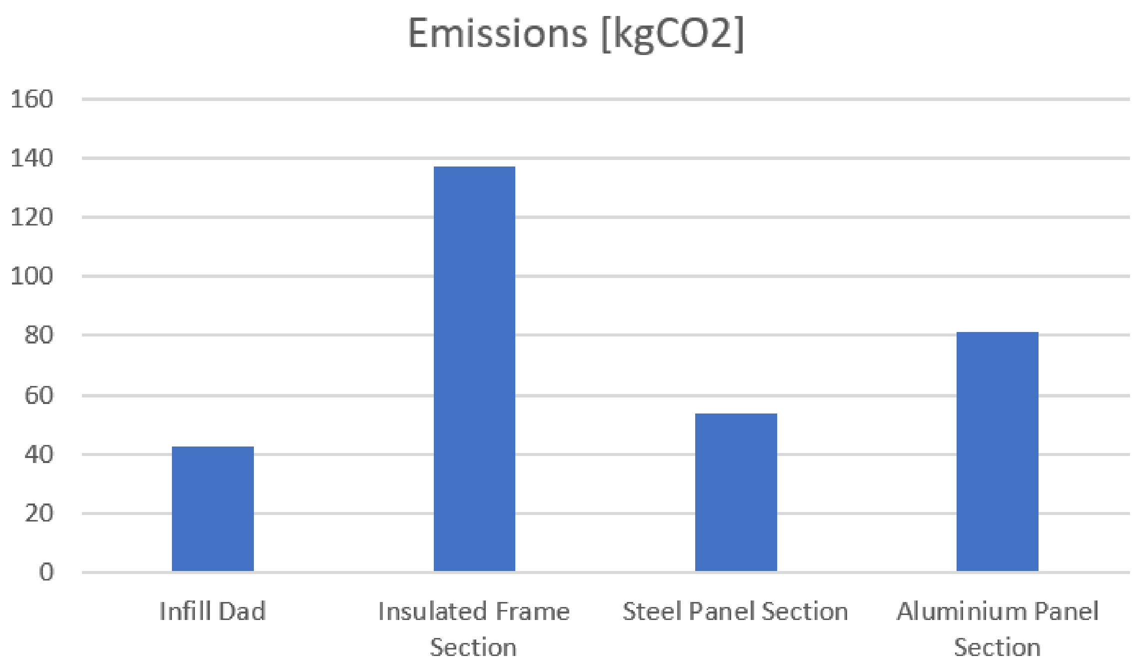


Figure 3.14: Carbon emissions for the shown components, each with a dimension 545x3600 mm.

As can be seen, the Insulated Frame Section emits roughly 140 kgCO_2, the Infill DAD approximately 40 kgCO_2, the Steel Panel Section around 55 kgCO_2, and the Aluminium Panel Section 80 kgCO_2.

Although figure 3.14 shows that an Insulated Frame Section has higher carbon emissions than a Panel Section, the Panel Section, which was the clear other contender from all the previous diagrams, was selected to focus on after a discussion with the supervisor at ASSA ABLOY. The main reason for this is that the Panel Section (in particular the Steel Panel Section) is by far the most common type of section being produced for the doors, and other types of doors with other sections still always contain Panel Sections. Frame Sections, on the other hand only appear on specific door configurations. And even for doors with Frame Sections, if they only contain one or two Frame Sections and a much higher amount of Panel Sections, the Panel Sections could contribute more in total.

Secondly, this part had a lot of potential for redesign with new types of materials, mainly for the surface metal and the insulation material that make up the vast majority of the part, due to its simple function. Switching out materials in the Insulated Frame without limiting performance would be more challenging. Because of these conclusions, the part selected for redesign is the Panel Section.

3.3 Detailed Description of Panel section

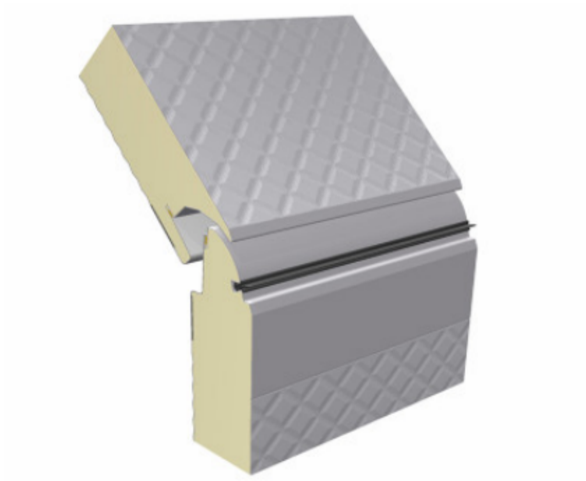
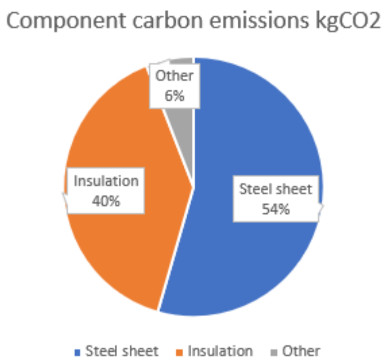
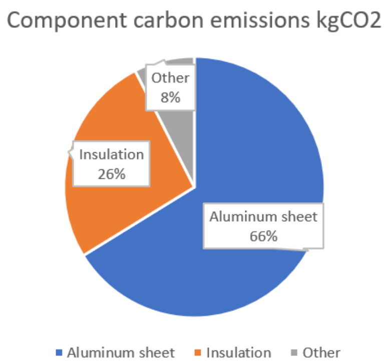


Figure 3.15: Insulated panel of door leaf filled with water-blown CFC-free polyurethane.

The current panel sections consist of a surface sheet made out of either aluminium or pre-coated steel, an insulation filling made out of CFC-free polyurethane, reinforcement strips, and different layers of coating, primer, and chromate layer. Each section is connected with hinges, horizontally, and the outer hinges have rollers that run in the tracks. The section height is 545 mm and the width of the sections is adjusted according to the customer's request. The available width range is 1200-10000 mm. The height of the top section can be between 275-820 mm and is achieved by trimcutting the top section. Figure 3.15 shows two cut-out pieces the panels in steel, loosely connected at the hinges.



(a) Panel section of configuration 1.



(b) Panel section of Configuration 2.

Figure 3.16: Carbon emission distribution in a Panel section.

Figure 3.16 shows the carbon emission distribution in a panel section for Configurations 1 and 2. The surface layer of the panel section stands for more than half of the emissions in both configurations. Insulation also has a high percentage, especially in a steel configuration. In Configuration 2 the aluminium sheet stands for almost 2/3 of the emissions.

3.4 Discussion

One issue at this stage was that the provided document with the BOM that provided the basis of the analysis was very much a work in progress, with the first version being released to us a few weeks into the project. In particular, numbers surrounding transport and suppliers were absent, and the group made attempts to contact supply managers directly, to limited success. However, the document was continuously updated, which brought changes to values. By one point though, the group had to decide to move on from this stage of the progress even though new updates kept coming to the BOM, in order to start analyzing materials. It simply had to be accepted that some of the numbers used here were not the most up to date by the end of the project. The group did however eventually gain access to the newest version of the document towards the end of the project to control that no changes that were made were too detrimental to the analysis conducted previously. However, due to the focus being on the contributions from the materials themselves (which was by far the largest contributor according to stats shown by ASSA ABLOY), inaccuracies when it came to transport and other later stages could be accepted.

While the numbers from the emission calculations differed slightly between the results from Ansys Granta and the Compass Calculator, the magnitude of the differences were deemed small enough to make the conclusion that both tools provided sufficiently accurate results. More importantly, the order of emissions of the different components were the same from both tools, with the the same components being the clear top emitters and bottom emitters in both. Therefore, the same conclusions could be drawn from the results of both tools, leading to the selection of the Panel Section as the component to redesign.

4 Product Specifications

The next step was to establish a product specification for the Panel Section. The purpose of this is to get an overview of what specific requirements are put on the part so that new materials and concepts can be tested against these metrics. Considering that this project focuses on a material change for a part within a specific type of ASSA ABLOY's industrial doors, product specifications are already available for this specific door model. Since the panel itself would need to fulfill many of these specifications in order for the whole door to be able to fulfill them, it was decided use several of these specifications for our panel. Other specifications not included in the datasheet of the specific door model were added with the help of the product manager of ASSA ABLOY. The product specification can be seen in Table 4.1.

ASSA ABLOY follows several European standards for industrial doors. For attributes with a standard, the ideal value presented does not fully describe the standard class. For further details on these standards, see Appendix B. The standard for thermal transmittance did not provide values, and instead only calculation method, and the value of 1.0 was obtained directly from the product datasheet for a door with the measurements 5000x5000 mm. [9].

The industrial door is assumed to be without windows, frames, and pass doors. The asterisk '*' indicates an attribute is of crucial importance.

Table 4.1: Product specification of Panel Section.

Metric No.	Metric	Importance	Units	Ideal Value	Standard
1	Section height	4	mm	545 [9]	
2	Top section height	5	mm	275-820 [9]	
3	Width	5	mm	800-10000 [9]	
4	Thickness	*	mm	42 [9]	
5	Weight	3	kg/m^2	13 [9]	
6	Price	4	sek		
7	Carbon emissions	*	$kgCO_2$	<54 [1]	
8	Post-life non-biodegradable waste	4	kg	0	
9	Life-time expectations	5	door cycles	200000 [9]	
10	Preventive maintenance	3	door cycles	200000	
11	Resistance to wind load	*	N/m^2	700	EN 12424 [64] class 3
12	Thermal transmittance	*	$W/(m^2*K)$	1.0 [65]	EN 12428 [65] for steel
13	Resistance to water penetration	5	N/m^2	>50	EN 12425 [63] class 3
14	Air permeability	4	$m^3/(m^2*h)$	6	EN 12426 [62] class 3
15	Acoustic insulation	3	dB	R-25	ISO 10140-2 [61]
16	Corrosion resistance	*	Yes/No	Yes [9]	
17	Burglar-proof	4	Yes/No	Yes	
18	Prone to dents and scratches	2	Yes/No	No	
19	Colorability	4	Yes/No	Yes	
20	Fire performance	*	Class	C-s3, d0 [60]	EN 13501
21	Operating temperature range	*	°C	-52.6 to 38	

The operating temperature range is chosen based on the record temperatures in Sweden. [66]

These metrics formed the basis of the various criteria we used to evaluate potential materials in the

[1]This value is calculated in previous chapter for a 545x3600 mm steel panel

next chapter. Later on in Chapter 6, values from these specifications were also used for calculations and simulations.

5 Material Selection

In this chapter, material candidates for the surface material and the insulation material were investigated, as these parts of the Panel Section contributed the majority of the carbon emissions, as previously shown in Figure 3.16.

For the first selection of materials, tables were made to rate the properties of the potential surface materials and potential insulation materials. The tables are divided into six different categories, being cost, mass, sustainability, mechanical properties, thermal properties, and environmental durability. See the tables down below.

Each category is weighted based on importance. This weight is used later in the scoring matrix (Table 5.17) where the scores from each criterion are put together for a total weighted score. The weights were established through discussion with the help of the product specifications. Motivations for each set weight can be found under the description of each category.

Each material is given a score between 0-5 depending on its performance. The reference material is given a score of 3 in all categories. 1 is much worse than the reference material, and 5 is much better. 0 means that the material fails the current criteria critically.

5.1 Selection of Surface Material

Before getting into the evaluation, a set of potential material candidates had to be established. These were found through online research as well as discussions with ASSA ABLOY employees. One goal was to have a variation of types of materials to investigate, including metals, polymers and organic materials, as these would have large variations in properties. Moreover, the supervisor at ASSA ABLOY encouraged the team to investigate uncommon and unconventional materials that they have not previously used or had time to look into.

Table 5.1: Initial set of surface materials.

Material
Steel
Aluminium (cast)
Bamboo
Cork
Hinoki
Scots pine
Teak
White oak
Magnesium (wrought)
Zinc (commercially pure)
Acetal (or polyoxymethylene, POM)
Acrylonitrile butadiene styrene (ABS)
Phenolics (bakelite)
Polycarbonate (PC)
Starch-based thermoplastics (TPS)

5.1.1 Cost

The first category of evaluation was cost, which only contained the single criteria of cost in SEK/kg. The weight of the cost is set to 20 % (putting it above the average weight of 16.7 % for each of the six categories) since the cost of the material will determine how feasible the new concept will be to launch in order for it to be profitable.

Table 5.2: Costs of surface materials.

Material	Cost [SEK/kg]	Score
Steel	6.18-6.5 [4]	3
Aluminium (cast)	17.8-19.3 [4]	2
Bamboo	11.9-17.8 [4]	2
Cork	23.7-119 [4]	1
Hinoki	518 [30]	0
Scots pine	5.49-11 [4]	3
Teak	59.3-95.6 [4]	1
White oak	59.3-95.2 [4]	1
Magnesium (wrought)	17.4-19.5 [4]	2
Zinc (commercially pure)	19.1-22.3 [4]	2
Acetal (or polyoxymethylene, POM)	11.5-13.3 [4]	2
Acrylonitrile butadiene styrene (ABS)	15.2-17.8 [4]	2
Phenolics (bakelite)	17.6-27.9 [4]	2
Polycarbonate (PC)	21.9-24.9 [4]	1
Starch-based thermoplastics (TPS)	20.6 [4]	2

Materials with a price range starting at 21 SEK per kilogram or higher are assigned a score of 1. Zinc and phenolics, despite having a price range exceeding 21 SEK per kilogram, possess a lower price limit below 20 SEK, thus assigned a score of 2. The cost of scots pine is close to that of steel, and therefore receives a score of 3. Conversely, hinoki's substantially higher price renders it unsuitable for consideration and thus receives a score of 0, leading to its elimination from further analysis.

5.1.2 Mass

The second category of evaluation was mass, which only contained the single criteria of density in kg/m^3. The weight of the density is set to 10 %. The density determines the mass, a surface material with higher density can be paired with an insulation material with lower density to make the mass of the panel section acceptable. While it is important for the eventual concept to not surpass the desired mass, this was not deemed as critical as the cost.

Table 5.3: Density of surface materials.

Material	Density [kg/m^3]	Score
Steel	7850 [20]	3
Aluminium (cast)	2650-2770 [4]	4
Bamboo	602-797 (699.5) [4]	5
Cork	160-240 [4]	5
Hinoki	390-450 [12]	5
Scots pine	730 [40]	5
Teak	630 [42]	5
White oak	890-930 [41]	5
Magnesium (wrought)	1500-1950 [4]	4
Zinc (commercially pure)	7130-7150 [4]	3
Acetal (or polyoxymethylene, POM)	1390-1410 [4]	4
Acrylonitrile butadiene styrene (ABS)	1030-1060 [4]	4
Phenolics (bakelite)	1240-1320 [4]	4
Polycarbonate (PC)	1190-1210 [4]	4
Starch-based thermoplastics (TPS)	1200-1500 [4]	4

In comparison to steel, all materials listed exhibit lower densities. Those with densities below 1000 kg/m^3 are awarded a score of 5. Materials with densities close to 7000 kg/m^3 receive a score of 3, indicating their similarity to the density of steel. Materials falling within density ranges between these extremes are assigned a score of 4.

5.1.3 Sustainability

The weight of the performance in sustainability is set to 35 %. Given that the project focuses extensively on sustainability and reducing the product's carbon footprint, this category carries significantly more weight in the scoring process compared to others.

Table 5.4: Sustainability criteria for the surface materials.

Material	GWP [kgCO_2eq/kg]	Recyclability	Biodegradability	Score
Steel	2.23 (från tidigare)	Yes [4]	No [4]	3
Aluminium (cast)	11.8-13 [4]	Yes [4]	No [4]	2
Bamboo	1-1.11 [4]	Yes [4]	Yes [4]	5
Cork	0.192-0.211 [4]	Yes [4]	Yes [4]	5
Hinoki	0.065 [45]	Yes	Yes	5
Scots pine	0.348-0.384 [4]	Yes [4]	Yes [4]	5
Teak	0.574-0.633 [4]	Yes [4]	Yes [4]	5
White oak	0.574-0.633 [4]	Yes [4]	Yes [4]	5
Magnesium (wrought)	42.5-46.8 [4]	Yes [4]	No [4]	1
Zinc (commercially pure)	3.46-3.82 [4]	Yes [4]	No [4]	3
Acetal (or polyoxymethylene, POM)	3.04-3.36 [4]	Yes [4]	No [4]	3
Acrylonitrile butadiene styrene (ABS)	3.27-6.61 [4]	Yes [4]	No [4]	3
Phenolics (bakelite)	1.77-1.96 [4]	No [4]	No [4]	2
Polycarbonate (PC)	4.53-4.99 [4]	Yes [4]	No [4]	3
Starch-based thermoplastics (TPS)	1.48-1.64 [4]	Yes [4]	Yes [4]	4

Carbon sequestration is not included in the calculation of the carbon emissions for wood in the table. With carbon sequestration included, the woods would most likely store more carbon than it releases during production. However, if burnt down or biologically degraded the stored carbon will be released into the atmosphere.

For the recyclability property of each material on the table, it will not be distinguished whether it is recyclable, that is, can be reused with minimal noticeable changes in durability or usability (e.g. aluminum), or downcyclable, that is, degrades after each recycling process (e.g. plastics) [39].

Organic materials were uniformly assigned a score of 5 due to their ability to sequester carbon and their lower GWP compared to steel, in addition to being both recyclable and biodegradable.

Aluminium received a score of 2 due to its higher emissions compared to steel, despite having high recyclability.

Magnesium was assigned a score of 1 owing to its elevated GWP value. However, it is highly recyclable, and its production from recycled sources results in significantly lower carbon emissions than primary production.

Materials with GWP values ranging between 3 and 5, and possessing recyclability, were given a score of 3, aligning with steel.

Phenolics exhibit low emissions but lack recyclability and biodegradability, thus earning a score of 2.

TPS, characterized by low emissions and both recyclability and biodegradability, received a score of 4.

5.1.4 Mechanical Properties

The mechanical properties of the materials are crucial as they dictate the panel's ability to withstand loads. However, the weight attributed to this criteria is only 10 % because finite-element method (FEM) simulations will be conducted later on using Solidworks, which will more accurately determine how well the different materials hold up mechanically.

Table 5.5: Mechanical Properties for the surface materials.

Material	Young's modulus [GPa]	Tensile strength [MPa]	Yield strength [MPa]	Score
Steel	210 [20]	270 [20]	376-929 (652.5) [4]	3
Aluminium (cast)	69-76 (72.5) [4]	193-341 [4]	118-263 (131.5) [4]	2
Bamboo	18.0-20.0 [67]	160-319 [4]	35.8-44.1 (40) [4]	1
Cork	0.025-0.05 [4]	1-2.5 [4]	1.1-2.2 [4]	0
Hinoki (parallell to grain)	10.67-11.64 [12]	114.3-137.9 [12]		1
Scots pine (parallel to grain)	10.08 [68]	102 [40]	35-45 [4]	1
Teak (parallel to grain)	12.28 [69]	118 [42]	51-62.3 (57) [4]	1
White oak (parallel to grain)	12.15 [70]	109 [41]	43.2-52.8 [4]	1
Magnesium (wrought)	42-47 [4]	185-450 [4]	115-410 [4]	2
Zinc (commercially pure)	90-110 [4]	105-165[4]	90-150 [4]	2
Acetal (or polyoxymethylene, POM)	2.6-3.2 [4]	71.5-89.6 [4]	57.2-71.7 [4]	1
Acrylonitrile butadiene styrene (ABS)	2.07-2.76 [4]	37.9-51.7 [4]	34.5-49.6 [4]	1
Phenolics (bakelite)	2.76-4.83 [4]	34.5-62.1 [4]	27.6-49.7 [4]	1
Polycarbonate (PC)	2.32-2.44 [4]	62.7-72.4 [4]	59.1-65.2 [4]	1
Starch-based thermoplastics (TPS)	1.32-1.34 [4]	19.8-30 [4]	19.8-30 [4]	1

The focus of the comparison lies primarily on Young's modulus of various materials over tensile and yield strength, since the FEM simulations later on will focus on those two properties.

