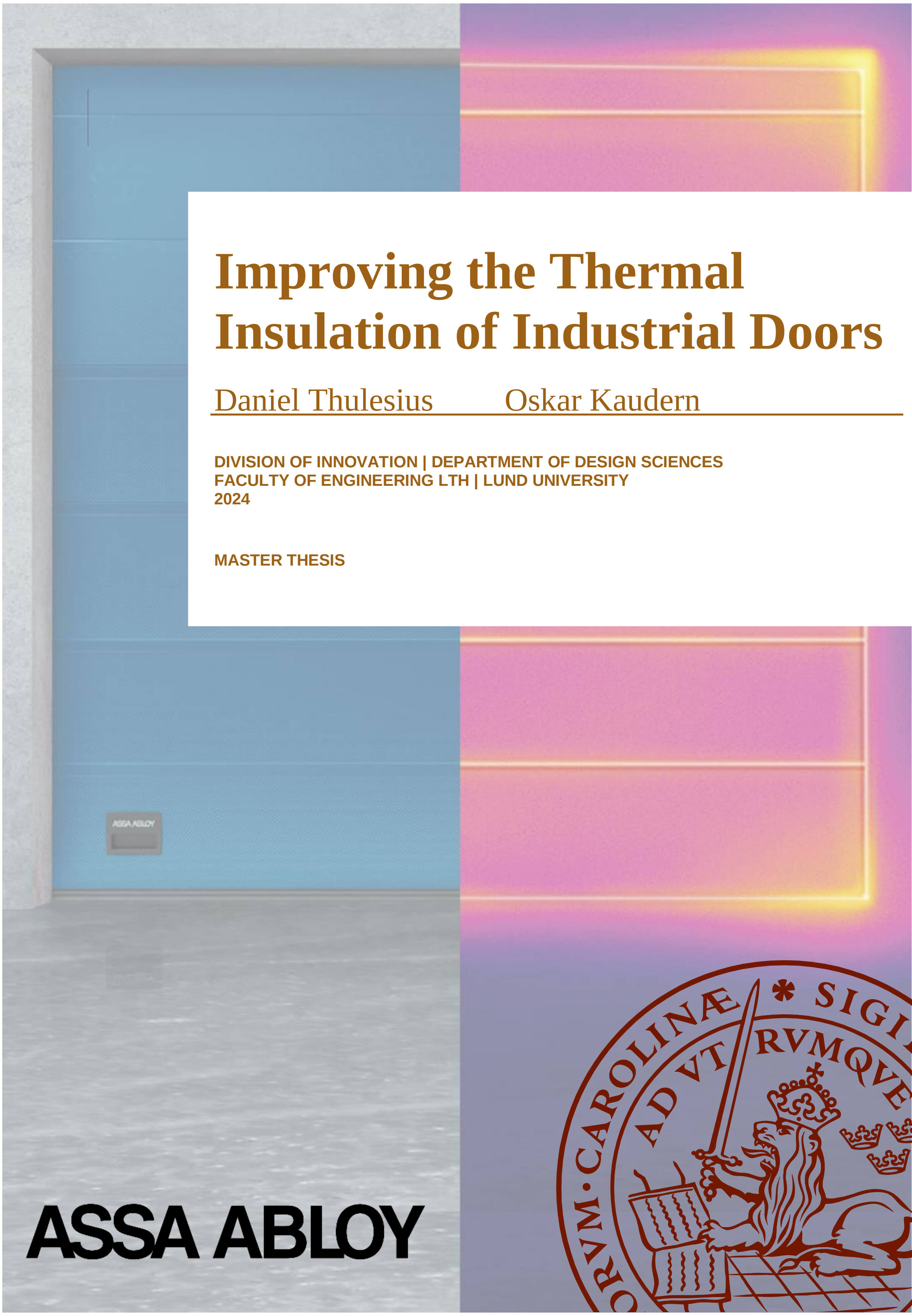

# Improving the Thermal Insulation of Industrial Doors

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DIVISION OF INNOVATION | DEPARTMENT OF DESIGN SCIENCES
FACULTY OF ENGINEERING LTH | LUND UNIVERSITY
2024

MASTER THESIS

ASSA ABLOY

# Improving the Thermal Insulation of Industrial Doors

A product development project to lower the U-value of industrial doors through the help of axiomatic design

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A product development project to lower the U-value of an industrial door through the help of axiomatic design



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# Abstract

This master thesis was conducted in collaboration with ASSA ABLOY Entrance Systems in Landskrona with the aim to lower the U-Value of their existing 42 mm overhead sectional door. U-value is a measurement of the energy that passes through a system per unit area and temperature. The goal was to achieve this without compromising its structural integrity while keeping economic and environmental factors in mind.