Given that none of the materials exhibit a Young's modulus higher than or close to that of steel, those with Young's moduli ranging from 40 GPa to 110 GPa are assigned a score of 2.

Materials with Young's moduli below 40 GPa but above 1 GPa are allocated a score of 1.

Cork, with a Young's modulus below 1 GPa, receives a score of 0 and is consequently excluded from further consideration.

5.1.5 Thermal Properties

Thermal properties, particularly thermal conductivity, hold greater significance in insulator materials compared to surface materials. Hence, the weighting is set to 10 %. However, it remains crucial to ensure that the operational temperature range complies with the specified criteria mentioned in product specifications.

Table 5.6: Thermal properties for surface materials.

Material	Thermal conductivity [W/mK]	Thermal expansion coefficient [μstrain/C]	Maximum service temperature [C]	Minimum service temperature [C]	Score
Steel	54 [20]	11.5-13 [4]	340 to 357 [4]	-68.2 to -38.2 [4]	3
Aluminium (cast)	110-162 (136) [4]	19.5-23.3 [4]	138 to 200 [4]	-273 [4]	2
Bamboo	0.148-0.195 (0.1715) [4]	2.59-4.11 (3.35) [4]	118 to 142 [4]	-73.2 to -22.2 [4]	4
Cork	0.04-0.048 [4]	130-180 [4]	120 to 140 [4]	-73.2 to -23.2 [4]	2
Hinoki	0.133 [35]				4
Scots pine	0.14 [43]	2.5-9.0 [4]	120 to 140 [4]	-100 to -70 [4]	5
Teak	0.116-0.128 (0.122) [73]	2.0-11 [4]	120 to 140 [4]	-73 to -23 [4]	4
White oak	0.19 [54]	2.0-11 [4]	120 to 140 [4]	-73.2 to -23.2 [4]	4
Magnesium (wrought)	50-126 [4]	24.6-28 [4]	120 to 200 [4]	-83.2 to -53.2 [4]	3
Zinc (commercially pure)	110-125 [4]	25-31 [4]	79.9 to 99.9 [4]	-20.2 to -0.15 [4]	0
Acetal (or polyoxymethylene, POM)	0.221-0.239 [4]	110-198 [4]	82.9 to 96.9 [4]	-50.2 to -40.2 [4]	2
Acrylonitrile butadiene styrene (ABS)	0.253-0.263 [4]	74-123 [4]	62.9 to 76.9 [4]	-45.2 to -35.2 [4]	2
Phenolics (bakelite)	0.141-0.152 [4]	120-125 [4]	142 to 157 [4]	-43.2 to 6.85 [4]	1
Polycarbonate (PC)	0.193-0.218 [4]	120-125 [4]	101 to 116 [4]	-47.2 to -37.2 [4]	2
Starch-based thermoplastics (TPS)	0.13-0.23 [4]	180-240 [4]	59.9 to 79.9 [4]	-60.2 to -50.2 [4]	4

As can be seen from Table 5.6 the thermal conductivity of every potential material is better than that of steel and aluminum. However, as mentioned before that is not as important in a surface material. The focus will therefore mainly be on comparing the thermal expansion and the operating temperature.

Scots pine is given a score of 5. It has a better thermal expansion coefficient than steel and the minimum and maximum operating temperature is beyond and above the required with great margin.

Materials given a score of 4 have a better thermal expansion coefficient than the reference material. Also, their operating temperature is within an acceptable range.

A score of 3 is given to magnesium which is within an acceptable operating temperature range but has a thermal expansion coefficient slightly higher than that of steel.

A score of 2 is given to materials that are within an acceptable operating temperature range but have a much higher thermal expansion coefficient than steel.

Phenolics are given a score of 1 because the thermal expansion coefficient is much higher than steel and the minimum service temperature is in the risk zone.

The minimum service temperature of zinc is too high. It does not fulfill the requirements and is therefore given a score of 0 and thereby being eliminated.

5.1.6 Environmental Durability Properties

The weight of the performance in environmental durability is set to 15 %. The durability of the surface materials is important since this is the outermost layer that will come into contact with the environment the most. However, the scoring here is done on untreated materials. The performance in durability may be improved with different treatments.

Table 5.7: Environmental Durability criteria for the surface materials.

Material	Water Resistance	Fire Resistance	UV Resistance	Durability: Industrial Atmosphere	Durability: Rural Atmosphere	Score
Steel	Acceptable [4]	Non-flammable [4]	Excellent [4]	Limited use [4]	Acceptable [4]	3
Aluminium (cast)	Excellent [4]	Non-flammable [4]	Excellent [4]	Excellent [4]	Excellent [4]	5
Bamboo	Limited use [4]	Highly flammable [4]	Good [4]	Limited use [4]	Acceptable [4]	1
Cork	Acceptable [4]	Self-extinguishing [4]	Good [4]	Acceptable [4]	Excellent [4]	2
Hinoki						1
Scots pine	Limited use [4]	Highly flammable [4]	Good [4]	Limited use [4]	Acceptable [4]	1
Teak	Limited use [4]	Highly flammable [4]	Good [4]	Limited use [4]	Acceptable [4]	1
White oak	Limited use [4]	Highly flammable [4]	Good [4]	Limited use [4]	Acceptable [4]	1
Magnesium (wrought)	Excellent [4]	Non-flammable [4]	Excellent [4]	Acceptable [4]	Excellent [4]	5
Zinc (commercially pure)	Excellent [4]	Non-flammable [4]	Excellent [4]	Acceptable [4]	Excellent [4]	5
Acetal (or polyoxymethylene, POM)	Excellent [4]	Highly flammable [4]	Poor [4]	Acceptable [4]	Excellent [4]	1
Acrylonitrile butadiene styrene (ABS)	Excellent [4]	Highly flammable [4]	Poor [4]	Acceptable [4]	Excellent [4]	1
Phenolics (bakelite)	Excellent [4]	Self-extinguishing [4]	Good [4]	Acceptable [4]	Excellent [4]	2
Polycarbonate (PC)	Excellent [4]	Slow-burning [4]	Fair [4]	Acceptable [4]	Acceptable [4]	2
Starch-based thermoplastics (TPS)	Limited use [4]	Highly flammable [4]	Fair [4]	Acceptable [4]	Acceptable [4]	1

A score of 1 is given to all materials with high flammability. Despite having no data on hinoki, it was still assigned a score of 1 since it is assumed its environmental durability is similar to the other wood materials scored. Materials with slightly better fire resistance are given a score of 2.

Magnesium and zinc are given a score of 5 due to their high fire resistance and excellent water resistance.

5.1.7 Weighted Scoring Matrix

To decide which materials would go through to the next round of evaluation, a weighted scoring matrix was set up as seen in table 5.17. The "Wt" in the second row represents the % weights of importance for the various categories as explained in the previous sections. The "R" in the second column represents the ratings (0-5) given to each material previously in the various categories. The "WS" stands for Weighted Score which is the product of the Score multiplied by the Weight value for each material. The scores were summarised in the final column, and the weighted scores were used to rank the materials in table 6.10.

Table 5.8: Surface material weighted scoring matrix.

		Cost	Mass	Sustainability	Mechanical	Thermal	Durability	Total
Material	Wt	0.20	0.10	0.35	0.10	0.10	0.15	1.00
Steel	R	3	3	3	3	3	3	18
	WS	0.6	0.3	1.05	0.3	0.3	0.45	3
Aluminium	R	2	4	2	2	2	5	17
	WS	0.4	0.4	0.7	0.2	0.2	0.75	2.65
Bamboo	R	2	5	5	1	4	1	18
	WS	0.4	0.5	1.75	0.1	0.4	0.15	3.3
Cork	R	1	5	5	0	2	2	15
	WS	0.2	0.5	1.75	0	0.2	0.3	2.95
Hinoki	R	0	5	5	1	4	1	16
	WS	0	0.5	1.75	0.1	0.4	0.15	2.9
Scots Pine	R	3	5	5	1	5	1	20
	WS	0.6	0.5	1.75	0.1	0.5	0.15	3.6
Teak	R	1	5	5	1	4	1	17
	WS	0.2	0.5	1.75	0.1	0.4	0.15	3.1
White Oak	R	1	5	5	1	4	1	17
	WS	0.2	0.5	1.75	0.1	0.4	0.15	3.1
Magnesium	R	2	4	1	2	3	5	17
	WS	0.4	0.4	0.35	0.2	0.3	0.75	2.4
Zinc	R	2	3	3	2	0	5	15
	WS	0.4	0.3	1.05	0.2	0	0.75	2.7
Acetal (or polyoxymethylene, POM)	R	2	4	3	1	2	1	13
	WS	0.4	0.4	1.05	0.1	0.2	0.15	2.3
ABS	R	2	4	3	1	2	1	13
	WS	0.4	0.4	1.05	0.1	0.2	0.15	2.3
Phenolics (bakelite)	R	2	4	2	1	1	2	12
	WS	0.4	0.4	0.7	0.1	0.1	0.3	2.0
Polycarbonate (PC)	R	1	4	3	1	2	2	13
	WS	0.2	0.4	1.05	0.1	0.2	0.3	2.25
Starch-based thermoplastics (TPS)	R	2	4	4	1	4	1	16
	WS	0.4	0.4	1.4	0.1	0.4	0.15	2.85

It was decided to eliminate the five worst-scoring materials seen in table 5.8. Additionally, it was decided that each material that scored a 0 in any criteria would be eliminated, despite how high it's total score was. The reasoning for this was that a 0 meant that it failed a criteria so severely, that a product using this material most likely would fail the product requirements. Thereby, the materials we kept scored similarly or higher than the existing surface materials (Steel and Aluminium), and a total of five materials (excluding steel and aluminium) went through for further testing.

Table 5.9: Material rankings after weighted scoring.

Material	Weighted Score	Ranking
Scots Pine	3.6	1
Bamboo	3.3	2
Teak	3.1	3
White Oak	3.1	3
Steel	3	4
Starch-based thermoplastics (TPS)	2.85	5
Aluminium	2.65	6
Magnesium	2.4	7
Acetal, POM	2.3	8
ABS	2.3	8
Polycarbonate (PC)	2.25	9
Phenolics (bakelite)	2.0	10
Cork	0 (2.95)	-
Hinoki	0 (2.9)	-
Zinc	0 (2.7)	-

5.2 Selection of Insulation Material

For the selection of insulation material, the same procedure as described in the preceding section was followed.

Table 5.10: Initial insulation materials.

Material
CFC-free polyurethane
Butyl rubber (IIR)
Cellulose
Coconut fiber (husk)
Corkboard (0.25)
Cotton
Expanded polystyrene (EPS)
Flexible polymer foam (VLD)
Glass wool
Hemp
Mycelium
Rigid polymer foam (LD)
Rock wool
Sheep's wool
Straw bales
Sugar cane bagasse
Wood fibre

5.2.1 Cost

Just like for the surface material, the weight of the cost was set to 20 % since the cost of the material will determine how feasible the new concept will be.

Table 5.11: Costs of insulation materials.

Material	Cost [SEK/kg]	Score
CFC-free polyurethane	25-30 [71]	3
Butyl rubber (IIR)	9.56-18.1 [4]	4
Cellulose	32.73 [24]	3
Coconut fiber (coir)	1.15-3.54 [4]	5
Corkboard (0.25)	81.1-110 [4]	1
Cotton	15.9-46 [4]	3
Expanded polystyrene (EPS)	9.65-11.9 [4]	4
Flexible polymer foam (VLD)	21.4-23.6 [4]	3
Glass wool	53.97 [19]	2
Hemp	5.84-17.7 [4]	4
Mycelium	6.79 [19]	5
Rigid polymer foam (LD)	123-138 [4]	1
Rock wool	56.97 [53]	2
Sheep's wool	18.3-36.7 [4]	3
Straw bales	5.01 [19]	5
Sugar cane bagasse	9.29-14 [4]	4
Wood fibre	4.51 [34]	5

A score of 3 is given to materials between the price range of 20 to 35 SEK.

Materials between the range of 9 to 20 SEK is given a score of 4. Anything under 9 is given a score of 5. Hemp has a bigger range and the average is above 9, therefore it gets a score of 4.

A score of 1 is given to materials above 80 SEK.

For some materials, reasonable prices per kg could not be found, so it instead had to be calculated using price per m2 or m3. Calculations can be seen below:

Glass Wool [19]:

$$Cost/m^2 = 11.16Euro = 129.52kr$$
$$Thickness = 0.05m$$
$$Cost/m^3 = 129.52/0.05 = 2590.4kr$$
$$Density = 48kg/m^3$$
$$Cost/kg = 2590.4/48 = 52.97kr$$

Rock Wool [53]:

$$Cost/m^2 = 8.81GBP = 119.66kr$$
$$Thickness = 0.05m$$
$$Cost/m^3 = 119.66/0.05 = 2393.2kr$$
$$Density = 42kg/m^3$$
$$Cost/kg = 2393.2/42 = 56.98kr$$

5.2.2 Mass

The weight of the density is set to 15 % which is slightly higher than for the surface material. The reason for this is the panel will contain a significantly higher volume of insulation compared to surface material, thereby having a greater impact on the total mass of the panel.

Table 5.12: Mass scoring of insulation materials.

Material	Density [kg/m^3]	Score
CFC-free polyurethane	44.1 [1]	3
Butyl rubber (IIR)	910-950 (950) [4]	1
Cellulose	85 [18]	2
Coconut fiber (husk)	250-350 [48]	1
Corkboard (0.25)	225-275 [4]	1
Cotton	20 [18]	5
Expanded polystyrene (EPS)	15-30 [3]	4
Flexible polymer foam (VLD)	16-35 (26) [4]	4
Glass wool	48 [56]	3
Hemp	30 [16]	3
Mycelium	51-1420 [3]	1
Rigid polymer foam (LD)	36-70 (53) [4]	3
Rock wool	20-64 [3]	3
Sheep's wool	20 [18]	5
Straw bales	100 [58]	2
Sugar cane bagasse	250-350 [48]	1
Wood fibre	110 [14]	1

[1] This value was obtained through an internal ASSA ABLOY document

Materials with a density above 100 kg/m^3 are assigned a score of 1. For densities between 71-100 kg/m^3, a score of 2 is given.

Materials with a density of 30-70 kg/m^3 receive a score of 3. Rock wool, which spans a broader range but averages over 30 kg/m^3, is also given a score of 3. Densities between 20 and 30 kg/m^3 are assigned a score of 4.

Sheep wool and cotton, having the lowest density at 20 kg/m^3 receives a score of 5.

5.2.3 Sustainability

The weight of the sustainability is set to 35 %. The goal of the project is to reduce the carbon footprint and increase the sustainability of the product. Therefore the score is much higher than any other category.

Table 5.13: Sustainability performance scoring of insulation materials.

Material	GWP [kgCO_2e/kg]	Recyclability	Biodegradability	Score
CFC-free polyurethane	5.29	Yes [21]	No [21]	3
Butyl rubber (IIR)	4.23-4.67 [4]	No [4]	No [4]	1
Cellulose	1.0-1.8 [26]		Yes [18]	5
Coconut fiber (coir)			Yes [18]	5
Corkboard (0.25)	1.68-1.85 [4]	No [4]		2
Cotton	0.46 [50]	Yes [50]	Yes [18]	5
Expanded polystyrene (EPS)	2.5 [26]	Yes [23]	No	4
Flexible polymer foam (VLD)	3.05-3.36 [4]	No [4]	No [4]	1
Glass wool	2.45 [37]	Yes [55]	No	4
Hemp	0 [16]	Yes [2]	Yes [16]	5
Mycelium			Yes [3]	5
Rigid polymer foam (LD)	4.9-5.4 [4]	No [4]	No [4]	1
Rock wool	1.2 [26]	Yes [59]		4
Sheep's wool	0.83 [37]	Yes [23]	Yes [18]	5
Straw bales			Yes	5
Sugar cane bagasse			Yes	5
Wood fibre	0.83 [33]	Yes [34]	Yes	5

As before, the recyclability property will not distinguish between whether a material is recyclable or downcyclable.

For materials missing values for certain criteria due to difficulties finding these, scoring was based on general research and similarities to other materials along with the values that could be obtained. For example, all organic materials received a score of 5 even though a lot of them were missing some values, since these materials overall are more environmentally friendly than non-organic materials, as these can capture carbon during their lifetimes.

Butyl rubber is assigned a score of 1 since it has almost the same GWP as PUR and is neither recyclable nor biodegradable. The same reasoning is behind the scoring of rigid polymer foam and flexible polymer foam.

Corkboard has a rather low GWP value but is not recyclable. Information could not be found on its biodegradability, and due to the presence of additives, its biodegradability may not be the same as organic materials. Therefore it is given a score of 2.

EPS, glass wool, and rock wool are assigned a score of 4 because it has a significantly lower GWP value than PUR and is recyclable. Although no sources can be found to confirm its biodegradability, it is assumed to be non-biodegradable.

5.2.4 Thermal Properties

The thermal properties were assigned a weight of 5 %. Similarily to the mechanical properties for the surface materials, this was scored with a low weight since simulations will be performed later in Chapter 6 to get a better evaluation of the thermal properties for the insulation materials.

Table 5.14: Thermal properties of insulation materials.

Material	Thermal conductivity [W/mK]	Specific thermal capacity [kJ/(kg*K)]]	Score
CFC-free polyurethane	0.025 [2]	2.36 - 3.00 (2.68) [49]	3
Butyl rubber (IIR)	0.08-0.13 (0.13) [4]	1.85-1.95 [4]	1
Cellulose	0.04 [18]	1.8 [18]	2
Coconut fiber (husk)	0.046-0.068 (0.068) [48]	1.6 [18]	1
Corkboard (0.25)	0.0446-0.0545 (0.0496) [4]	1.8-2.2 [4]	1
Cotton	0.04 [18]	0.84 [18]	2
Expanded polystyrene (EPS)	0.03-0.04 (0.033) [3]	1.5 [18]	3
Flexible polymer foam (VLD)	0.036-0.048 (0.042) [4]	1.75-2.26 [4]	2
Glass wool	0.032 [56]	0.84 [18]	3
Hemp	0.039 [16]	1.6-1.7 [29]	2
Mycelium	0.029-0.081 (0.055) [3]	7.4-10.2 [3]	2
Rigid polymer foam (LD)	0.023-0.04 (0.0315) [4]	1.12-1.91 [4]	3
Rock wool	0.03-0.04 (0.036) [3]	0.84 [18]	3
Sheep's wool	0.033-0.04 (0.037) [3]	0.9 [18]	3
Straw bales	0.052 [58]	0.6 [29]	1
Sugar cane bagasse	0.049-0.055 (0.052) [48]		1
Wood fibre	0.038 [34]	2.1 [34]	2

For thermal properties, a lower thermal conductivity and higher specific thermal capacity is desired. The values shown in parentheses are the values used as inputs during simulations. The comparison primarily focuses on the thermal conductivity of the materials, since this is what determines the U-value.

As shown in Table 5.14, none of the materials have a lower thermal conductivity than PUR, indicating that none surpass PUR in thermal performance.

Materials with a thermal conductivity below 0.038 W/mK receive a score of 3. Those with a thermal conductivity of 0.038 W/mK to approximately 0.045 W/mK are assigned a score of 2. Mycelium, which has a broad range with an average above 0.045 W/mK but potential for great thermal properties, is also given a score of 2.