The different steps of the axiomatic design process were followed in the project, which included establishing customer needs, functional requirements, and design parameters. Additionally, methods from Ulrich & Eppingers product development process were used. These include concept selection and external decision. The concepts were compared and validated through physical testing, U-value simulations, cost analysis and environmental analysis.

The project resulted in two different concepts that could be implemented individually or combined. One concept involved creating a slit in the panel through post processing, while the other involved replacing steel with a polymer in the endcap to break the thermal bridge. Combining these concepts resulted in a reduced U-value of approximately 19% while only increasing the overall cost with approximately 1%. This improvement was achieved without introducing any unwanted side effects such as reduced fire safety, decreased mechanical strengths, or negative environmental impacts.

**Keywords:** Product development, U-value, Insulation, Industrial door, Axiomatic design, ASSA ABLOY

# Sammanfattning

Detta examensarbete utfördes i samarbete med ASSA ABLOY Entrance Systems i Landskrona med målet att sänka U-värdet för deras befintliga 42 mm industriport. Målet var att göra detta utan att påverka dess strukturella integritet och med hänsyn till ekonomiska och miljömässiga faktorer.

De olika stegen i den axiomatiska designprocessen följdes i projektet, inklusive fastställande av kundbehov, funktionella krav och designparametrar. Dessutom användes metoder från Ulrich & Eppingers produktutvecklingsprocess. Dessa inkluderar val av koncept och externt beslutsfattande. Koncepten jämfördes och validerades genom fysiska tester, U-värdesimuleringar, kostnadsanalyser och miljöanalyser.

Projektet resulterade i två olika koncept som kunde implementeras både individuellt och tillsammans. Ett koncept var en slits i panelen gjord genom efterbearbetning. Det andra var att ersätta stål-”*endcapen*” med en i polymer, vilket bryter ”*endcapens*” köldbrygga. Kombinationen av dessa koncept resulterade i en minskning av U-värdet med ~19% samtidigt som kostnaden endast ökade med ~1%. Detta gjordes utan att introducera några försämringar såsom reducerad brandsäkerhet, minskade hållfasthetsegenskaper, negativa miljöeffekter etc.

**Nyckelord:** Produktutveckling, U-värde, Industriport, termisk isolering, Axiomatic design, ASSA ABLOY

# Acknowledgments

Thank you to all the people at ASSA ABLOY, especially our company supervisor Anders Löfgren. You have done a great job at making us feel at home on your site in Landskrona, and you have provided us with all the resources, hardware and coffee one could possibly need to be able to finish a project like this.

A big thank you to the supervisor of this project, Jože Tavčar, for providing valuable feedback throughout the whole project.

Lund, May 2024

Daniel Thulesius Oskar Kaudern

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# List of acronyms and abbreviations

| | |
|---|---|
| AA | ASSA ABLOY |
| AD | axiomatic design |
| C | constraint |
| CN | customer need |
| DP | design parameter |
| DARP | double acrylic rectangular pane |
| FR | functional requirement |
| $\lambda$ | linear thermal conductance |
| OHSD | overhead sectional door |
| PV | process variable |
| $\psi$ | thermal conductivity |
| U | thermal conductance |
| Q | thermal transmittance |
| U&E | Ulrich & Eppinger |
| $U_D$ | U-value for the complete door |

# 1 Introduction

*This section aims to introduce the reader to the project by displaying background, goals and delimitations.*

## 1.1 Background to the project

ASSA ABLOY (AA) Entrance Systems is an international company specializing in the various means through which people and vehicles enter and exit buildings through doors of various shapes and sizes. This project is in collaboration with AA’s business segment for industrial doors. These industrial doors are quite large as they often need to fit the rear of a truck, and they are closed most of the time. This essentially makes them a significant part of the outer wall. Consequently, companies care a lot about how well thermally insulated these industrial doors are.

AA offers two options when it comes to thickness of their overhead sectional doors (OHSDs) today; the 42 mm and the 82 mm.