Materials with a thermal conductivity above 0.045 W/mK are given a score of 1.

5.2.5 Mechanical Properties

The mechanical properties were assigned a weight of 15 %. This is slightly higher than the weight used for the evaluation of the surface materials. This is due to the fact that no mechanical simulations will be performed on the insulation materials, and therefore this score is the only evaluation these materials get from a mechanical standpoint. While not as important as for the surface materials, the robustness of the insulation material could still contribute to the overall strength of the panel.

[2] This value was obtained through an internal ASSA ABLOY document

Table 5.15: Scoring of mechanical properties for insulation materials.

Material	Young's modulus [MPa]	Yield strength [MPa]	Score
CFC-free polyurethane	13.02 (PUR 35) [51]	0.39 (PUR 35) [51]	3
Butyl rubber (IIR)	0.7-1.5 [4]	2.4-10 [4]	2
Cellulose			1
Coconut fiber (husk)		175-405 (Tensile) [1]	4
Corkboard (0.25)	45.5-55.7 [4]	1.98-2.42 [4]	4
Cotton	0.055		1
Expanded polystyrene (EPS)	1.38-3.31 [28]	28.7 - 41.4 [4]	4
Flexible polymer foam (VLD)	0.25-1.0 [4]	0.01-0.12 [4]	2
Glass wool	0.055 [47]	0.02 (Ultimate tensile) [32]	1
Hemp	0.65-1.55 [31]	0.007-0.015 (Tensile) [38]	2
Mycelium		0.01-0.24 (Tensile) [5]	1
Rigid polymer foam (LD)	23.0-80.0 [4]	0.3-1.7 [4]	4
Rock wool	0.07 [22]	0.10 [52]	2
Sheep's wool	0.055	0.0033 -0.02954 (Tensile) [72]	1
Straw bales	0.06-0.32 [74]	0.519-8.877 (Tensile) [74]	2
Sugar cane bagasse	102-392 [48]		4
Wood fibre	0.80 [13]	0.15 (Compressive) [34]	2

The mechanical properties of the insulation materials were the most difficult to obtain from sources, likely due to the materials being unconventional, and mechanical properties not being the priority for insulation materials, so a lot of the scoring in this table had to be based on general research and comparisons as opposed to strictly on the numbers.

The value of Young's modulus could not be found for cotton and sheep's wool. For later analyses, Young's modulus is required. Due to the similarity in consistency to glass wool, it is assumed that cotton and sheep's wool have the same Young's modulus.

Due to difficulties in obtaining the yield strength values for all materials, some values have been replaced with tensile strength, compressive strength, or ultimate tensile strength. Additionally, the strength values obtained might correspond to materials with different densities and Young's moduli than those specified in Table 5.15.

A score of 4 is assigned to materials with Young's modulus above 20, such as corkboard and rigid polymer foam. EPS and coconut fiber are also assigned a score of 4 due to their high yield strength.

For materials with Young's modulus below 0.06 with low yield strength, a score of 1 is assigned. For materials with Young's modulus ranging from 0.06 to 2 with low yield strength, a score of 2 is given.

5.2.6 Environmental Durability

Environmental durability is assigned a weight of 10 %, which is slightly lower than that of surface materials. This is because the outer layer has more direct contact with the environment than the insulation layer. Also, the scoring is based on untreated materials, which means the performance in durability may be improved with different treatments.

Table 5.16: Scoring of environmental durability for insulation materials.

Material	Fire resistance	Water resistance	Rating
CFC-free polyurethane	Flammable (B2) [51]	Good [29]	3
Butyl rubber (IIR)	Highly flammable [4]	Excellent [4]	2
Cellulose	Normally flammable (class E) [29]	Vulnerable [29]	1
Coconut fiber (husk)	Highly flammable [4]	Excellent [4]	2
Corkboard (0.25)	Normally flammable (class E) [29]	Acceptable [4]	2
Cotton	Normally flammable (class E) [7]		2
Expanded polystyrene (EPS)	Normally flammable (Class E) [23]	Good [29]	2
Flexible polymer foam (VLD)	Highly flammable [4]	Acceptable [4]	1
Glass wool	Excellent (class A1) [56]	Good [29]	5
Hemp	Normally flammable (class E) [16]	Vulnerable [29]	1
Mycelium		High Absorption [3]	1
Rigid polymer foam (LD)	Self-extinguishing [4]	Excellent [4]	4
Rock wool	excellent (class A1) [29]	Good [29]	5
Sheep's wool	Normally flammable (Class E) [23]	Vulnerable [29]	1
Straw bales	Normally flammable (Class E) [29]	Vulnerable [29]	1
Sugar cane bagasse	Normally flammable [11]		2
Wood fibre	Normally flammable (Fire class E-D) [29]	Acceptable [29]	2

Both fire resistance and water resistance are critical properties, and neither should have the worst possible rating. If a material has excellent water resistance but is highly flammable, it receives a low score, as is the case with butyl rubber and coconut fiber, which are assigned a score of 2. Materials with less than decent resistance in both categories also receive a score of 2.

Materials with one resistance rating at the worst possible level and the other at a decent level are given a score of 1.

Rigid polymer foam is rated with a score of 4 due to its excellent water resistance and self-extinguishing properties.

Glass wool and rock wool both receive a score of 5 for their excellent fire resistance and good water resistance.

5.2.7 Weighted Scoring Matrix

A weighted scoring matrix was set up for the insulation materials in the same way as for the previous surface materials (see section 5.1.7).

Table 5.17: Insulation material weighted scoring matrix.

		Cost	Mass	Sustainability	Thermal	Mechanical	Durability	Total
Material	Wt	0.20	0.15	0.35	0.05	0.15	0.10	1.00
CFC-free polyurethane	R	3	3	3	3	3	3	18
	WS	0.6	0.45	1.05	0.15	0.45	0.3	3
Butyl rubber (IIR)	R	4	1	1	1	2	2	11
	WS	0.8	0.15	0.35	0.05	0.3	0.2	1.85
Cellulose	R	3	2	5	2	1	1	14
	WS	0.6	0.3	1.75	0.1	0.15	0.1	3
Coconut fiber (coir)	R	5	1	5	1	4	2	18
	WS	1	0.15	1.75	0.05	0.6	0.2	3.75
Corkboard (0.25)	R	1	1	2	1	4	2	11
	WS	0.2	0.15	0.7	0.05	0.6	0.2	1.9
Cotton	R	3	5	5	2	1	2	18
	WS	0.6	0.75	1.75	0.1	0.15	0.2	3.55
Expanded polystyrene (EPS)	R	4	4	4	3	4	2	21
	WS	0.8	0.6	1.4	0.15	0.6	0.2	3.75
Flexible polymer foam (VLD)	R	3	4	1	2	2	1	13
	WS	0.6	0.6	0.35	0.1	0.30	0.1	2.05
Glass wool	R	2	3	4	3	1	5	18
	WS	0.4	0.45	1.4	0.15	0.15	0.5	3.05
Hemp	R	4	3	5	2	2	1	17
	WS	0.8	0.45	1.75	0.1	0.3	0.1	3.5
Mycelium	R	5	1	5	2	1	1	15
	WS	1	0.15	1.75	0.1	0.15	0.1	3.25
Rigid polymer foam (LD)	R	1	3	1	3	4	4	16
	WS	0.2	0.45	0.35	0.15	0.6	0.4	2.15
Rock wool	R	3	3	4	3	2	5	20
	WS	0.6	0.45	1.4	0.15	0.3	0.5	3.4
Sheep's wool	R	4	5	5	3	1	1	19
	WS	0.8	0.75	1.75	0.15	0.15	0.1	3.7
Straw bales	R	5	2	5	1	2	1	16
	WS	1	0.3	1.75	0.05	0.3	0.1	3.5
Sugar cane bagasse	R	4	1	5	1	4	2	17
	WS	0.8	0.15	1.75	0.05	0.6	0.2	3.55
Wood fibre	R	5	1	5	2	2	2	17
	WS	1	0.15	1.75	0.1	0.3	0.2	3.5

Table 5.18: Insulation material rankings after weighted scoring.

Material	Weighted Score	Ranking
Coconut fiber (coir)	3.75	1
Expanded polystyrene (EPS)	3.75	1
Cotton	3.55	2
Sugarcane bagasse	3.55	2
Straw bales	3.5	3
Sheep wool	3.5	3
Wood fibre	3.5	3
Hemp	3.5	3
Mycelium	3.25	4
Rock wool	3.2	5
Glass wool	3.05	6
CFC-free polyurethane	3.0	7
Cellulose	3.0	7
Rigid polymer foam	2.15	8
Flexible polymer foam	2.05	9
Corkboard	1.9	10
Butyl rubber	1.85	11

The results of the weighted scoring of the insulation materials will be used together with the results of Flixo simulations, which is software for 2D FEM thermal simulations, to decide which materials go through further testing. For now, no materials will be eliminated. The reasoning behind this is that Flixo simulations are very quick to perform and can be easily done on all materials, as opposed to FEM simulations of the surface materials which are more time-consuming.

5.3 Discussion

During the material selection process, several challenges were encountered, impacting the accuracy and fairness of the comparison between different materials.

One of the biggest issues was the difficulty in obtaining reliable material property values. Material properties can vary significantly across different sources, leading to discrepancies. Additionally, for some materials, it was necessary to rely on product datasheets to obtain values, which may not be entirely representative. These products might have been treated or mixed with additives which could have improved the property of the material, resulting in an unfair comparison.

For some materials, reliable values for certain parameters were entirely unavailable. In such cases, the research team had to make informed assumptions. For example, organic materials lacking reliable carbon emission data were rated a 5 in sustainability, based on their natural growth and carbon dioxide absorption properties. This broad assumption places these materials well above metals or polymers in terms of sustainability. However, inconsistencies in the reported GWP values for wood, where some sources include carbon sequestration and others do not further complicate fair comparisons.

In instances where specific values for a particular tree species were unavailable, values for the broader "family" species were used. For example, some values for oak have been substituted for white oak. This approximation introduces a level of inaccuracy, as it is uncertain how different the specific values may be, potentially affecting the results.

Cost estimation presented another challenge. Material costs were obtained from suppliers' websites, and conversions to price per kilogram and the appropriate currency were performed. These conversions may have impacted the accuracy of the cost estimates, introducing another layer of uncertainty. The price of expanded polystyrene might be inaccurate. The value is taken from Granta of the price for polystyrene.

With this being said, the majority of material data could be obtained from databases which appeared to be reliable. The difficulties with finding data were mostly the case for some of the most unconventional materials, with most of these being the insulation materials. In particular, the costs and mechanical property data for these insulation materials were the most difficult to obtain, so for these further research would be beneficial.

6 Material Testing

After having gone through the first round av material evaluation and elimination, the remaining materials were tested in order to further reduce the number of candidates. This testing was done analytically through calculations and simulations to determine how well the panels with the different materials would live up to their requirements.

6.1 Surface Material

The remaining surface materials were tested by performing manual solid mechanics calculations as well as FEM simulations using SolidWorks. The point of these calculations and simulations was to determine how well panels using each material as the surface layer would sustain the mechanical requirements. The hand calculations are for calculating the beam deflection whereas the FEM analyses are for stress, safety factors, and max deformation of the panel. The wind load was used as the primary parameter for testing, since as mentioned in the product specifications Table 4.1 the door must be able to sustain a wind load of class 3, corresponding to a pressure on the surface of 700 Pa (See table 6 wind load classes).

Table 6.1: List of cover materials that went through to this round of testing.

Steel
Aluminium (cast)
Bamboo
Scots pine
Teak
White oak
Starch-based thermoplastics (TPS)

6.1.1 Beam Deflection Calculations

For the manual calculation, the industrial door with measurements 3600x3600 mm was modeled as a simply supported beam, as illustrated in Figure 6.1. This beam model is chosen because the door is best represented this way during wind loading.

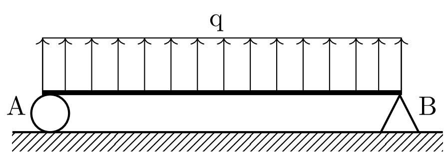


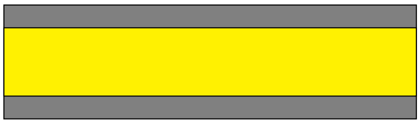
Figure 6.1: Simply supported beam.

One crucial parameter of interest is the maximum deflection v_{max} observed within the beam structure. The maximum deflection occurs at the midpoint of the beam and is mathematically expressed as:

$$v_{max} = v(0.5L) = \frac{5qL^4}{384EI}$$

Here, q denotes the load intensity, L signifies the length of the beam, E represents the modulus of elasticity, and I is the moment of inertia. However, this formula exclusively pertains to beams composed of a single material, with material-dependent values for I and E.

The industrial door consists mainly of two materials: a surface material (steel) and an insulation material (polyurethane foam), see Figure 6.2. To go around the problem with the single-material formula, adjustments in geometry are necessary. The solution involves modifying the geometry of the steel component such that the entire beam can be represented by the insulation material alone.



Grey = surface material, material 1
Yellow = insulation material, material 2

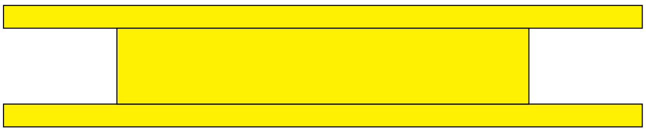
Figure 6.2: Beam cross-section area with two materials.

Consider a scenario where the steel has an elasticity modulus E_1 x times larger than that of the polyurethane foam E_2. If we aim to describe the beam solely in terms of polyurethane foam while keeping the same geometry, the stiffness would be compromised. However, by scaling the moment of inertia I of the former steel segment by a factor of x, the stiffness can be appropriately adjusted.

The moment of inertia I is computed as:

$$I = \frac{b \cdot h^3}{12} \tag{6.1}$$

To achieve a moment of inertia x times larger, the base length b needs to be scaled accordingly. This adjustment yields a modified geometry, as depicted in Figure 6.3.



Yellow = insulation material, material 2

Figure 6.3: Beam cross-section area with changed geometry represented by insulation material.

The scaled base length b_1 is expressed as:

$$b_1 = \frac{E_1}{E_2} \cdot b_2 \tag{6.2}$$

Given that the beam geometry consists of three rectangles, the total moment of inertia I_{tot} is computed by summing the individual contributions from each rectangle, considering their corresponding base lengths and heights.

$$I_{tot} = 2(I_1 + A_1 \cdot d_1^2) + I_2 \tag{6.3}$$

The final expression for maximum deflection v_{max} becomes:

$$v_{max} = v(0.5L) = \frac{5qL^4}{384E_2 I_{tot}} \tag{6.4}$$

Where q is determined as the product of wind load P and the beam length L, with a wind load of 700 Pa.

Maximum beam deflection calculations were conducted for all materials listed in Table 6.2, maintaining the same material thicknesses with those of the original industrial door. The insulation material used for these calculations is polyurethane foam.

Result

Table 6.2: Results from beam deflection calculations.

Material	Young's modulus [GPa]	Deflection v [m]	Ranking
Steel	210	0.0210	1
Aluminium	72.5	0.0608	2
Bamboo	19	0.2301	3
Teak	12.28	0.3539	4
White oak	12.15	0.3576	5
Scots pine	10.08	0.4295	6
Starch-based thermoplastics (TPS)	1.33	2.855	7

As can be seen from the results in Table 6.2, the metals had the smallest deflection. Wood was second best and polymer (starch-based thermoplastics) performed the least well with a deflection of 2.86 m.

6.1.2 Mechanical FEM Simulations

After having performed the manual calculations shown above, a set of computational FEM calculations were performed using SolidWorks' Simulation add-on. These were performed on a cut-out section of the Panel Section with measurement 573x773 mm. The goal of these simulations was to compare the different surface materials to each other.

Simulation Setup

The simulations were performed on ASSA ABLOY's existing CAD model of the door panel. The insulation material was set as the original PUR for all of the simulations, while the material of the outer sheet of the panel was switched for each iteration. The materials that were tested were those that went through the first round of testing in the last chapter (as seen in Table 6.1). The materials were created in SolidWorks using the material data specified in the tables in section 5.1. Smaller and moving parts were excluded from the analysis, leaving the cover plate and the insulation.

The boundary conditions applied were "Fixed" type fixtures at the edges in order to simplify the model. A 700 Pa pressure is applied on the outward-facing surface of the panel (see Figure 6.4), simulating the wind load specified in the Product Specifications (Table 4.1). For the hardware to be able to run the simulation, a simple mesh had to be used, using the "Draft" type mesh quality with a total of 217349 elements.

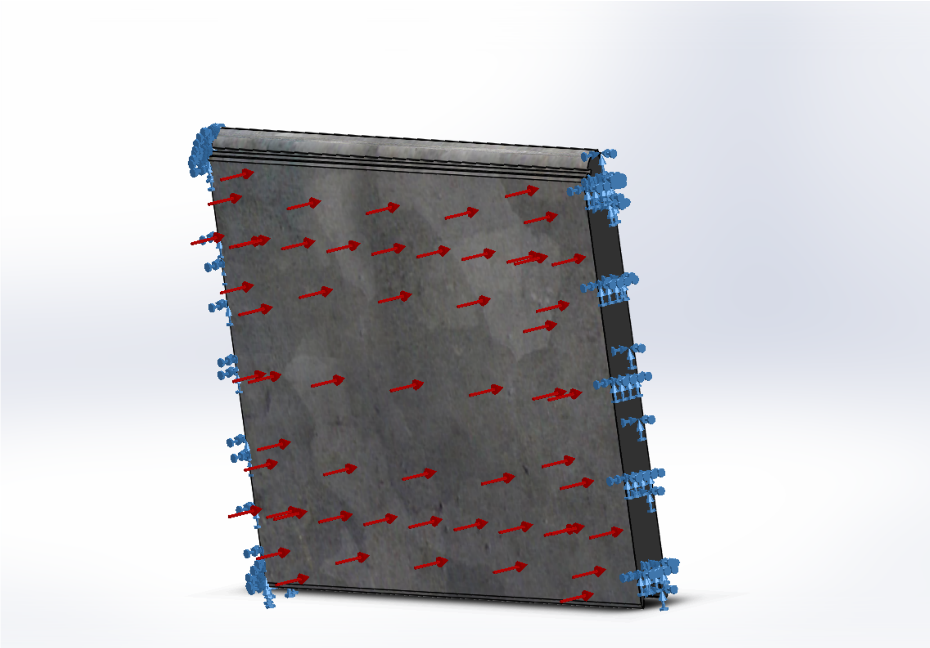


Figure 6.4: Solidworks simulation boundary conditions: Blue = fixed fixture, Red = Pressure.

Simulation Results

The stress results were ranked based on the safety factor that each material achieved when used as the surface material. The safety factor is the yield strength divided by the maximum achieved stress, meaning that a high safety factor represents the material being far from failure.

Table 6.3: SolidWorks stress simulation results ranked after safety factor.

Material	Max von Mises Stress [MPa]	Yield Strength [MPa]	Safety Factor	Ranking
Steel	13.07	652.5	49.92	1
Aluminium (cast)	9.881	190.5	19.28	2
Teak	3.838	56.65	14.76	3
White oak	3.861	48	12.43	4
Scots pine	3.701	40	10.81	5
Bamboo	4.568	39.95	8.75	6
Starch-based thermoplastics (TPS)	3.803	24.9	6.55	7

The deformation results ranked the materials based on how high maximum deformations they achieved. The rankings here were identical to the previous deflection calculations, but differed on on point compared to the stress results. This difference was that bamboo is placed three ranks higher on deformation compared to stress, showing that it is stiffer but weaker compared to the other wood materials that were tested.

Table 6.4: SolidWorks deformation simulation results.