There is a significant gap between these models when it comes to *U-value*, which is the market standard for identifying thermal insulation capacity. U-value is however first and foremost a measurement of the energy that passes through a system per unit area and temperature ($W/(m^2 * K)$). The industry standard way of specifying the U-value for industrial doors are for 5x5 m doors without any windows or pass doors. The U-value of the 42 mm door in this configuration is 1,0 and for the 82 mm door it is 0,46 [1].

Some of AA’s competitors offer mid-range panel thickness with mid-range U-values, but there is no business justification for AA to enter this small market with a whole new model, e.g. a 62 mm. However, it would be justified to enter this market if features could be added to the 42 mm to lower its U-value.

## 1.2 Goal

The goal of this project is to lower the U-value of AA’s most popular industrial door, the 42 mm overhead sectional panel door. This should be done without compromising its structural integrity and keeping economic and environmental factors in mind. The project also aims to accomplish this through axiomatic design (AD).

## 1.3 Delimitations

Axiomatic design (AD) was selected as the primary methodology for this project, despite the authors' inexperience with it. This decision was driven by two primary goals: to assess the effectiveness of the methodology itself and to evaluate the ability of designers to learn and apply a new methodological approach to design. Some methods from Ulrich & Eppinger’s (U&E’s) product development methodology were used where the authors deemed it necessary. This was because the authors have more experience with U&E, and some steps of the product development needed more pragmatic methods.

The project will be limited in time to 20 weeks, in line with the guidelines for writing a master’s thesis.

Thermal transmittance, U- and ψ-value will only be calculated and simulated through a software called Flixo. No physical testing will be done in this regard, as the cost and time for this would far exceed the scope of this project.

The project will be limited to door configurations that falls within 80% of what AA sells in the industrial doors section:

- Size < 5500 x 5500 mm.
- Only panels, no frames.
- No pass door.
- Only steel panels, no aluminum panels.
- Not the high-speed variant.
- Windows will not be attempted to redesign but are allowed on the door.

The project will be limited to only redesigning components of the door leaf, not the whole door system.

# 2 Theory

*This section presents the theory that lay the foundation for the project. It is split into thermal transmittance, design methodology, the door itself and the industry standards that concern industrial doors.*

## 2.1 Thermal transmittance theory

Thermal transmittance is the transfer of heat from one system to another. It occurs through one of three methods:

- **Conduction**: Heat travelling between molecules, through a material or from one material to another. Occurs in materials of all phases (as solids, liquids and gases).
- **Convection**: Occurs in liquids and gases where a change in density causes heat to flow as less dense regions rise while more dense regions sink. E.g. hot air rising.
- **Radiation**: Heat emitted from a system in the form of radiation, like radio or light waves. Does not require a medium to transfer.

**Thermal transmittance** (Q) is the thermal energy flow (also known as heat flow), which is measured in $J/s = W$.

**Thermal conductivity** (λ) is a material's ability to transmit heat and is measured in $Wm/m^2K = W/mK$.

**Thermal conductance** (U) is a material's thermal conductivity through a specific thickness, $W/mK/m = W/m^2K$ .

[2, pp. 30.3-30.5]

**Linear thermal conductance** (ψ) is the thermal conductance between two elements, e.g. the joint between the window and the wall, $W/mK$ [3, p. 10].

An example calculation of Q and U-value of a 5x4 m industrial door with 7 panels i.e. 6 panel joints are shown below, see Figure 2.1 and equation (1) The values below for thermal transmittance and linear thermal transmittance are example values and are not obtained from a real door.

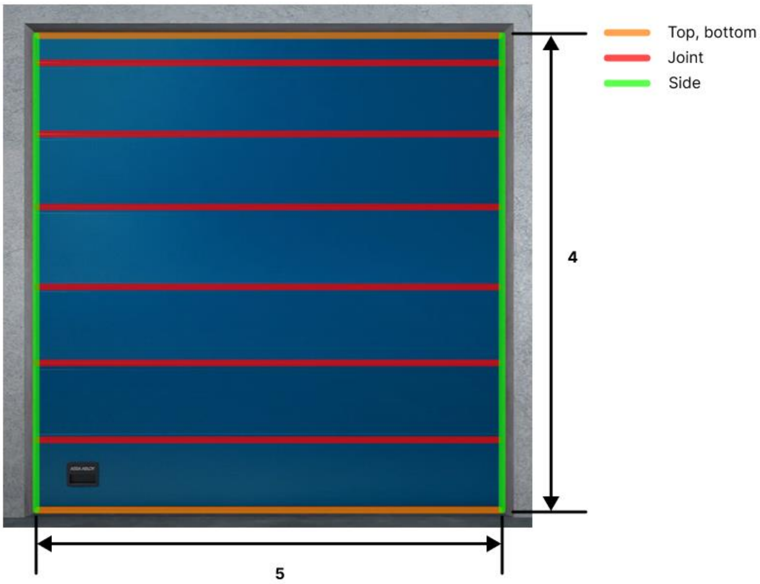



**Figure 2.1 AA OHSD with joint declaration**

| | | | |
|---|---|---|---|
| w | = | $5\ m$ | width |
| h | = | $4\ m$ | height |
| A | = | $20\ m^2$ | area |
| U | = | $1{,}0\ W/m^2K$ | thermal conductance panel |
| ψ | = | $0{,}2\ W/mK$ | linear thermal conductance in sides, top, bottom and joints |
| ΔT | = | $20\ ^\circ C.$ | temperature difference out- and inside |

$$Q = Q_{Panels} + Q_{Sides} + Q_{top,bottom} + Q_{joints}$$

$$Q = \left(U * A + 2 * \psi_{side} * w + 2 * \psi_{top,\ bottom} * h + 6 * \psi_{joints} * w\right) * \Delta T \qquad (1)$$

$$Q = 592\ W$$

$$U = \frac{Q}{A * \Delta T} = 1{,}48\ W/m^2K$$

A **thermal bridge** (also known as a **cold bridge**) occurs when a material, such as steel, with a higher λ-value than the insulating material creates a path for thermal transfer. The overall U-value can get significantly affected by a thermal bridge leading to an increased value higher than if just the insulation had been considered [2, p. 30.8]. In Figure 2.2 a comparison of heat flow between a sandwich panel of steel and low conductivity foam with and without a thermal bridge is shown (Figure 2.3 clarifies the section view). The sandwich panel with a thermal bridge has 4,5 times higher heat flow. A thermal bridge can be broken by inserting a material with lower thermal conductivity between the bridge and is then referred as a thermal break or a broken cold bridge, as is also seen in Figure 2.2. The length of the broken cold bridge also has impact on heat flow, as can be seen in Figure 2.4.