Material	Max Deformation [mm]	Ranking
Steel	0.02483	1
Aluminium (cast)	0.04134	2
Bamboo	0.07471	3
Teak	0.0937	4
White oak	0.09437	5
Scots pine	0.1059	6
Starch-based thermoplastics (TPS)	0.9803	7

An example of simulation results (here using steel as surface material) can be seen below. For the rest of the simulation results, see Appendix C.

Steel

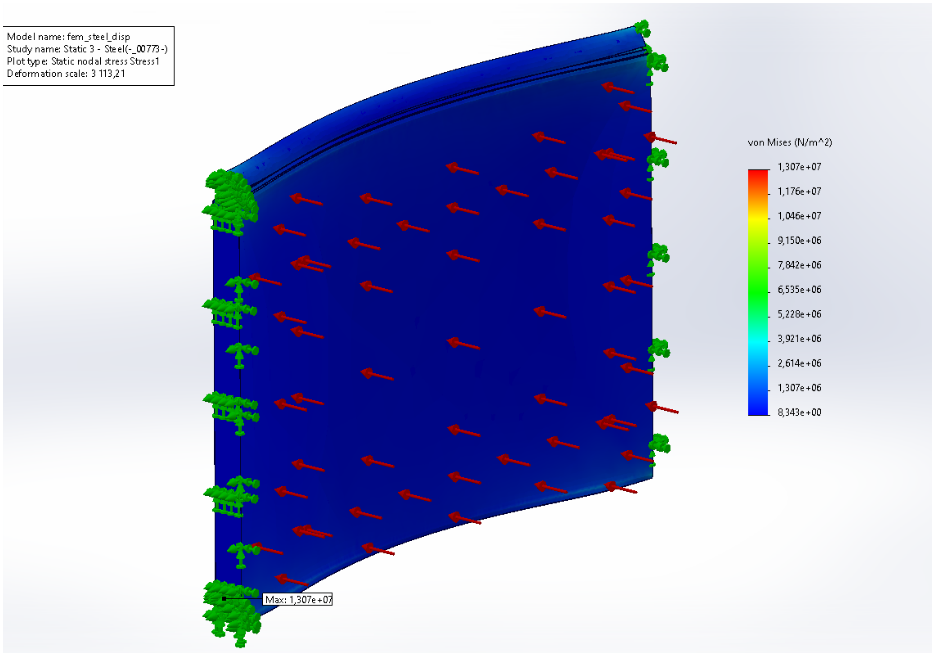


Figure 6.5: Stress results from Solidworks on Steel panel.

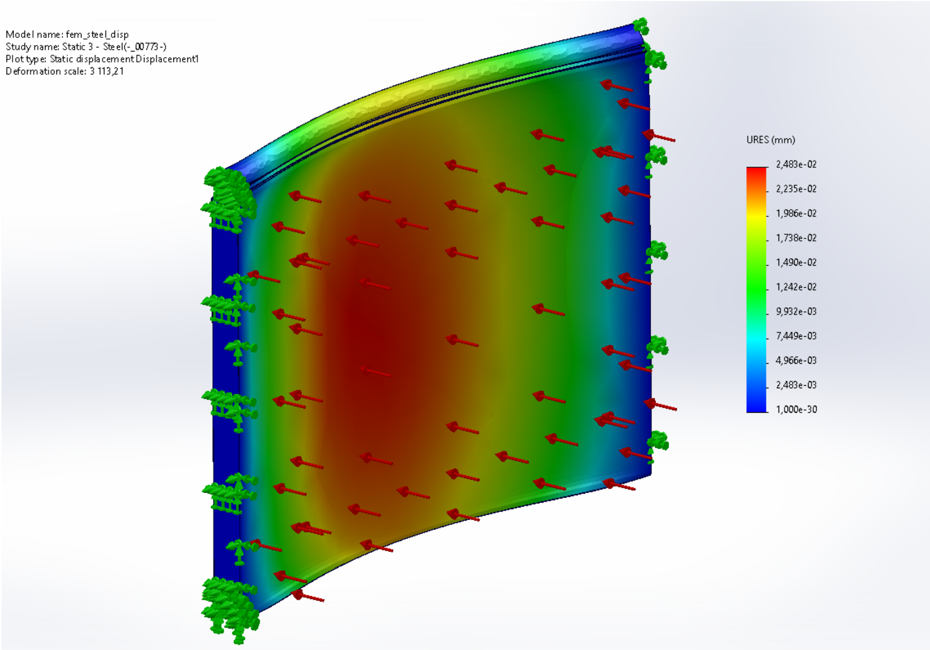


Figure 6.6: Displacement results from Solidworks on Steel panel.

None of the remaining surface materials were eliminated directly at this stage as a result of the simulations. The reasoning for this is that none of the tests appeared to result in any critical failures, due to high safety factors and relatively low deformations for all materials (except perhaps TPS). Additionally, the designs could be optimised later on with higher thicknesses in order to improve the mechanical ability of concepts using materials that performed worse in these tests.

6.2 Insulation Material

Flixo was used to simulate the thermal insulation performance of the different insulation materials. Flixo is a 2D FEM simulation tool focused on thermal simulations. All insulation materials from the previous section were tested since these simulations were less time-consuming than the SolidWorks simulations.

6.2.1 Thermal Flixo Simulations

Flixo was used to determine how the thermal transmittance, also known as the U-value, of the panel changed depending on the insulation material.

Setup

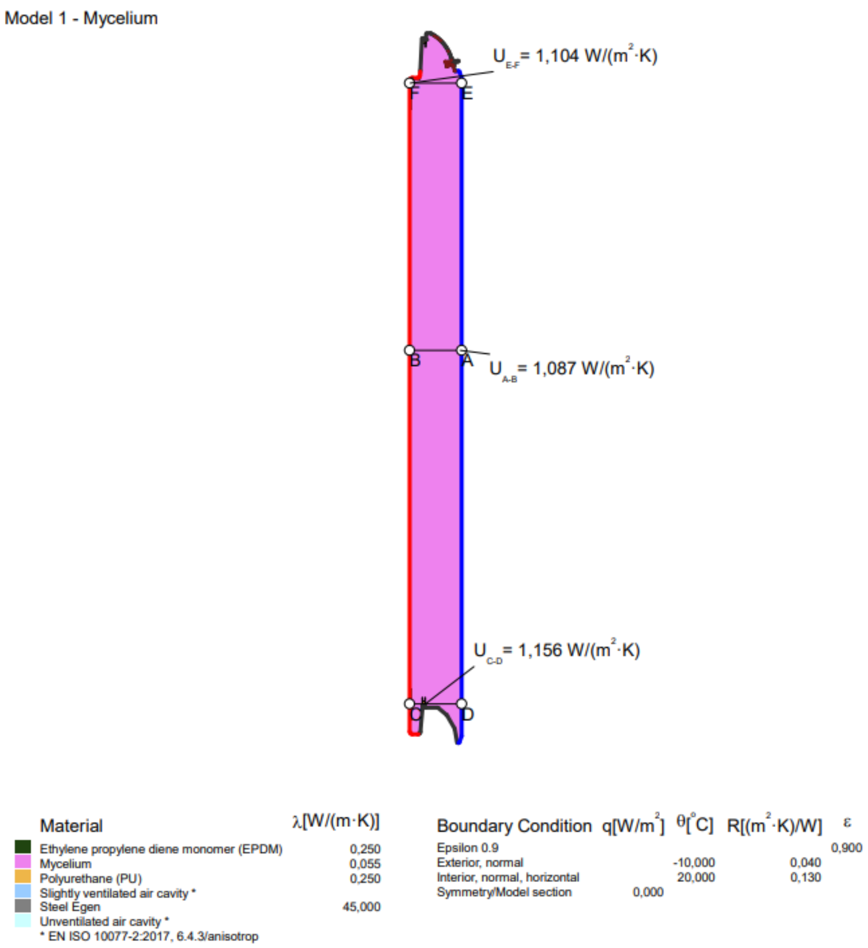


Figure 6.7: Setup with boundary conditions for panel with mycelium as insulation material.

For the setup of the panel, the boundary conditions were set up so that the panels experienced an exterior temperature of -10 degrees celsius and an inside temperature of +20 celsius, while the top and bottom parts were isolated. The surface sheet was set to steel for all simulations, while the insulation material was switched between the different candidates.

Results

The results that were obtained from the simulations were the U-values at the midsection of the panels for each insulation material in order to compare all insulation materials. Some examples of these results directly from Flixo can be seen below in Figure 6.8. A list of all results can be seen in table 6.5.

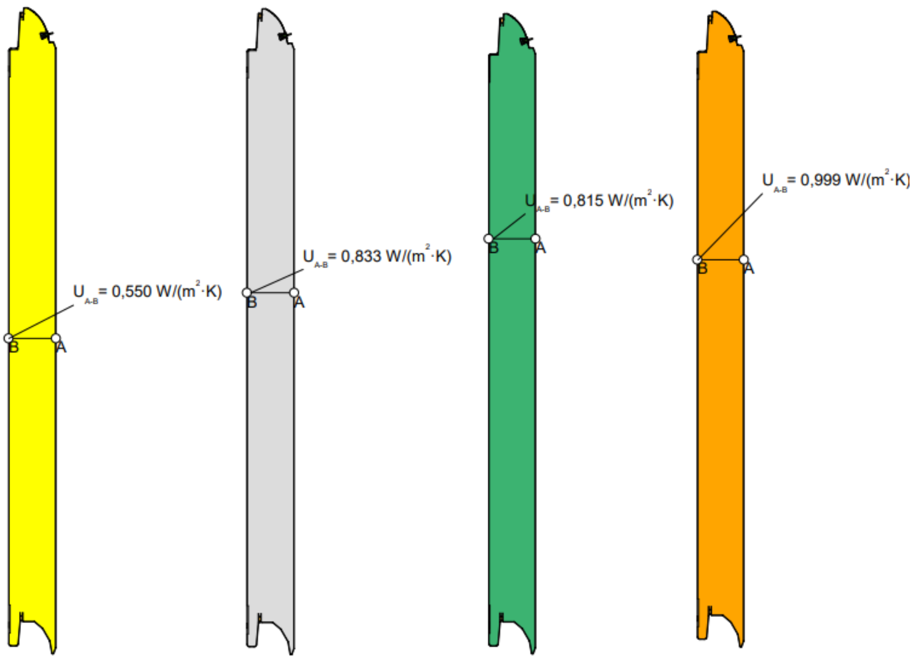


Figure 6.8: Results with U-values for the panels using the insulation materials from left to right: PUR, Cotton, Hemp, Corkboard.

Table 6.5: U-value results from the Flixo simulations.

Material	Thermal conductivity [W/mK]	U-value [W/(m^2K)]	Increase [%]	Ranking
CFC-free polyurethane	0.025	0.550	0	1
Rigid polymer foam (LD)	0.0315	0.676	22.9	2
Glass wool	0.032	0.686	24.7	3
Expanded polystyrene	0.035	0.704	28.0	4
Rock wool	0.035	0.760	38.2	5
Sheep's wool	0.037	0.778	41,5	6
Wood fibre	0.038	0.797	44.9	7
Hemp	0.039	0.815	48.2	8
Cellulose	0.04	0.833	51.5	9
Cotton	0.04	0.833	51.5	9
Flexible polymer foam (VLD)	0.042	0.868	57.8	10
Corkboard	0.0496	0.999	81.6	11
Straw bales	0.052	1.038	88.7	12
Sugar cane bagasse	0.052	1.038	88.7	12
Mycelium	0.055	1.087	97.6	13
Coconut fiber (coir)	0.057	1.288	134.2	14
Butyl rubber (IIR)	0.103	2.052	273.1	15

6.2.2 Material Elimination

The results obtained from Flixo rankings and Material rankings are presented side by side in Table 6.6.

Table 6.6: Material and Flixo ranking of insulation materials.

Material	Material Ranking	Flixo Ranking
Expanded polystyrene (EPS)	1	4
Cotton	2	9
Sheep wool	3	6
Wood fibre	3	7
Hemp	3	8
Rock wool	5	5
Glass wool	6	3
CFC-free polyurethane	7	1
Rigid polymer foam	8	2
Coconut fiber (coir)	1	14
Sugarcane bagasse	2	12
Straw bales	3	12
Mycelium	4	13
Cellulose	7	9
Flexible polymer foam	9	10
Corkboard	10	11
Butyl rubber	11	15

Insulation materials with poor performance, indicated by low rankings, were decided to be eliminated.

Although coconut fiber, sugarcane bagasse, straw bales and mycelium rank highly in the Material rankings, their thermal insulation performance is very poor (U-values over 1), leading to their elimination. It was decided that all materials that received a U-value higher than 1 (see Table 6.5) regardless of their other ranking would be eliminated as this would fail the requirement specified in the product specifications.

Butyl rubber also failed this while at the same time scoring the worst in the material rankings, making this a clear elimination.

Cellulose, flexible polymer foam and corkboard were below the U-value of 1, but not by much. This combined with the fact that they all scored poorly in the material rankings as well lead to them being eliminated.

6.3 Final Material Ratings

After the testing was complete, the weighted scoring matrices from Chapter 5 were updated based on the test results.

For the cover material matrix (Table 6.7), the ”mechanical” column was replaced with the two columns ”Safety Factor” and ”Deformation”, where each material's score was based on their results from the calculations and FEM simulations in Chapter 6.1.

For the insulation material matrix Table 6.9), the ”thermal” column was replaced with the column ”Thermal (Flixo)”, where each material's score was based on their results from the thermal simulations with Flixo from Chapter 6.2.

Table 6.7: Surface material weighted scoring matrix updated with mechanical test results.

		Cost	Weight	Sustainability	Thermal	Durability	Safety Factor	Deformation	Total
Material	Wt	0.15	0.05	0.35	0.05	0.10	0.15	0.15	1
Steel	R	3	3	3	3	3	3	3	21
	WS	0.45	0.15	1.05	0.15	0.3	0.45	0.45	3
Aluminium	R	2	4	2	2	5	2	2	19
	WS	0.3	0.2	0.7	0.1	0.5	0.3	0.3	2.4
Bamboo	R	2	5	5	4	1	1	2	20
	WS	0.3	0.25	1.75	0.2	0.1	0.15	0.3	3.05
Scots Pine	R	3	5	5	5	1	2	1	22
	WS	0.45	0.25	1.75	0.25	0.1	0.3	0.15	3.25
Teak	R	1	5	5	4	1	2	1	19
	WS	0.15	0.25	1.75	0.2	0.1	0.3	0.15	2.9
White Oak	R	1	5	5	4	1	2	1	14
	WS	0.15	0.25	1.75	0.2	0.1	0.3	0.15	2.9
Starch-based thermoplastics (TPS)	R	2	4	4	4	1	1	1	17
	WS	0.3	0.2	1.4	0.2	0.1	0.15	0.15	2.5

When setting up this new weighted scoring matrix using the mechanical test results, it was intended that the mechanical categories (safety factor & deformation) now would hold a higher weight than previously. Therefore they were put at 15 % weight each, and to achieve this, all other categories except sustainability had their weight reduced by 5 %.

For the "Safety Factor" scores, steel with a safety factor of 49.92 was set as the baseline 3 score. Any materials with a safety factor between 10 and 30 (Aluminium, Scots Pine, Teak and White Oak) got a score of 2. Materials with a safety factor less than 10 (Bamboo and TPS) got a score of 1.

For the "Deformation" scores, steel with a max deformation of 0.02483 mm was set as the baseline 3 score. Materials with a max deformation between 0.03 and 0.09 (Aluminium and Bamboo) got a score of 2. Materials with a deformation above 0.09 (Teak, White Oak, TPS and Scots pine) got a score of 1.

The updated scoring matrix gave the surface materials the rankings seen in the table below:

Table 6.8: Surface material rankings after weighted scoring.

Material	Weighted Score	Ranking
Steel	3	-
Aluminium	2.4	-
Scots Pine	3.25	1
Bamboo	3.05	2
Teak	2.9	3
White Oak	2.9	3
Starch-based thermoplastics (TPS)	2.5	4

Table 6.9: Insulation material weighted scoring matrix updated with thermal test results.

		Cost	Weight	Sustainability	Thermal (Flixo)	Mechanical	Durability	Total
Material	Wt	0.15	0.10	0.35	0.25	0.10	0.05	1.00
CFC-free polyurethane	R	3	3	3	3	3	3	18
	WS	0.45	0.3	1.05	0.75	0.3	0.15	3.0
Cotton	R	3	5	5	2	1	2	18
	WS	0.45	0.5	1.75	0.5	0.1	0.1	3.4
Expanded polystyrene (EPS)	R	4	4	4	3	4	2	21
	WS	0.6	0.4	1.4	0.75	0.4	0.1	3.65
Glass wool	R	2	3	4	3	1	5	18
	WS	0.30	0.3	1.4	0.75	0.1	0.25	3.1
Hemp	R	4	3	5	2	2	1	17
	WS	0.6	0.3	1.75	0.5	0.2	0.05	3.4
Rigid polymer foam (LD)	R	1	3	1	3	4	4	16
	WS	0.15	0.3	0.35	0.75	0.4	0.2	2.15
Rock wool	R	2	3	4	3	2	5	19
	WS	0.30	0.3	1.4	0.75	0.2	0.25	3.2
Sheep's wool	R	3	5	5	3	1	1	18
	WS	0.45	0.5	1.75	0.75	0.1	0.05	3.6
Wood fibre	R	5	1	5	2	2	2	17
	WS	0.75	0.1	1.75	0.5	0.2	0.1	3.4

For the updated scoring matrix of the insulation materials, the thermal simulation results now received a weight of 0.25 instead of 0.05, which was achieved by reducing the weights of all other categories except sustainability by 0.05.

Cotton, hemp, and wood fibre received a score of 2, with U-values around 0.8, and the rest of the materials with lower U-values scored a 3.

Table 6.10: Insulation material rankings after weighted scoring.

Material	Weighted Score	Ranking
CFC-free polyurethane	3.0	-
Expanded polystyrene (EPS)	3.65	1
Sheep wool	3.6	2
Cotton	3.4	3
Wood fibre	3.4	3
Hemp	3.4	3
Rock wool	3.2	4
Glass wool	3.1	5
Rigid polymer foam (LD)	2.15	-

Rigid polymer foam was eliminated at this stage, due to its total score being significantly lower than the other materials (in large part due to poor sustainability).

6.4 Discussion

6.4.1 Surface Materials

The FEM simulations run on Solidworks were simplified, and the specific decimal values gained from them should not be taken at face value. One example of a simplification was that the mesh used in the simulation was very primitive, which needed to be the case in order for the hardware to have sufficient memory to run the simulations. If the simulations would be redone on more powerful hardware, they could use more detailed meshes to get more accurate results. Another simplification was that a lot of smaller parts were excluded from the analysis, leaving the outer sheet and the insulation material. Finally, two other simplifications where that the CAD model used in the simulation was a cut out section of a panel and not the whole length (which also lowered demands of the simulation) and that the restricting boundary conditions at the sides of the panel where both set as fixed, as opposed to allowing free rotation as seen in the beam calculations.

The final two points are the main reason for the difference between the deflections from the beam deflection calculations and the deformations in the FEM simulations. However, when comparing the simulation results for the simulated deformation with the deflection calculations, the rankings turned out the same, and the scale of the deformations was in similar magnitudes in both cases.

In conclusion, despite the slight differences in results from the calculations and simulations, they both provided the same rankings to evaluate the materials on when it came to deformations. When it came to stress, the rankings provided differed slightly from the deformation rankings, which would also be taken into account during evaluations. However, since all materials had such high safety factors, with no risk of reaching their maximum stress, it would be prioritized to instead compare the deflection caused by different materials in later chapters, as this was more likely to lead to issues. In general, for all the results, none were deemed critical enough to directly eliminate any materials solely based on them, and each material instead received further evaluations based on how they ranked.