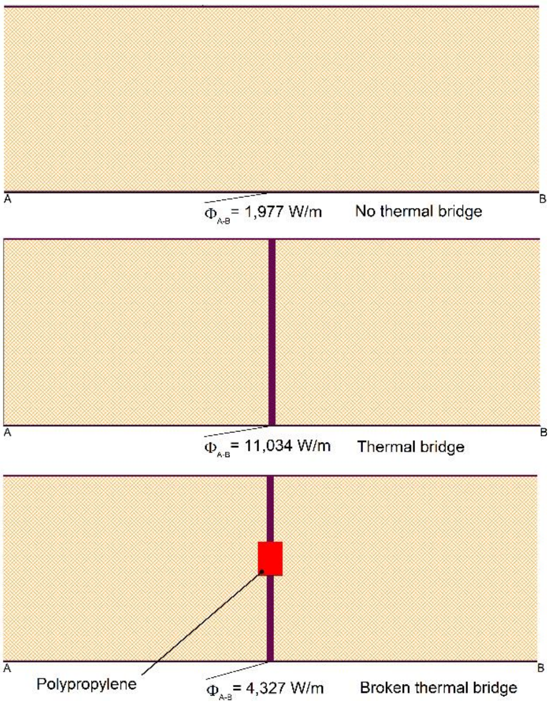



**Figure 2.2 Heat flow comparison. Heat flows perpendicular through surface A-B**

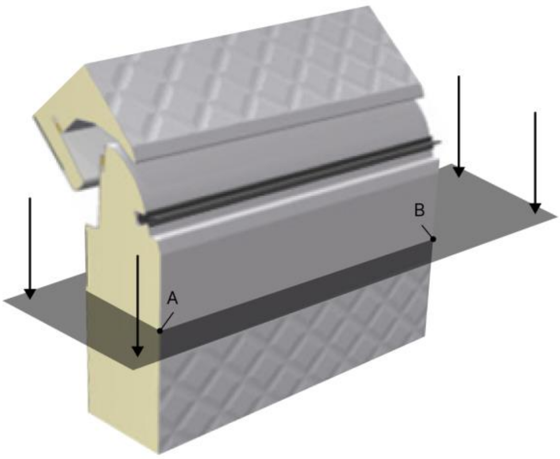



**Figure 2.3 Illustration of section view**

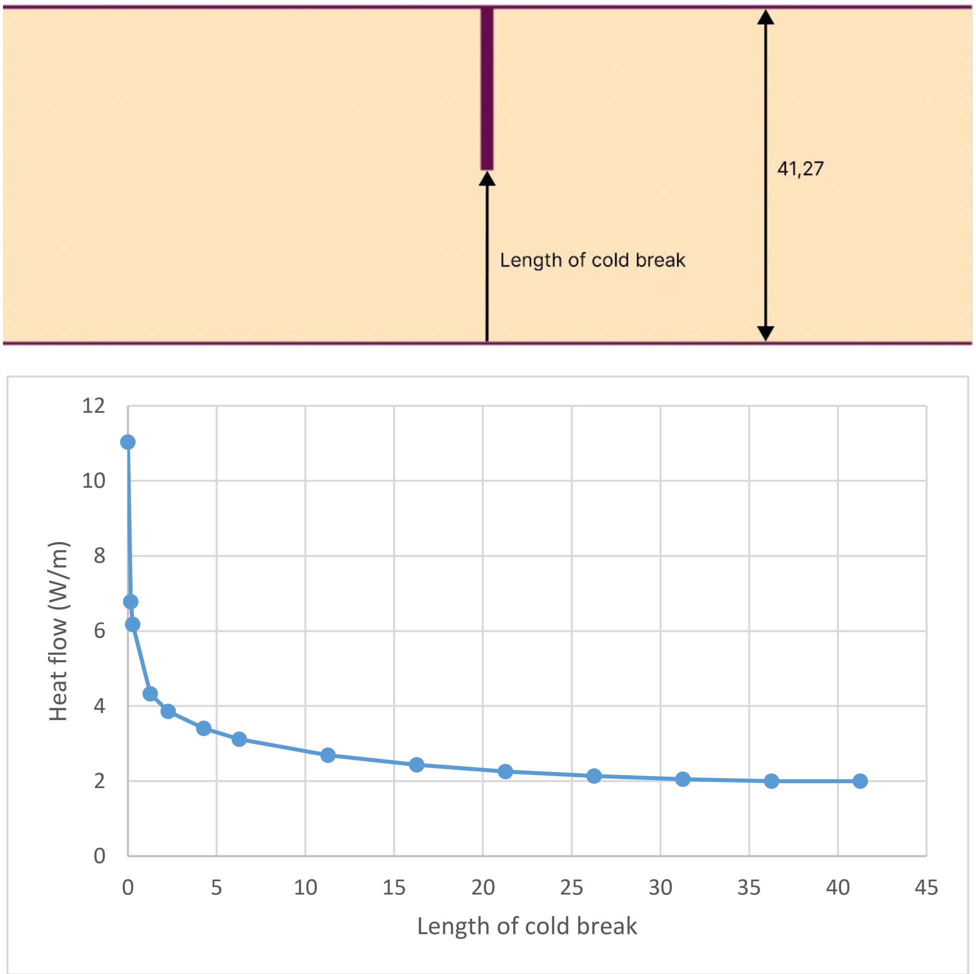



**Figure 2.4 Impact of heat flow as a function of cold break length**

# 2.2 Axiomatic design

### 2.2.1 Introduction

AD is a methodology developed in the 1990's by Dr. Nam Pyo Suh. It seeks to approach design through two axioms that should objectively distinguish good from bad and better from worse design. These axioms are stated as follows:

1. **The Independence Axiom**. Maintain the independence of the functional requirements (FRs).
2. **The Information Axiom**. Minimize the information content of the design.

The first axiom is all about identifying the fewest number of independent FRs that adequately describe the solution to a problem. The second axiom can be expressed and compared mathematically for different designs, but at its core it simply says that the least complex design that fulfills all FRs is the best one.

The methodology can roughly be described as transforming customer needs (CNs) into independent FRs, FRs into design parameters (DPs) and finally DPs into process variables (PV). If done correctly, this should result in an objectively good design. The methodology emphasizes the importance of finding the correct FRs, as these lay the foundation of the design.

A common way to exemplify AD is through the simple water faucet which essentially has two FRs:

1. Control the flow of water.
2. Control the temperature of water.

Figure 2.5 shows two design solutions to the same FRs that has different DPs. The design matrix for design A looks like:

| | DP1 Cold water valve | DP2 Warm water valve |
|---|---|---|
| FR1 Control the flow of water | x | x |
| FR2 Control the temperature of water. | x | x |

While the design matrix for design B looks like:

| | DP1 Turn handle up & down | DP2 Turn handle left & right |
|---|---|---|
| FR1 Control the flow of water | x | |
| FR2 Control the temperature of water. | | x |

Where the X marks if a DP affects a FR. These matrices show that design A is coupled while design B is uncoupled. By AD standards, design B would therefore be considered a good design and would be preferrable. This is explained more in detail further below. [4, 5]

**Figure 2.5 Two-handle faucet (A) and water mixer faucet (B)**

### 2.2.2 Domains

The problem that is being addressed in the design process can be divided into four design domains: customer domain, functional domain, physical domain, and process domain. These domains create a design space helping the designer turn the customer needs into a solution through an iterative process, as illustrated in Figure 2.6 [6].

The customer domain contains the customer needs and specifications regarding a product, process system, or material. These requirements can sometimes be challenging to define or may be ambiguous. Nonetheless, it is crucial to understand them thoroughly. Collaborating with the customer will help the designer in achieving this understanding [7].

FRs and Constraints (Cs) are defined in the functional domain. The FRs represent the essential requirements that fully represent the functional needs of the product or system and according to the independence axiom should be independent of each other. The FRs are usually expressed in verbs. Cs represent the restrictions put on the designer to choose DPs, and Cs are divided into system Cs and input Cs. Input Cs are a part of the initial design specifications like size and material cost. System Cs come from design decisions, where the high-level decisions set the Cs for the low-level decisions. E.g. a certain type of engine is chosen for a vehicle, and now the body of the vehicle is constrained by the engine. Unlike FRs, Cs does not need to be independent of each other. Increasing the number of Cs can lead to more focused design schemes. However they are optionable and frequently overused, so it is important to question their necessity before implementing them, as to not constraining possible solutions [7]. Various sources within AD mention non-functional requirements (nFRs), which is an extension of Cs. It should supposedly improve the design process in various ways [8] [9]. But due to the scale of this project and the fact that the authors are novice AD users, nFRs are not used in this report.

In the physical domain, DPs are set to fulfill the specified FRs and restricted by Cs. Depending on what FRs the functional domain consists of (product, material, software, system) the corresponding DPs can be physical variables, microstructure, algorithms, components. The DPs are usually expressed in nouns [7].

The process variables (PVs) are the key actors in the process domain, and they characterize the process that can achieve the DPs set in the physical domain [7]. In the design of physical things, a PV can be seen as the choice of the manufacturing process for a part.

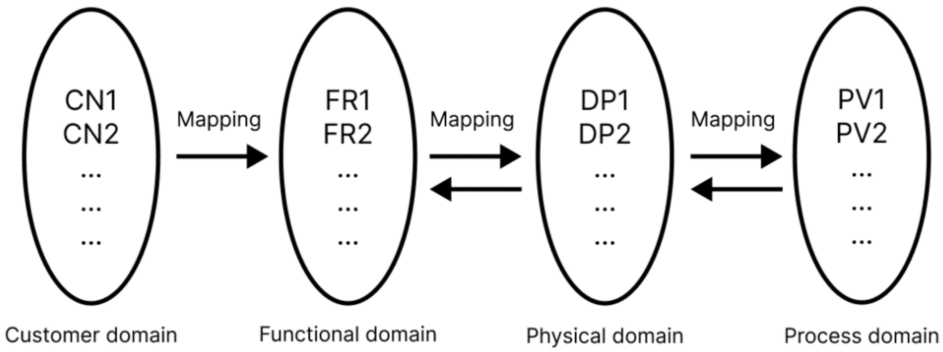



**Figure 2.6 Domains in axiomatic design**

### 2.2.3 Mapping

The mapping process could be described as moving between the domains transforming the elements from one domain into another as illustrated in Figure 2.6. This is done in an iterative manner, zigzagging between the domains to decompose the FRs, DPs and PVs until the design is completed. One important aspect when mapping is that it should be done in a solution neutral environment to obtain the possibility of an innovative solution. In other words, not thinking about a current solution that could influence your design choices, resulting in a similar design [7].