6.4.2 Insulation Materials

When using the U-value of 1 as a cut off point for eliminating insulation materials, it should be noted that this is the requirement for the U-value put on the entire door and not specifically on the panels. Therefore a panel that reaches a U-value below 1 could still be part of a door that fails this requirement due to another sensitive area. However, the materials that had a U-value above 1 already here in just the panel would be guaranteed to fail for the whole door, so it still made sense to eliminate those that failed here.

Additionally, the U-value results obtained from the Flixo simulations where all from the center point of the panel which is the part with the best insulation, with slightly higher U-values in other parts as seen in the setup image. However these differences within the different locations weren't too extreme, so the midpoint was used as a point of comparison mainly for simplicity. Most importantly, the main point of these tests, as was the case for the mechanical simulations, was to compare the different materials in order to see which performed best and how much they differed. For this, these tests provided sufficient results for evaluation. For more insight into how well the doors would fulfill the insulation requirements with new materials, more comprehensive insulation testing would need to be done.

7 Concept Generation

With the remaining materials, concepts were generated by combining a surface material with an insulation material. It was decided to generate eleven concepts in total, see Table 7.1. These will later be tested during Concept Testing to see how well it performs.

7.1 Concept Combination

Table 7.1: Concept generation matrix.

		Surface Material				
		Bamboo	Scots Pine Top score	Teak	White oak	TPS
Insulation Material	Cotton	Concept 11				
	Expanded polystyrene (EPS)			Concept 8		Concept 10
	Glass wool		Concept 7		Concept 9	
	Hemp		Concept 4			
	Rock wool	Concept 5		Concept 3		
	Sheep's wool - Top Score	Concept 6	Concept 1			
	Wood fibre		Concept 2			

When combining the materials into concept, it was ensured each material was used at least once, as all of the ones that had gone through to this stage had been assessed to have potential. When deciding on which combinations to form though, more concepts were generated with the materials that had scored higher. For materials that were lacking in certain aspects, some combinations were made where the two materials could compensate for each other's weaknesses. For example, TPS, which was by far the weakest surface material used EPS as insulation which was the strongest. Other combinations with TPS would very likely be far too weak.

7.2 Discussion

With only 11 out of the 35 possible concepts generated a significant number of potential ideas are left unexplored. Consequently, there is a risk that some of the ungenerated concepts might have been viable or even superior. However, the approach taken during concept combination is believed to have reduced the risk of this happening.

Firstly, each material was ensured to be used at least once in the concept generation process. This inclusion ensured that no promising material was entirely overlooked.

Secondly, more concepts were generated with higher-scoring materials since they were more likely to be effective combinations. However, there is the risk of missing the better concept even among the high-scored-material concepts. For example, scots pine as the top scorer generated four concepts, but there are three other insulation materials it did not combine with which might be a better concept.

8 Concept Testing

In this chapter, the optimal thickness of the surface materials of the selected concepts was calculated along with its mass, by setting the deflection to be as the original panel in steel. Thereafter, the thermal transmittance was simulated, and the carbon emissions were computed with the new design. Comparisons were made and a few final concepts were selected in the end.

8.1 Calculation of Thickness for Surface Material

For different materials, different thicknesses might be more favorable in terms of deflection and maximum stress, since the stiffness is different. To find a suitable thickness of the surface material for each concept, the beam deflection formula was used to solve for h_1.

The maximum deflection was assumed to be equal to that of the original steel panel, $v_{max} = 21.0$ mm.

With the same definition as before in Eq.(6.1), Eq.(6.2), Eq.(6.3), and Eq.(6.4), and all the expressions that are dependent on the unknown h_1 defined as:

$$h_2 = 0.042 - 2h_1$$
$$d_1 = \frac{h_1}{2} + \frac{h_2}{2}$$
$$A_1 = b_1 h_1$$

Matlab was then used to solve h_1, which is the thickness of the surface material. This calculation was conducted for each generated concept. With the known thickness, the mass of each generated concept was also calculated.

8.1.1 Initial Concept Results

Table 8.1: Initial results of the ten generated concepts.

Concept	Surface material	Insulation material	Thickness [mm]	Deflection [mm]	Mass [kg]
Original	Steel	PUR	0.4	21.0	104.9
1	Scots pine	Sheep wool	21.0	24.6	397.4
2	Scots pine	Wood fibre	21.0	24.6	397.4
3	Teak	Rock wool	13.8	21.0	233.2
4	Scots pine	Hemp	21.0	24.6	397.4
5	Bamboo	Rock wool	5.79	21.0	121.6
6	Bamboo	Sheep wool	5.79	21.0	112.9
7	Scots pine	Glass wool	21.0	24.6	397.4
8	Teak	EPS	13.8	21.0	229.5
9	White oak	Glass wool	14.5	21.0	349.5
10	TPS	EPS	21	186	734.8
11	Bamboo	Cotton	5.79	21.0	112.9

The computation of the eleven generated concepts yielded unexpected results. In the case of scots pine, it was found that the required thickness of the surface material to achieve equivalent deflection to the original panel exceeded the total maximum allowable panel thickness of 42 mm. Consequently, the maximum deflection was recalculated using the maximum allowable thickness of 21 mm for one surface. The analysis revealed that at a thickness of 21 mm for each outer layer, the maximum deflection reached 24.6 mm, resulting in a corresponding mass of 397.4 kg for a solid block of scots pine wood. From the Product specifications, Table 4.1, the ideal value of the mass is 13 kg/m^2. For a 3600x3600 mm door, that would be approximately 168 kg. In conclusion, the mass of the scots pine block has surpassed the acceptable limit.

For the TPS material, despite maximizing the thickness, the observed deflection remained unacceptably high. Thus, scots pine and TPS are consequently excluded.

The thickness of the teak and white oak concepts did not surpass the maximum allowable thickness. However, the mass exceeded the acceptable limit. Therefore, it was decided to allow teak and white oak to have a higher deflection, 25.0 mm instead of 21.0, to see if it would reduce the mass to within an allowable limit.

It was observed that Young's modulus values of the insulation materials' impact on the required thickness of the surface material were negligible. Only the mass varied, while the thickness remained largely unaffected. Considering this, it would be most beneficial to prioritize those with low thermal conductivity and high sustainability.

8.1.2 New Concept Results

Teak and white oak require a thicker outer layer than bamboo due to their lower Young's modulus. This leads to a much higher panel weight, than the original panel made out of steel and polyurethane foam. Alternatively, if the deflection can be allowed to be slightly higher the mass and thickness might reduce to a more acceptable value.

To test this theory, Concepts T2 and W2 are computed with a permissible deflection of 25 mm.

Table 8.2: Teak and white oak with low density sheep wool as insulation.

Concept	Surface material	Insulation material	Thickness [mm]	Deflection [mm]	Mass [kg]
T2	Teak	Sheep wool	8.88	25.0	151.3
W2	White oak	Sheep wool	9	25.0	220.0

Even when combined with an insulation material with the lowest density the mass of Concept W2 is still too high, see Table 8.2. It is therefore decided to not proceed with concepts with white oak.

The mass of T2 is below the limit. Therefore, the teak-concepts are recalculated allowing a higher deflection to see if the mass is within acceptable span.

Since there are only two surface materials and seven insulation materials remaining, it was decided to calculate the mass, U-value, and carbon emissions of all the possible combinations. PUR as an insulation material is also considered a possible concept and therefore also calculated.

Table 8.3: Bamboo concepts.

Concept	Surface material	Insulation material	Thickness [mm]	Deflection [mm]	Mass [kg]
B2	Bamboo	Sheep wool	5.79	21.0	112.9
B6	Bamboo	Cotton	5.79	21.0	112.9
B5	Bamboo	EPS	5.79	21.0	113.9
B7	Bamboo	Hemp	5.79	21.0	116.9
B1	Bamboo	Rock wool	5.79	21.0	121.6
B0	Bamboo	PUR	5.79	21.0	122.4
B4	Bamboo	Glass wool	5.79	21.0	124.0
B3	Bamboo	Wood fibre	5.79	21.0	148.4

Table 8.3 show that the thickness is 5.8 mm for all bamboo-concepts. The bamboo and wood fibre combination has a noticeably higher mass than all the other, but is still under the limit.

Table 8.4: Teak concepts.

Concept	Surface material	Insulation material	Thickness [mm]	Deflection [mm]	Mass [kg]
T2	Teak	Sheep wool	8.88	25.0	151.3
T6	Teak	Cotton	8.88	25.0	151.3
T5	Teak	EPS	8.88	25.0	152.0
T7	Teak	Hemp	8.88	25.0	154.4
T1	Teak	Rock wool	8.88	25.0	158.2
T0	Teak	PUR	8.88	25.0	158.8
T4	Teak	Glass wool	8.88	25.0	160.1
T3	Teak	Wood fibre	8.88	25.0	179.5

It seems that allowing a higher deflection minimizes the thickness significantly, as presented in Table 8.4. This in turn reduces the mass greatly so that most of the concepts are within acceptable range. However, Concept T3 with wood fibre as insulation exceeds the allowed value. It will therefore not be looked into any further.

8.2 Calculation of U-Value

Flixo simulations were performed to calculate the U-values of the new concepts with their respective material combinations and thicknesses. With a new thickness on the surface material on the remaining concepts, new CAD models were prepared. These models were then used to calculate the U-value of the concepts.

8.2.1 New CAD Models

The models prepared in CAD were greatly simplified since the purpose is only to calculate new U-value of the panel in its middle part. The thickness of the surface material was changed depending on material based on the results from the previous tables. The connecting parts of the panel were disregarded.

Figure 8.1: New CAD models for the Teak and Bamboo concepts with new surface thickness applied.

Three blocks of rectangles were created and assembled to resemble the outer surfaces and the insulator.

8.2.2 Flixo Setup

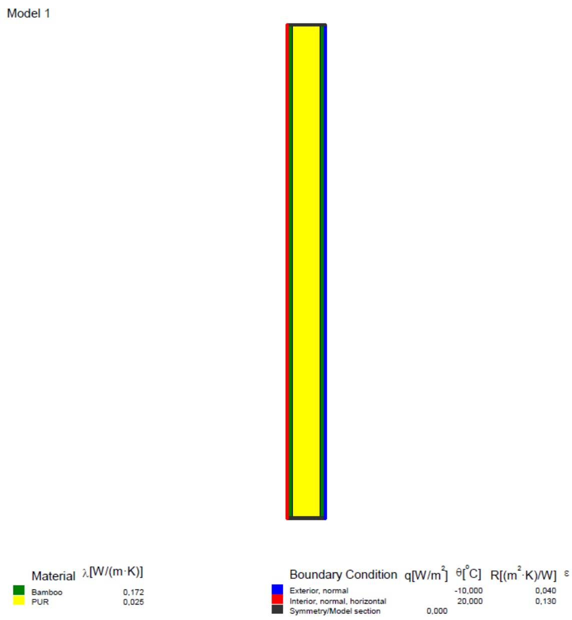


Figure 8.2: Boundary conditions used for this round of Flixo testing.

The setup of the panel is the same as the setup from the previous Flixo simulation, with the model being slightly different. The boundary conditions were set to the exterior temperature being -10 degrees Celsius and an inside temperature of +20 degrees Celsius. The top and bottom parts were isolated. The U-value of the bamboo concepts and teak concepts presented in Table 8.3 and 8.4, were then calculated.

8.2.3 Flixo Results

Table 8.5: U-values of the bamboo concepts.

Concept	Surface material	Insulation material	U-Value [W/m^2K]
B0	Bamboo	PUR	0.688
B4	Bamboo	Glass wool	0.842
B5	Bamboo	EPS	0.863
B1	Bamboo	Rock wool	0.924
B2	Bamboo	Sheep wool	0.944
B3	Bamboo	Wood fibre	0.964
B7	Bamboo	Hemp	0.983
B6	Bamboo	Cotton	1.002

Table 8.6: U-values of the teak concepts.

Concept	Surface material	Insulation material	U-Value [W/m^{2}K]
T0	Teak	PUR	1.029
T4	Teak	Glass wool	1.182
T5	Teak	EPS	1.201
T1	Teak	Rock wool	1.256
T2	Teak	Sheep wool	1.273
T3	Teak	Wood fibre	1.290
T7	Teak	Hemp	1.306
T6	Teak	Cotton	1.322

The concepts in Table 8.5 and 8.6 is ordered with the lowest U-value at the top and highest at the bottom of the list. As can be seen, the combination of bamboo and PUR has the best thermal insulation out of all concepts. The teak and cotton combination has the least beneficial thermal insulation.

Another thing worth noting is that all the concepts with teak as the surface material has a significantly higher U-value than concepts with bamboo as the surface material. This is due to the reason that the teak concepts has a higher thickness on the outer layer. The surface material does not insulate well. Therefore, It will be less beneficial with a thinner insulation.

Seeing that all teak concepts are above the U-value of 1.0 W/m^{2}K, it means they do not fulfill the requirements. Therefore, the teak concepts will not be further analyzed.

The U-value of the bamboo and cotton concept is right at the limit. This will be taken into consideration further on.

8.3 Calculation of Carbon Emissions

The carbon emission of each potential concept was calculated. This was done with the help of data gathered on the density and GWP values in Chapter 5. By computing the mass of individual components and multiplying them by the respective material's GWP value, the carbon emissions were determined. The results are shown below in Table 8.7.

Table 8.7: Carbon emissions of bamboo concepts.

Concept	Surface material	Insulation material	Carbon emission [kgCO2]
B7	Bamboo	Hemp	110.8039
B6	Bamboo	Cotton	114.4355
B2	Bamboo	Sheep wool	117.3524
B1	Bamboo	Rock wool	130.6751
B5	Bamboo	EPS	132.9703
B3	Bamboo	Wood fibre	146.7933
B4	Bamboo	Glass wool	157.1632
B0	Bamboo	PUR	202.6769

Results show that Concept B7 consisting of bamboo and hemp emits the least carbon emissions out of the remaining concepts. Conversely, Concept B0 consisting of bamboo and PUR is the least sustainable option with almost double the emission as Concept B7 and significantly higher emissions than the other options.

8.4 Calculation of Costs

The cost of the concept panels is calculated with the help of previously gathered data in Chapter 5. In the same way as before, the mass of individual components is computed and then multiplied by the cost value to determine the cost of the panel. The measurement of the panel is 545x3600 mm. Results are shown in Table 8.8.

Table 8.8: Costs of the bamboo concept panels with the measurements 545x3600 mm.

Concept	Surface material	Insulation material	Cost [SEK]
B5	Bamboo	EPS	176
B2	Bamboo	Sheep wool	249
B6	Bamboo	Cotton	249
B7	Bamboo	Hemp	255
B1	Bamboo	Rock wool	263
B4	Bamboo	Glass wool	267
B3	Bamboo	Wood fibre	307
B0	Bamboo	PUR	308

Concept B5 consisting of bamboo and EPS has the lowest cost out of all the concepts. It is also the only concept under 200 SEK. Once again, Concept B0 consisting of bamboo and PUR shows the least promising result, being the highest cost. Concept B3 with wood fibre as insulation is equally as expensive as B0.

8.5 Concept Selection

8.5.1 Weighted Scoring Matrix

A new weighted scoring matrix was setup to score the remaining concepts in order to decide the final ones. In this matrix, the concepts were scored only from 1-3 since they did not have large spreads in the different categories. The original panel was not used as a reference material (that only scored 3) like previously since all of the new concepts would just end up on one side of this anyway. This way gave a more valuable comparison between the concepts themselves.

Table 8.9: Weighted scoring matrix for remaining concepts.

		Cost	Weight	Sustainability	U-value	Total
Concept	Wt	0.20	0.10	0.4	0.3	1.00
B0	R	1	3	1	3	8
	WS	0.2	0.3	0.4	0.9	1.8
B1	R	2	2	2	1	7
	WS	0.4	0.2	0.8	0.3	1.7
B2	R	2	3	3	1	9
	WS	0.4	0.3	1.2	0.3	2.2
B3	R	1	1	2	1	5
	WS	0.2	0.1	0.8	0.3	1.4
B4	R	2	2	2	2	8
	WS	0.4	0.2	0.8	0.6	2.0
B5	R	3	3	2	2	10
	WS	0.6	0.3	0.8	0.6	2.3
B6	R	2	3	3	1	9
	WS	0.4	0.3	1.2	0.3	2.2
B7	R	2	3	3	1	9
	WS	0.4	0.3	1.2	0.3	2.2

For the cost criteria, the scoring weight was set to 15 % as the cost of the eventual product would have a large impact on whether it is feasible to produce. For this critera, the scores were based on the costs calculated for the concepts in Table 8.8. Here, concepts with a cost above 300 SEK scored a 1, concepts with a cost between 200-300 SEK scored a 2 and concepts with a cost below 200 SEK scored a 3.

For the weight (mass) criteria the score weight was set low at 10 % as all of the concepts were below the required weight anyway, and a further reduced weight would not have as major advantages as other categories. However, low weight is still advantageous for example when it comes to transport and energy required to lift the eventual door. The scores given to the concepts for this criteria were based on the masses the concepts received in Table 8.3. Concepts with a weight of 110 - 120 kg were scored a 3, concepts with a weight of 120-130 kg were scored a 2, and the concept with a weight of 148.4 kg was scored a 1.

For the sustainability criteria, this was once again set to the highest weight, at 40 %, as improved sustainability was the main goal of the new concepts. The scores were based on the emissions calculated in Table 8.7. The concepts with emissions below 130 kgCO2 scored a 3, the ones with emissions above 200 scored a 1, and the ones in between scored a 2.

For the U-value (thermal) criteria, this was set to the second highest weight of 0.3 as this is a major part of the panels functionality. The scores were based on the U-values calculated for the concepts in Table 8.5. The concepts with a U-value below 0.7 scored a 3, the concepts with a U-value between 0.8-0.9 scored a 2 and the concepts with a U-value above 0.9 scored a 1.

No mechanical criteria was used in these evaluations, as all concepts used the same surface material, and the insulation material had minimal effect on the deflection as shown previously.

8.5.2 Final Concept Decision

After having completed the scoring matrix, concept B5 (Bamboo and EPS) was the overall winner with the highest score. This became Concept 1 of our final concept, which overall performed best.

In second place, however there were three concepts tied at a score of 2.2. Although these generally performed quite similar when going back and looking at the values for the different criteria, it was decided to go through with concept B7 (Bamboo and Hemp) as an alternative concept, since this overall performed best of all concepts when it came to emissions. This became Concept 3, which was our sustainability focused alternative.

As our final concept, concept B0 (Bamboo and PUR) was selected as another candidate. Although this concept in total only scored 1.8 in the scoring matrix, this was by far the best concept from an insulation perspective when looking at the U-values for the different concepts. Therefore this became Concept 2, which is the more performance-focused alternative.

A detailed presentation of the final concepts and a comparison between those and the original panels will be presented in the next chapter.

9 Final Concepts

From the previous chapter, three final concepts were chosen: the first concept consisting of bamboo and EPS which scored the highest, the second concept with bamboo and PUR which is performance-focused offering the best thermal insulation of the remaining concepts, and the third concept with teak and hemp which is sustainability-focused with lowest total emissions. In the following section, a detailed presentation of each final concept is provided. These concepts will then be compared to the original panels and be given a final evaluation.

9.1 Concept Presentation

Concept 1 – B5 (Bamboo & EPS)

Sustainability and Carbon emissions:
Concept B5, which combines bamboo and EPS, presents a highly sustainable solution with significantly reduced carbon emissions. According to calculations presented in Chapter 8.3, this combination emits more than 2.5 times lower carbon emissions compared to the original steel panel. Additionally, the entire panel is fully recyclable, enhancing its environmental benefits.

Thermal Insulation Performance:
The thermal performance of Concept B5, measured by its U-value, is the third best among the evaluated concepts in Chapter 7. Although the U-value is still 1.5 times higher than that of the original steel panel, it represents a substantial improvement in insulation relative to other sustainable alternatives.

Cost Analysis:
In terms of cost, both bamboo and EPS are relatively inexpensive materials. Using previously gathered data, the cost for a 545x3600 mm panel of Concept B5 is calculated to be 251 SEK, compared to 176 SEK for the original steel panel. This indicates a moderate increase in material cost for a significantly more sustainable product.

Durability and Treatment Enhancements:
While bamboo's environmental durability is initially lacking, its water and fire resistance can be significantly improved through appropriate treatment processes. EPS, on the other hand, inherently possesses good water resistance but requires treatment to meet fire resistance standards. These treatments are essential to ensure the panel meets all necessary durability requirements.

Structural Integrity:
Simulations in Chapter 6 revealed that bamboo has the lowest safety factor among the materials tested. However, adjustments to the thickness of the surface layer have been made, which are expected to enhance the overall strength and safety of the panel.

In summary, Concept B5 demonstrates a promising balance between sustainability and performance. While there are areas needing improvement, particularly in durability and structural safety, the environmental and economic benefits make it a viable alternative to traditional steel panels.

Concept 2 (Performance) - B0 (Bamboo & PUR)

Thermal Insulation Performance:
The second selected concept which focuses on performance, combines bamboo with polyurethane (PUR), achieving the best U-value among all evaluated concepts. However, this concept does not take sustainability into account.

Sustainability and Carbon Emissions:
Despite having the highest carbon emissions among the evaluated concepts, Concept B0 still achieves a significant reduction of approximately 43 % in emissions compared to the original steel panel, as shown in Chapter 7. Additionally, both bamboo and PUR are recyclable, with bamboo also being biodegradable, enhancing the overall environmental performance of the panel.

Cost Analysis: Bamboo remains a relatively low-cost material, while PUR is moderately priced. According to previously gathered data, the cost for a 545x3600 mm panel of Concept B0 is calculated to be 308 SEK. This represents an increase in cost compared to the original steel panel, but reflects the improved sustainability.

Durability and Treatment Enhancements:
Bamboo's environmental durability is initially limited, but it can be enhanced through treatments to improve water and fire resistance. PUR, on the other hand, has acceptable environmental durability with good water resistance and a B2 fire classification, making it a suitable material for this application.

Structural Integrity:
As noted before, bamboo has the lowest safety factor among the materials tested. However, the thickness of the surface layer has been adjusted, which is expected to improve the overall strength and safety of the panel.

In summary, Concept B0 offers exceptional thermal insulation and a considerable reduction in carbon emissions compared to traditional steel panels. While there are cost and durability considerations, the improvements in sustainability with a decent thermal performance make this bamboo-PUR concept a promising option for high-performance applications.

Concept 3 (Sustainability) - B7 (Bamboo & Hemp)

Sustainability and Carbon Emissions:
Concept B7 with a focus on sustainability combining bamboo and hemp, is designed to maximize sustainability. As detailed in Chapter 8, this concept has the lowest carbon emissions of all evaluated options. Additionally, both bamboo and hemp are recyclable and biodegradable which further enhances the environmental benefits of this panel.

Thermal Insulation Performance:
The U-value of Concept B7, however, is the second highest among the concepts simulated in Chapter 8. It has more than twice the thermal conductivity of the original steel panel, indicating lower insulation efficiency.

Cost Analysis:
Hemp is a relatively inexpensive material, as is bamboo. From the previous calculations, this concept would end up at a cost of 255 kr making it the lowest out of the three concepts.

Durability and Treatment Enhancements:
Hemp has very low water resistance and fire resistance. Potential treatments to improve these properties need to be explored.

Structural Integrity:
Mechanically this concept performs similarly to the previous concepts, as it also contains bamboo for the surface layer, which has the highest impact.

In summary, Concept B7 offers the best sustainability with significantly lower carbon emissions and biodegradable materials, while also being the cheapest. However, it falls behind in performance with the worst insulation ability out of the three concepts.

9.2 Final Evaluation

In order to further evaluate how the three final concepts performed against each other as well as the original steel and aluminium panels, a set of bar charts where put together to clearly demonstrate differences. These were made for carbon emissions, thermal insulation and cost.

9.2.1 Carbon Emissions

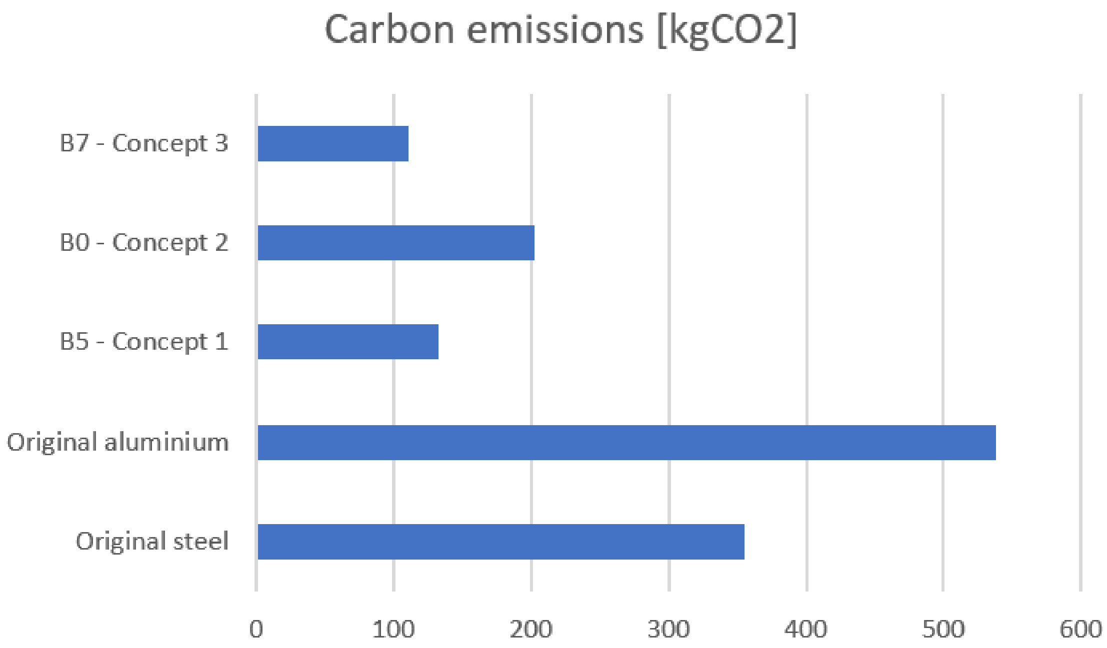


Figure 9.1: Carbon emissions of the final concepts compared to the original panel designs.

Figure 9.1 presents a comparison of carbon emissions across various concepts and to the original steel design and aluminium. According to the data depicted, Concept 3 exhibits the least carbon emissions, followed by Concept 1, Concept 2, the original steel configuration, and lastly the original aluminium configuration. This analysis suggests that Concept 3 demonstrates the most favourable environmental performance among the evaluated alternatives.

In considering the end-of-life implications for our concepts, it's essential to note their environmental impact post-utilization. Concept 3, with a combination of teak and hemp, exhibits great biodegradability, offering a possibility for natural decomposition. It also retains some recyclability potential, underscoring its versatility in waste management strategies.

Meanwhile, Concepts 1 and 2, consisting of bamboo and EPS respectively bamboo and PUR, emphasizes recyclability as its primary end-of-life strategy. While the recyclable aspect is promising, the non-biodegradable nature of EPS raises concerns regarding long-term environmental consequences.

9.2.2 Thermal Insulation

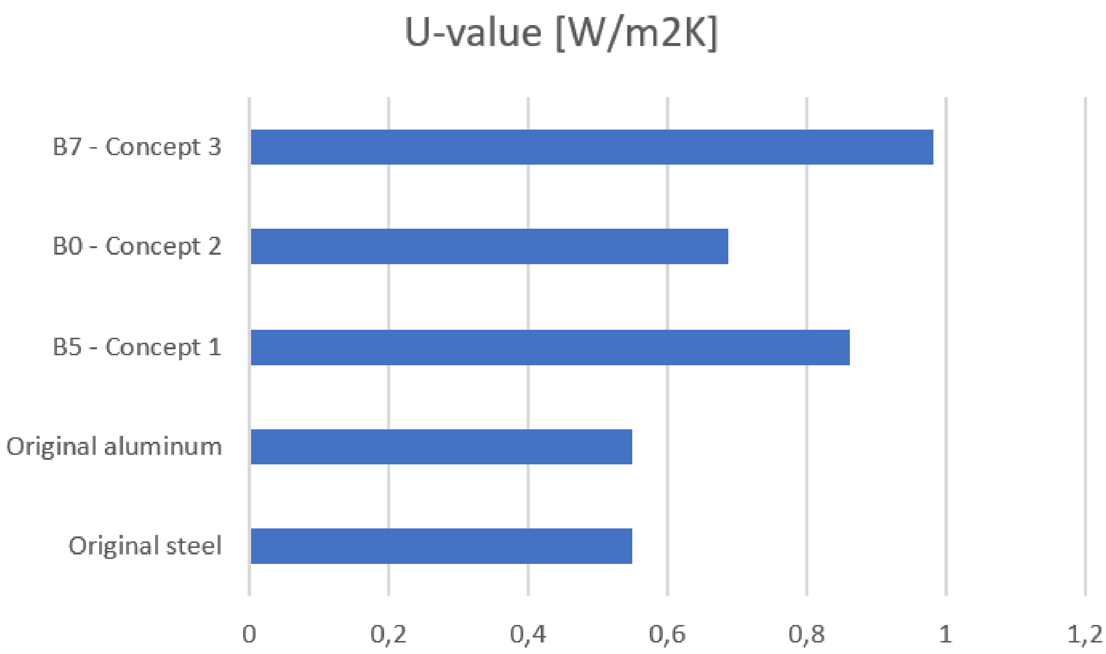


Figure 9.2: U-value of the final concepts compared to the original panel designs.

Figure 9.2 presents the calculated U-value of the final concepts and the original panel designs in steel and aluminium. Results show that the original panels perform the best thermally, followed by B0, B5, and B7.

All three concepts had higher U-values than the original panels, with Concept 2 being the closest. The lowered thermal insulation performance in the final concepts is primarily due to the increased thickness of the surface layer which reduced the insulation layer when keeping the same total thickness in the panel. It should however be noted that all three concepts had a U-value below 1.0 which was set by the group as the maximum allowed cut off point, due to this value being in the requirements for the door.

9.2.3 Price

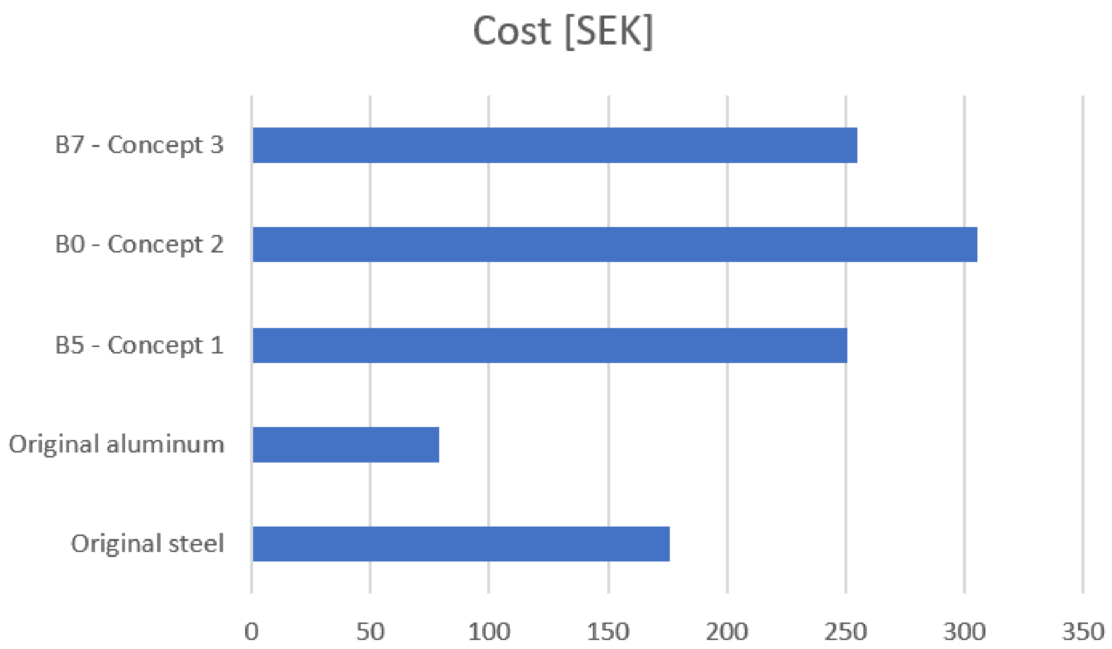


Figure 9.3: Costs of the final concepts compared to the original panel designs.

Figure 9.3 shows the price of a 545x3600 mm panel for each final concept and original panels in steel and aluminium. As can be seen, the panel in aluminium has the lowest price, followed by the steel panel, B5, B7, and finally B0.

10 Conclusion

This paper aimed to explore alternative materials for an overhead sectional door to improve sustainability. Initially, an investigation was conducted to determine which part of the door to target by performing emission calculations. The results indicated that changing the material in the Panel Section would have the most significant impact.

Subsequently, the research identified several promising materials to replace the existing ones in the Panel Section. These alternatives demonstrated significant improvements in environmental impact compared to traditional materials. Three final concepts, B0 (bamboo and PUR), B5 (bamboo and EPS), and B7 (bamboo and hemp) were chosen for a final evaluation. Calculations showed that the surface layers of these concepts need to be increased from 0.4 mm to 5.8 mm to achieve the same strength as the current panels.

Concepts B0, B5, and B7 showed a significant reduction in carbon footprint compared to the original panels. However, their thermal insulation performance is somewhat lower due to the increase in thickness of the surface layer. Concept B0 offers the best thermal insulation, Concept B7 offers the lowest carbon emissions and price, and Concept B5 performs best overall among the different categories.

With the improved sustainability and biodegradability of the recommended concepts, these suggestions have the potential to reduce industrial waste and carbon footprint to a significant degree. The choice between these options depends on the primary focus: achieving higher sustainability, high thermal insulation performance, or a balanced solution.

10.1 Final Discussion and Future Work

While significant insights were gained, several limitations and areas for future research have been identified.

Firstly, the data obtained for this study is subject to uncertainties. The use of unconventional materials not present in ASSA ABLOY's database posed a challenge in finding accurate data online. Additionally, attempts to contact suppliers were unsuccessful and correct values could not be gathered. To reduce errors multiple sources were consulted and compared to obtain reliable estimates, and subjective assessments were made based on qualitative factors beyond numerical data. However, this represents only initial background work. For future research, ASSA ABLOY should establish direct contact with suppliers as well as conduct physical testing of suitable materials to obtain more accurate numbers.

Secondly, this study focused solely on investigating base materials (One single material for the surface layer and one single material for the insulation layer) without any treatments or combinations with other materials. However, some material data gathered from suppliers most certainly have additives or been treated to improve its properties. There is also considerable potential for further exploration of composites and alloys, which could offer additional benefits in terms of sustainability and performance.

Moreover, the design considerations in this study were limited. Only the old design and a simple sandwich design were tested for U-value in the section with the best thermal insulation. The design of the connecting parts of the concept panels was not considered which could be a potential issue with the new material. Future research should explore new physical designs viable for bamboo and optimize both thermal performance and material sustainability.

The study focused solely on a single door model with a thickness of 42 mm. This limitation made it challenging to achieve a low U-value with the concept panels while maintaining a thicker surface layer for acceptable strength. However, the potential for using thicker panels was not fully explored and could be worth investigating with the new materials.

Lastly, simplified simulations were conducted to compare and rank the different materials. While these simulations were effective for initial comparisons, more advanced simulations should be carried out to obtain more accurate and comprehensive results.

In conclusion, while this study provides a promising foundation and concept suggestions for improving the sustainability of overhead sectional doors, further research is necessary. By addressing the identified limitations and exploring new materials and designs, ASSA ABLOY can significantly contribute to reducing industrial waste and carbon footprint, thereby advancing environmental conservation efforts in the industry.

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Appendix A - Door Configurations

Configuration 1 - Steel Panel with 0 Frame Sections

Table 1: Amount of material in each part in configuration 1.

Part	Material	Total weight [kg]
Panel section	Ethylene propylene diene elastomer (EPDM)	0.45
	Polycarbonate (PC)	0.33
	Polyurethane foam	26.73
	Steel	95.37
Bottom section assembly	Acrylonitrile butadiene (ABS)	1.44
	Ethylene propylene diene elastomer (EPDM)	5.3
	Polystyrene High Impact (HIPS)	0.48
	Steel	0.10
Rollers and roller brackets	Polyamide (PA)	0.91
	Steel	7.88
Truss	Polystyrene high impact (HIPS)	0.055
	Steel	10.83
Wall-angle and V-track	Polypropylene (PP)	1.28
	Steel	30.46
H-track and C-profile	Steel	19.35

Configuration 2 - Aluminium Panel with 0 Frame Sections

Table 2: Amount of material in each part in configuration 2.

Part	Material	Total weight [kg]
Panel section	Aluminium	36.86
	Ethylene propylene diene elastomer (EPDM)	0.45
	Polycarbonate (PC)	1.00
	Polyurethane foam	26.73
	Steel	15.91
Bottom section assembly	Acrylonitrile butadiene (ABS)	1.44
	Ethylene propylene diene elastomer (EPDM)	5.3
	Polystyrene High Impact (HIPS)	0.48
	Steel	0.10
Rollers and roller brackets	Polyamide (PA)	0.91
	Steel	7.88
Truss	Polystyrene high impact (HIPS)	0.055
	Steel	10.83
Wall-angle and V-track	Polypropylene (PP)	1.28
	Steel	30.46
H-track and C-profile	Steel	19.35

Configuration 3 - Steel Panel with 4 Frame Sections

Table 3: Amount of material in each part in configuration 3.

Part	Material	Total weight [kg]
Panel section	Ethylene propylene diene elastomer (EPDM)	0.18
	Polycarbonate (PC)	0.13
	Polyurethane foam	10.53
	Steel	37.57
Infill dad for 545x3600 frame section	Aluminium	2.12
	Siloxane	2.93
	Styrene acrylonitrile (SAN)	34.62
Insulated frame section 545x3600	Acrylonitrile butadiene (ABS)	4.98
	Aluminium	51.21
	Ethylene propylene diene elastomer (EPDM)	0.42
	Polyisobutylene	1.00
	Polyamide (PA)	3.92
	Steel	0.52
Bottom section assembly	Acrylonitrile butadiene (ABS)	1.44
	Ethylene propylene diene elastomer (EPDM)	5.3
	Polystyrene High Impact (HIPS)	0.48
	Steel	0.10
Rollers and roller brackets	Polyamide (PA)	0.91
	Steel	7.88
Truss	Polystyrene high impact (HIPS)	0.055
	Steel	10.83
Wall-angle and V-track	Polypropylene (PP)	1.28
	Steel	30.46
H-track and C-profile	Steel	19.35

Configuration 4 - Aluminium Panel with 4 Frame Section

Table 4: Amount of material in each part in configuration 4.