Firstly, the customer needs are translated into FRs by mapping between the customer domain and functional domain. After the FRs are established, they are translated to DPs by mapping from the functional to the physical domain, conceptualizing the design solution [7]. The FRs and DPs can be expressed as vectors with ($n$, $m$) components. The transformation from the FR vector to the DP vector is done through a design matrix that can be seen as a representation of the design process [5]. The relationship between the FR and DP vector can be expressed as following.

$$\overrightarrow{FR} = \boldsymbol{A} * \overrightarrow{DP}$$

Where **A** is the design matrix. For vectors containing *m* amount FRs and *n* amount DPs, the design matrix will have the following form:

$$\boldsymbol{A} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix}$$

Mapping the FRs to DPs could be done in several ways. In Figure 2.7 the zigzagging process between the functional and physical domain is shown. Starting by declaring the higher-level FR and its corresponding DP, then decomposing into lower-level FR. This is done until all the FRs can be satisfied by a corresponding DP of the same level.

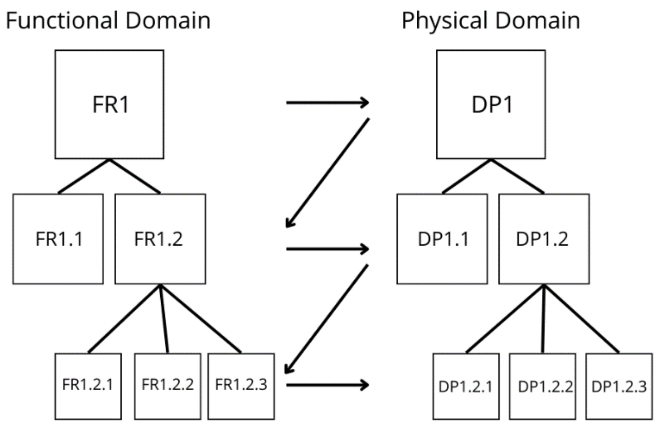



**Figure 2.7 Illustration of the mapping process**

The matrix can achieve three different forms depending on how well it satisfies the independence axiom. The ideal form is a diagonal matrix when each FR has a unique DP and is referred as an uncoupled design. If the matrix is triangular, it can satisfy the independence axiom if the DPs are defined in a correct sequence, such a solution is called decoupled design. If the matrix is not a diagonal or triagonal matrix, the design solution will be coupled which is not optimal [7]. The three variants are illustrated in Figure 2.8.

Diagonal Matrix

| FR\DP | 1.1 | 1.2 | 1.3 |
|---|---|---|---|
| 1.1 | x | | |
| 1.2 | | x | |
| 1.3 | | | x |

Triangular Matrix

| FR\DP | 1.1 | 1.2 | 1.3 |
|---|---|---|---|
| 1.1 | x | | |
| 1.2 | x | x | |
| 1.3 | x | x | x |

Coupled Matrix

| FR\DP | 1.1 | 1.2 | 1.3 |
|---|---|---|---|
| 1.1 | x | | x |
| 1.2 | | x | |
| 1.3 | x | x | x |

**Figure 2.8 Illustration of a diagonal, triangular and coupled matrix**

## 2.3 Ulrich & Eppinger's methodology

In addition to the axiomatic design, some methods from Ulrich & Eppinger's (U&E's) product development process were applied in this project. These methods include a combination of *external decision, concept screening* & *concept testing* [10, pp. 145-155, 167-169]. This was done to see how different design methodologies could be combined in a useful way, utilizing AD's objective approach to find viable concepts, and then U&E's pragmatic concept selection methods to go forward with concepts that the company was interested in.

**External decision** simply let's a stakeholder have the final say in concept selection, in this case the AA industrial development team.

**Concept screening** lets the designer quickly narrow down the number of concepts through a selection matrix where every concept is compared to a reference concept. The concepts are then rated as better (+) worse (-) or equal (0) to the reference in regard to a number of criteria, and through this matrix a rough concept score can be obtained, see Table 2.1

**Table 2.1 Example concept screening matrix**

| | ***Concepts*** | | | |
|---|---|---|---|---|
| ***Criteria*** | ***Reference*** | ***A*** | ***B*** | ***C*** |
| ***1*** | *0* | - | + | 0 |
| ***2*** | *0* | - | + | 0 |
| ***3*** | *0* | + | 0 | - |
| ***4*** | *0* | + | 0 | 0 |
| ***5*** | *0* | + | 0 | + |
| ***Sum +'s*** | *0* | *3* | 2 | 1 |
| ***Sum -'s*** | *0* | *2* | 0 | 1 |
| ***Sum 0's*** | *5* | *0* | 2 | 3 |
| ***Net Score*** | *0* | *1* | 2 | 0 |