Part	Material	Total weight [kg]
Panel section	Aluminium	14.52
	Ethylene propylene diene elastomer (EPDM)	0.18
	Polycarbonate (PC)	0.39
	Polyurethane foam	10.53
	Steel	6.27
Infill dad for 545x3600 frame section	Aluminium	2.12
	Siloxane	2.93
	Styrene acrylonitrile (SAN)	34.62
Insulated frame section 545x3600	Acrylonitrile butadiene (ABS)	4.98
	Aluminium	51.21
	Ethylene propylene diene elastomer (EPDM)	0.42
	Polyisobutylene	1.00
	Polyamide (PA)	3.92
	Steel	0.52
Bottom section assembly	Acrylonitrile butadiene (ABS)	1.44
	Ethylene propylene diene elastomer (EPDM)	5.3
	Polystyrene High Impact (HIPS)	0.48
	Steel	0.10
Rollers and roller brackets	Polyamide (PA)	0.91
	Steel	7.88
Truss	Polystyrene high impact (HIPS)	0.055
	Steel	10.83
Wall-angle and V-track	Polypropylene (PP)	1.28
	Steel	30.46
H-track and C-profile	Steel	19.35

Table 5: Amount of material in Infill DAD and Insulated frame section with measurements 545x3600 mm

Part	Material	Total weight [kg]
Infill dad for 545x3600 frame section	Aluminium	0.53
	Siloxane	0.73
	Styrene acrylonitrile (SAN)	8.65
Insulated frame section 545x3600	Acrylonitrile butadiene (ABS)	1.24
	Aluminium	12.80
	Ethylene propylene diene elastomer (EPDM)	0.11
	Polyisobutylene	0.25
	Polyamide (PA)	0.98
	Steel	0.13

Appendix B - European Standards

This appendix presents the European standards introduced in the Product specification that ASSA ABLOY follows.

SS-EN 12424:2000 – Industrial, commercial and garage doors and gates - Resistance to wind load - Classification

"This European Standard specifies the classification for wind load for doors in a closed position. The doors are intended for installation in areas in the reach of people, for which the main intended uses are giving safe access for goods, vehicles and persons in industrial, commercial or residential premises.". [64]

Swedish Standards Institute [64] states:

- Wind load is understood as differential pressure of one side of the fully closed door leaf to the other.
- A test specimen belongs to a specified class, if the results of a full scale test, model test, component part test and/or calculations in accordance with prEN 12444:1996 show that the test specimen is able to withstand the reference wind load specified for that class.
- Tests or calculations shall also show, that the door leaf will remain in position under a peak load 1,25 times greater than the reference wind load unless otherwise required. Permanent deformations of door components are allowed in this case.
- The classes shown in table 1 indicate positive pressure. Suction or reverse direction loads have to be specified as a negative class i.e. a wind load of 300 Pa applied to the inside face of the door is shown as class -1.

Table 6: Wind load classes.

Class	Reference wind load [Pa]	Specification
0		No perfomance determined
1	300	
2	450	
3	700	
4	1000	
5	>1000	Exceptional; Agreement between manufacturer and purchaser

SS-EN 12425:2000 – Industrial, commercial and garage doors and gates - Resistance to water penetration - Classification

"This European Standard specifies the classification for resistance to water penetration for doors in a closed position, when tested in accordance with EN 12489. The doors are intended for installation in areas in the reach of people, for which the main intended uses are giving safe access for goods, vehicles and persons in industrial, commercial or residential premises.". [63]

Swedish Standards Institute [63] states:

- A test specimen belongs to a specified class when it allows no water penetration under the test conditions, if measured in accordance with EN 12489.

- The test pressure measured in pascal (Pa) is the differential pressure of one side to the other of the fully closed door.

Table 7: Classes of resistance to water penetration.

Class	Test pressure Pa (N/m^2)	Water spray specification
0		No perfomance determined
1	30	Waterspray for 15 minutes
2	50	Waterspray for 20 minutes
3	>50	Exceptional; Agreement between manufacturer and purchaser

SS-EN 12426:2000 – Industrial, commercial and garage doors and gates - Air permeability - Classification

"This European Standard specifies the classification for air permeability for doors in a closed position, when tested in accordance with EN 12427. The doors are intended for installation in areas in the reach of people, for which the main intended uses are giving safe access for goods, vehicles and persons in industrial, commercial or residential premises.". [62]

Swedish Standards Institute [62] states:

- A test specimen belongs to a specified class, if the test results measured in accordance with EN 12427 do not exceed the value specified for that class as given in table 1.

Table 8: Air permeability classes.

Class	Air permeability Δp at a pressure of 50 Pa [m^3/m^2h]	Specification
0		No performance determined
1	24	
2	12	
3	6	
4	3	
5	1.5	
6		Exceptional; Agreement between manufacturer and purchaser for both leakage and pressure.

SS-EN 12428:2013 – Industrial, commercial and garage doors - Thermal transmittance - Requirements for the calculation

"This European Standard specifies a method for calculating the thermal transmittance of industrial, commercial and garage doors in a closed position. The doors are intended for installation in areas in the reach of people, for which the main intended uses are giving safe access for goods, vehicles and persons in industrial, commercial or residential premises.". [65]

SS-EN 13501-1:2019 – Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests

"This document provides the reaction to fire classification procedure for all construction products, including products incorporated within building elements with the exception of power, control and communication cables which are covered by EN 13501-6.". [60]

Table 9: Classes of reaction to fire performance for construction products excluding floorings and linear pipe thermal insulation products.

Class	Test method(s)	Classification criteria	Additional classification
A1	EN ISO 1182 [a] and	$\Delta T \leq 30$°C; and $\Delta m \leq 50$ %; and $t_f = 0$ s (i.e. no sustained flaming)	
	EN ISO 1716	PCS $\leq 2.0 MJ/kg^{a}$ and PCS $\leq 2.0 MJ/kg^{b\ c}$ and PCS $\leq 1.4 MJ/m^{2\ d}$ and PCS $\leq 2.0 MJ/kg^{e}$	
A2	EN ISO 1182 [a] or	$\Delta T \leq 50$°C; and $\Delta m \leq 50$ %; and $t_f \leq 20\ s$	
	EN ISO 1716 and	PCS $\leq 3.0 MJ/kg^{a}$ and PCS $\leq 4.0 MJ/m^{2\ b}$ and PCS $\leq 4.0 MJ/m^{2\ d}$ and PCS $\leq 3.0 MJ/kg^{e}$	
	EN 13823	$FIGRA_{0.2\ MJ} \leq 120 W/s$ and LFS < edge of specimen and $THR_{600s} \leq 7.5 MJ$	Smoke production [f] and Flaming droplets/particles [g]
B	EN 13823 and	$FIGRA_{0.2MJ} \leq 120 W/s$ and LFS < edge of specimen and $THR_{600s} \leq 7.5 MJ$	Smoke production [f] and Flaming droplets/particles [g]
	EN ISO 11925-2 [i] : Exposure = 30 s	$F_s \leq 150$ mm within 60 s	
C	EN 13823 and	$FIGRA_{0.4MJ} \leq 250 W/s$ and LFS < edge of specimen and $THR_{600s} \leq 15 MJ$	Smoke production [f] and Flaming droplets/particles [g]
	EN ISO 11925-2 [i] : Exposure = 30 s	$F_s \leq 150$ mm within 60 s	
D	EN 13823 and	$FIGRA_{0.4MJ} \leq 750 W/s$	Smoke production [f] and Flaming droplets/particles [g]
	EN ISO 11925-2 [i] : Exposure = 30 s	$F_s \leq 150$ mm within 60 s	
E	EN ISO 11925-2 [i] : Exposure = 15 s	$F_s \leq 150$ mm within 20 s	Flaming droplets/particles [h]
F	EN ISO 11925-2 [i] : Exposure = 15 s	$F_s \leq 150$ mm within 20 s	

[a] For homogeneous products and substantial components of non-homogeneous products.

[b] For any external non-substantial component of non-homogeneous products.

[c] Alternatively, any external non-substantial component having a PCS $\leq 2,0 MJ/m^2$, provided
that the product satisfies the following criteria of EN 13823: FIGRA $\leq 20 W/s$, and LFS < edge of specimen, and $THR_{600s} \leq 4,0 MJ$, and s1, and d0.

[d] For any internal non-substantial component of non-homogeneous products.

[e] For the product as a whole.

[f] s1 = SMOGRA $\leq 30m^2/s^2$ and $\text{TSP}_{600s} \leq 50m^2$; s2 = SMOGRA $\leq 180m^2/s^2$ and $\text{TSP}_{600s} \leq 200m^2$; s3 = not s1 or s2.

[g] d0 = No flaming droplets/particles in EN 13823 within 600 s;
d1 = no flaming droplets/particles persisting longer than 10 s in EN 13823 within 600 s;
d2 = not d0 or d1.
Ignition of the paper in EN ISO 11925-2 results in a d2 classification.

[h] Pass = no ignition of the paper (no classification);
Fail = ignition of the paper (d2 classification).

[i] Under conditions of surface flame attack and, if appropriate to the end-use application of the product, edge flame attack.

SS-EN ISO 10140-2:2021 – Acoustics - Laboratory measurement of sound insulation of building elements - Part 2: Measurement of airborne sound insulation (ISO 10140-2:2021, IDT)

"This document specifies a laboratory method for measuring the airborne sound insulation of building products, such as walls, floors, doors, windows, shutters, façade elements, façades, glazing, small technical elements, for instance transfer air devices, airing panels (ventilation panels), outdoor air intakes, electrical raceways, transit sealing systems and combinations, for example walls or floors with linings, suspended ceilings or floating floors.

"The test results can be used to compare the sound insulation properties of building elements, classify elements according to their sound insulation capabilities, help design building products which require certain acoustic properties and estimate the in situ performance in complete buildings.". [61]

Appendix C - FEM Simulation Results

All of the results from the FEM simulations performed using SolidWorks to test the surface materials in Chapter 6 can be seen in the following pages.

Simulation Results

Table 11: SolidWorks stress simulation results ranked after safety factor.

Material	Max von Mises Stress [MPa]	Yield Strength [MPa]	Safety Factor	Ranking
Steel	13.07	652.5	49.92	1
Aluminium (cast)	9.881	190.5	19.28	2
Teak	3.838	56.65	14.76	3
White oak	3.861	48	12.43	4
Scots pine	3.701	40	10.81	5
Bamboo	4.568	39.95	8.75	6
Starch-based thermoplastics (TPS)	3.803	24.9	6.55	7

Table 12: SolidWorks deformation simulation results.

Material	Max Deformation [mm]	Ranking
Steel	0.02483	1
Aluminium (cast)	0.04134	2
Bamboo	0.07471	3
Teak	0.0937	4
White oak	0.09437	5
Scots pine	0.1059	6
Starch-based thermoplastics (TPS)	0.9803	7

Steel

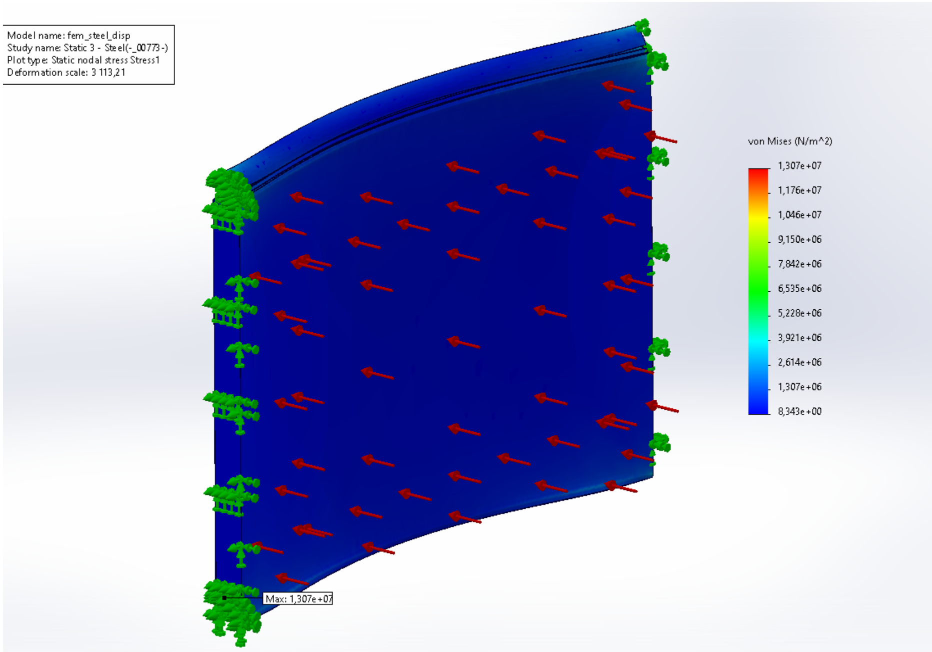

Figure 1: Stress results from Solidworks on Steel Panel.

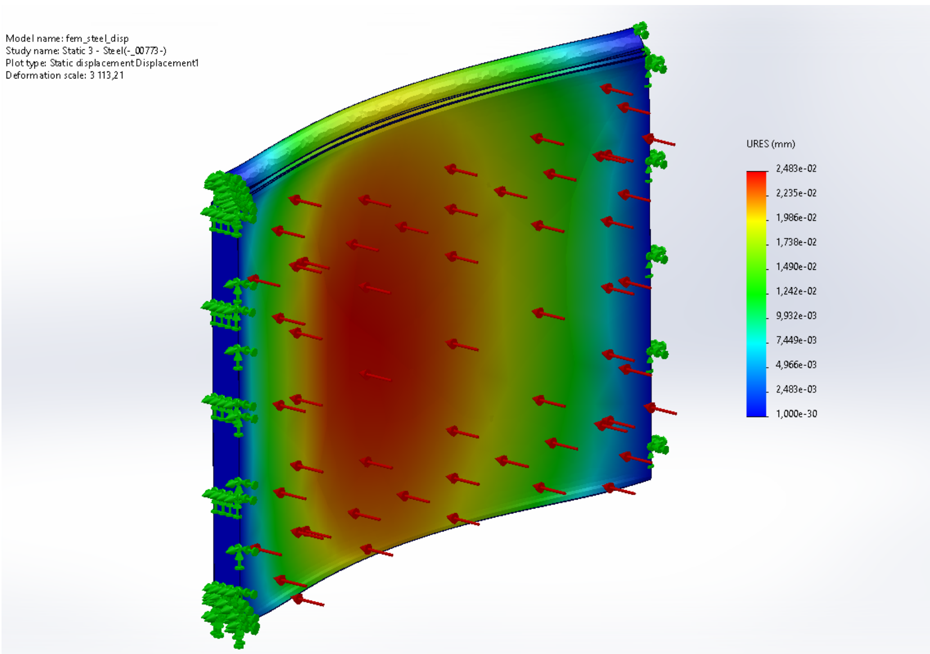

Figure 2: Displacement results from Solidworks on Steel Panel.

Aluminium

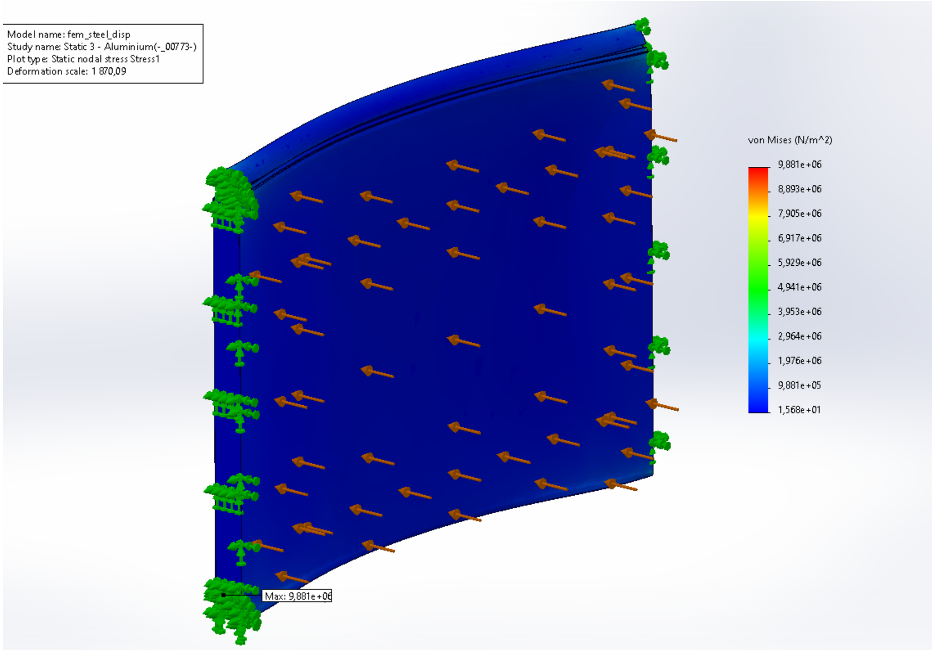

Figure 3: Stress results from Solidworks on Aluminium Panel.

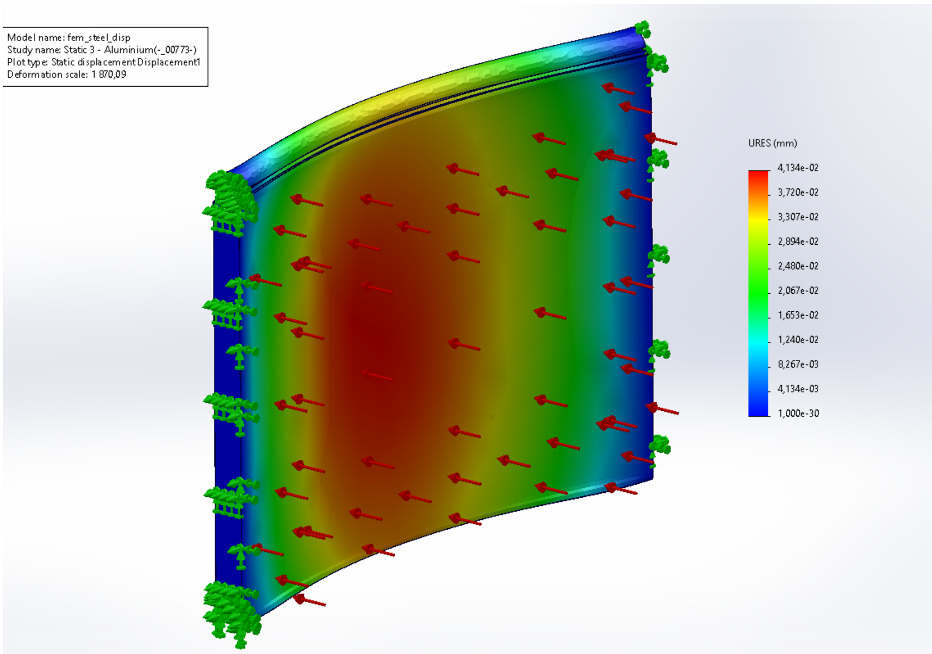

Figure 4: Displacement results from Solidworks on Aluminium Panel.

Teak

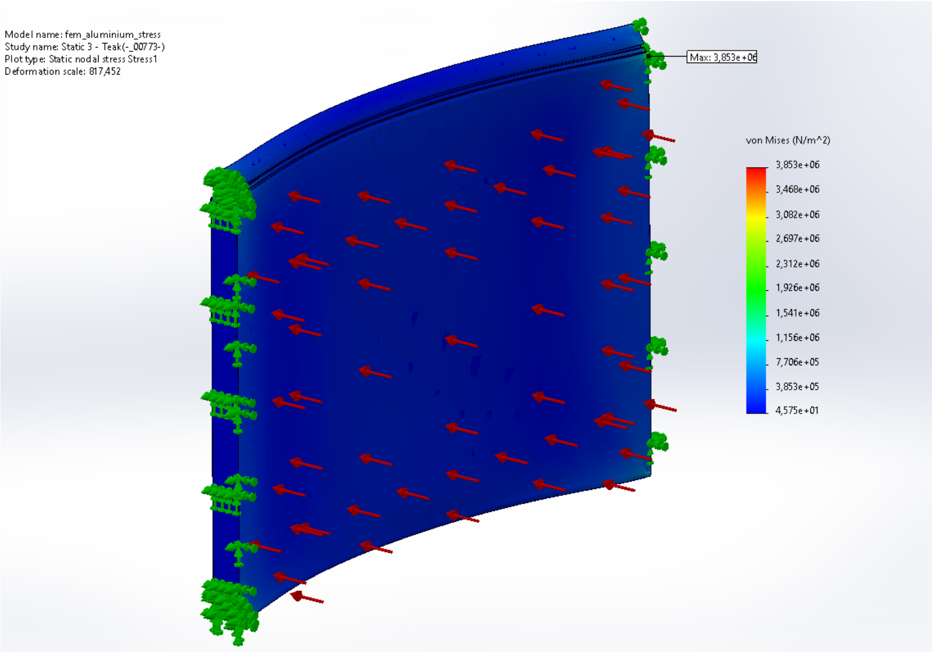

Figure 5: Stress results from Solidworks on Teak Panel.

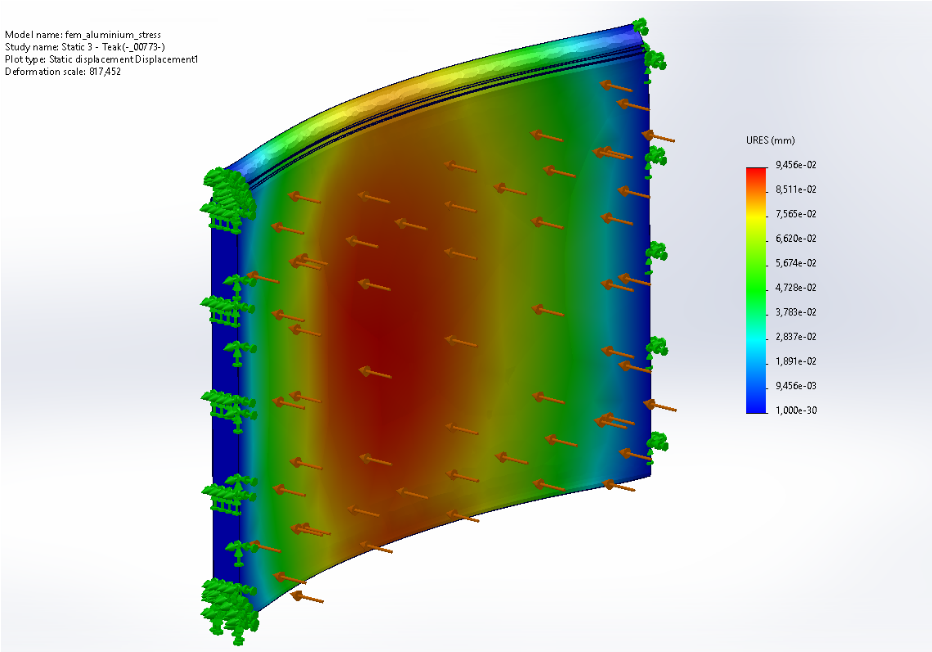

Figure 6: Displacement results from Solidworks on Teak Panel.

White Oak

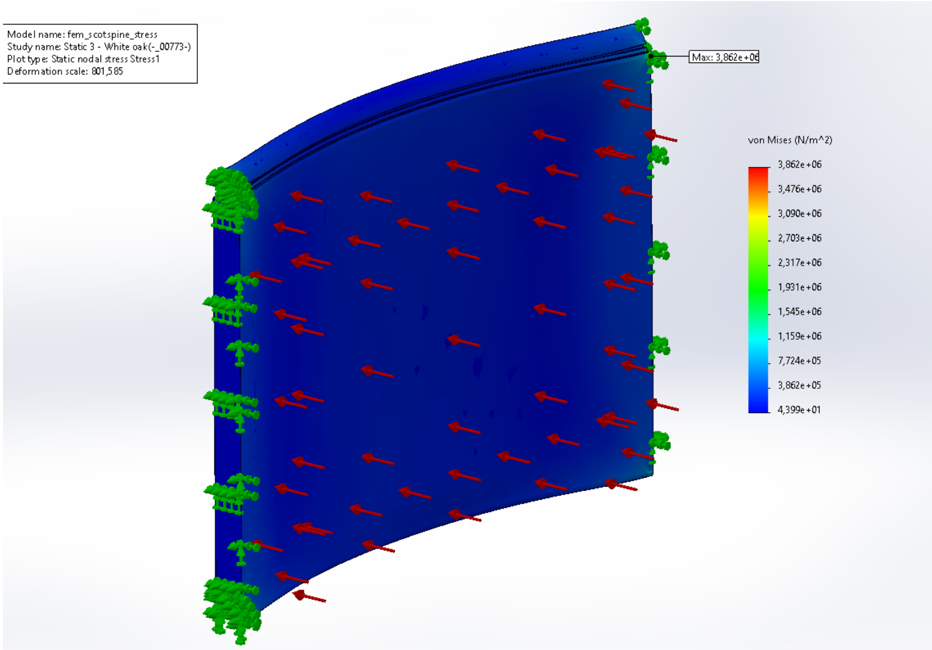

Figure 7: Stress results from Solidworks on White Oak Panel.

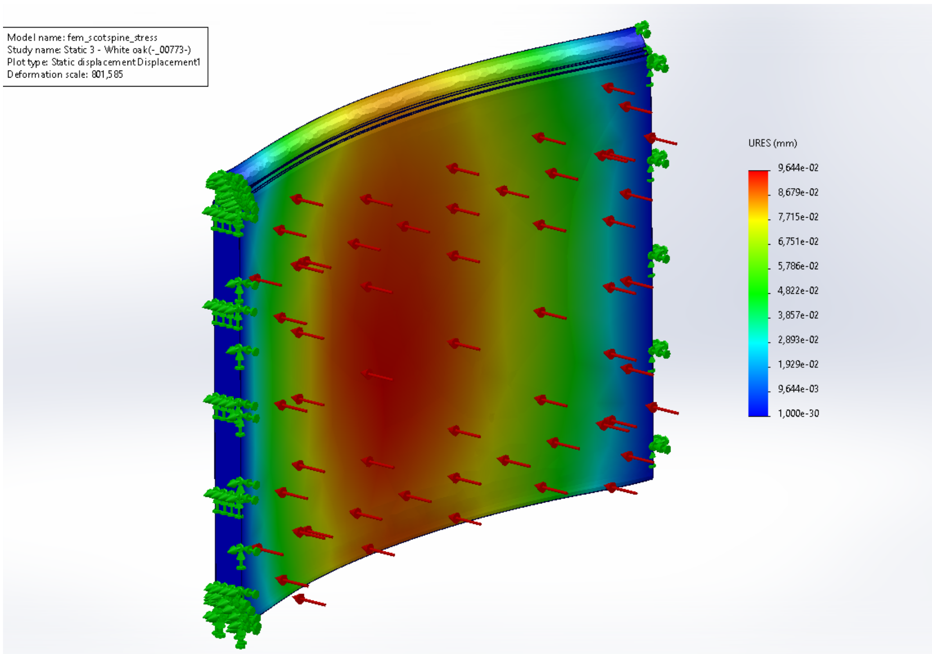

Figure 8: Displacement results from Solidworks on White Oak Panel.

Scots Pine

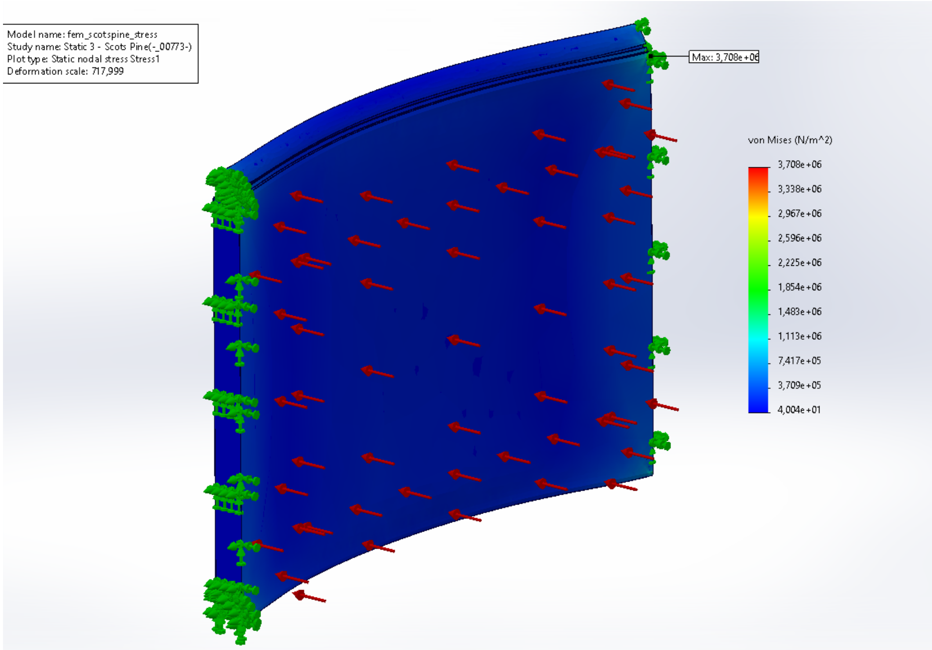

Figure 9: Stress results from Solidworks on Scots Pine Panel.

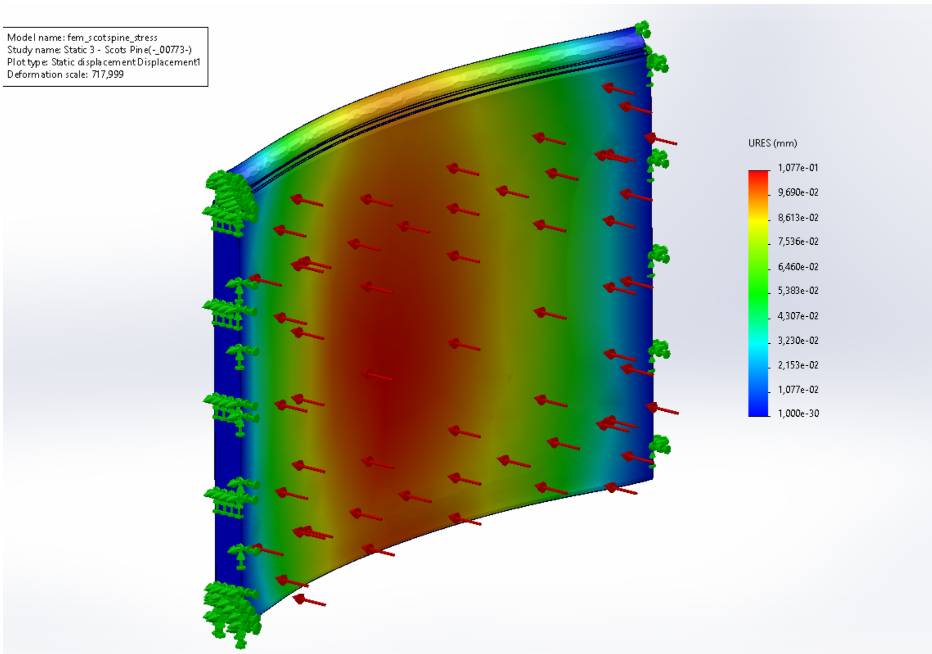

Figure 10: Displacement results from Solidworks on Scots Pine Panel.

Bamboo

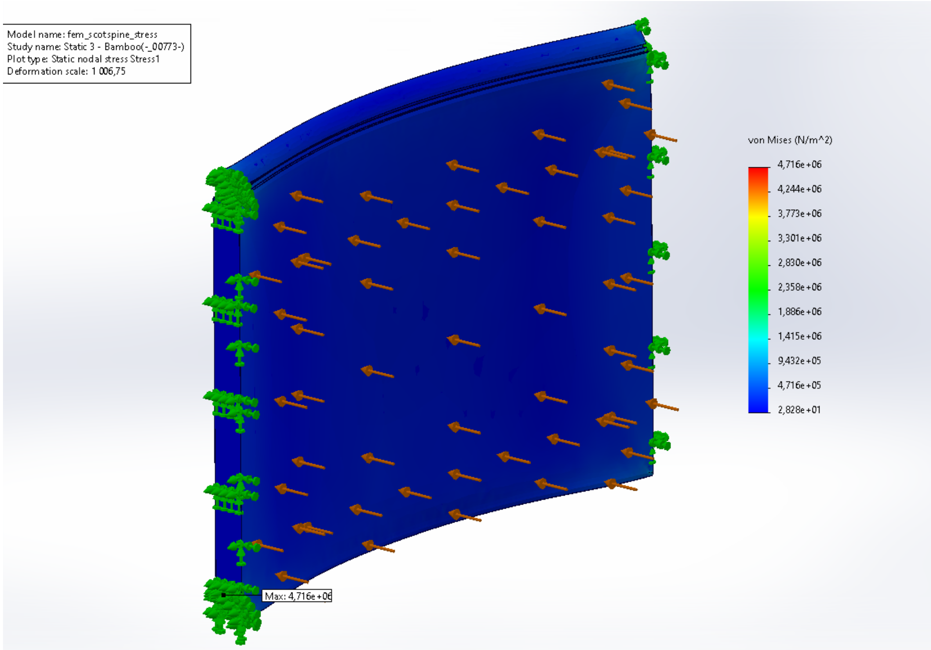

Figure 11: Stress results from Solidworks on Bamboo Panel.

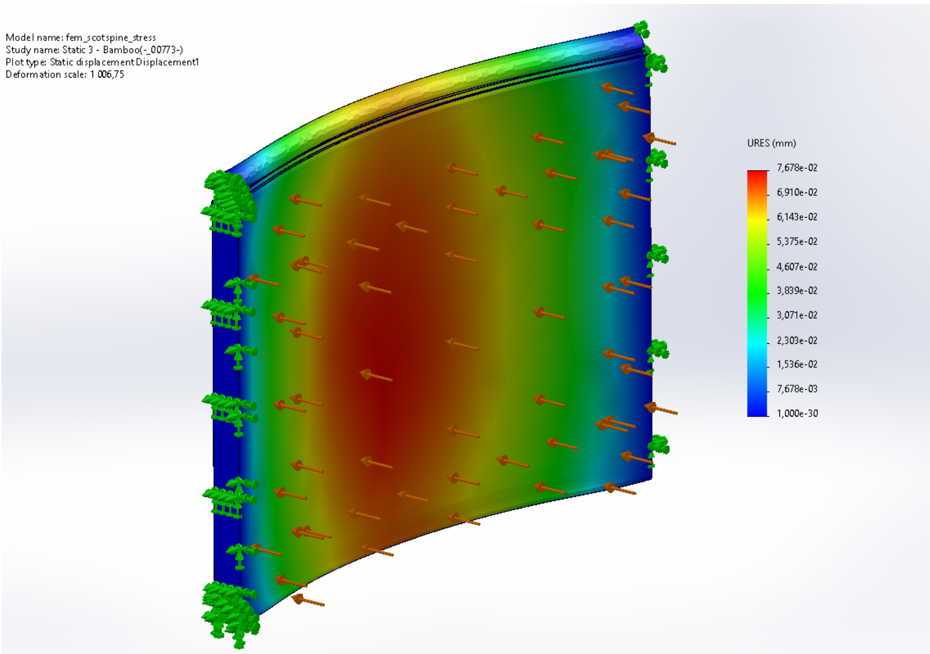

Figure 12: Displacement results from Solidworks on Bamboo Panel.

TPS

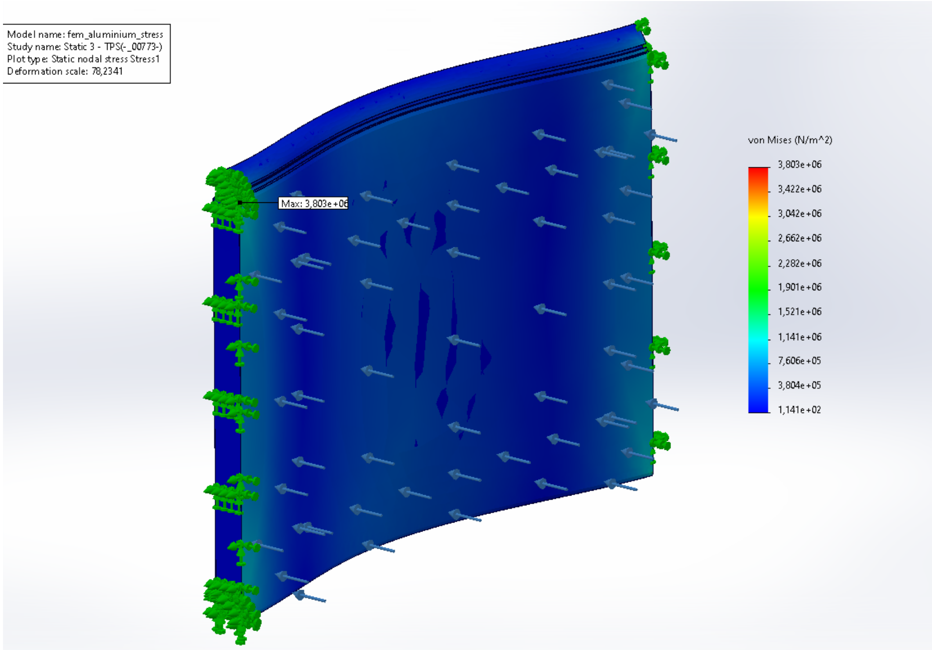

Figure 13: Stress results from Solidworks on TPS Panel.

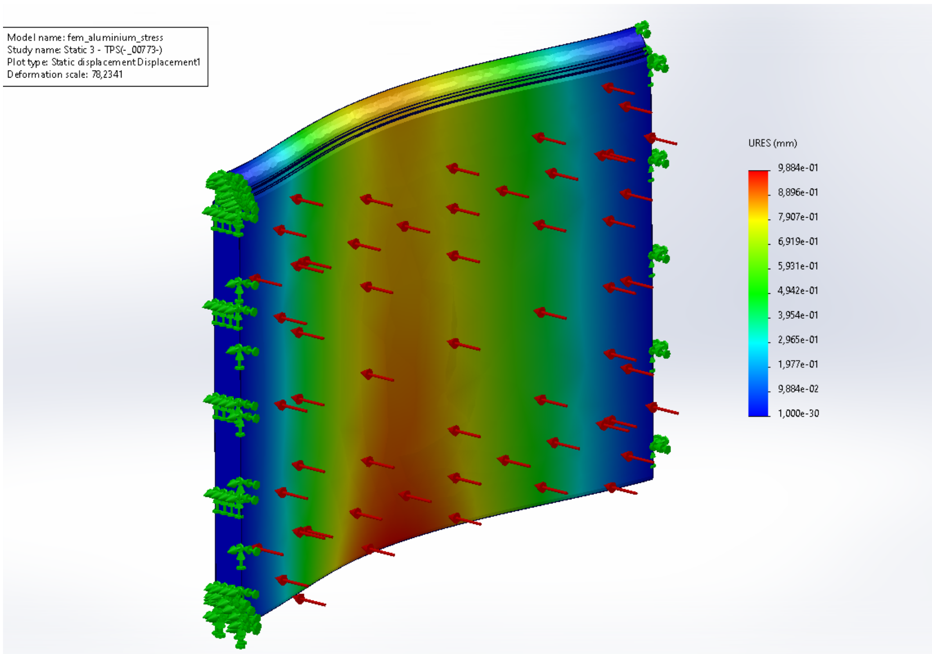

Figure 14: Displacement results from Solidworks on TPS Panel.