**Concept testing** was conducted as concept validation in this project.

## 2.4 The Industrial Door

### 2.4.1 Components and their interconnection

Figure 2.9 shows the Industrial OHSD with its 4 primary parts:

1. Door leaf
2. Track set
3. Balancing system
4. Operating system

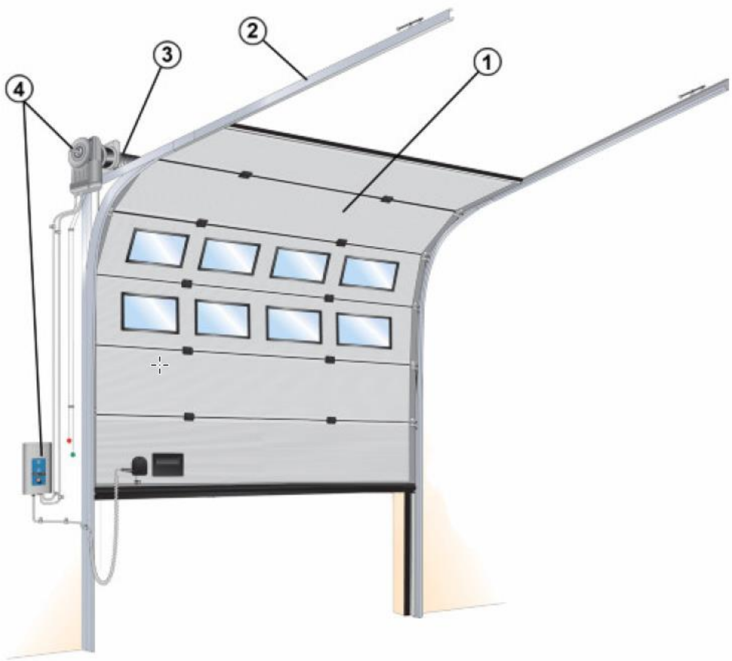



**Figure 2.9 Illustration of the OHSD seen from the inside**

The door leaf is made up of stacked panels that are connected to each other through hinges and brackets, see Figure 2.10. The rollers are then connected to the brackets that interact with the track set, guiding the door leaf in the predetermined path that is the track set, see Figure 2.11. A steel wire (door cable) is fastened in the bottom corners of the door leaf and rolled onto drums connected to the operating and balancing system, see Figure 2.12. The balancing system is made up of springs that balance the door leaf, making it possible to operate manually. The operating system lifts and releases the door leaf automatically. There are rubber and plastic seals on the top, bottom and sides of the door that minimize air permeability of the door, see Figure 2.13.

The datasheet for the 42 mm door with all technical information can be found in *Appendix I*.

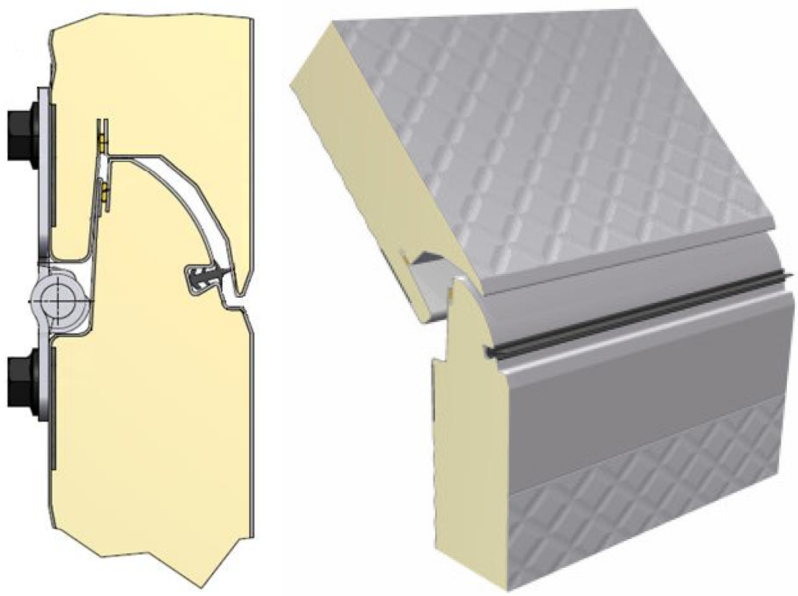


**Figure 2.10 42 mm panel design**

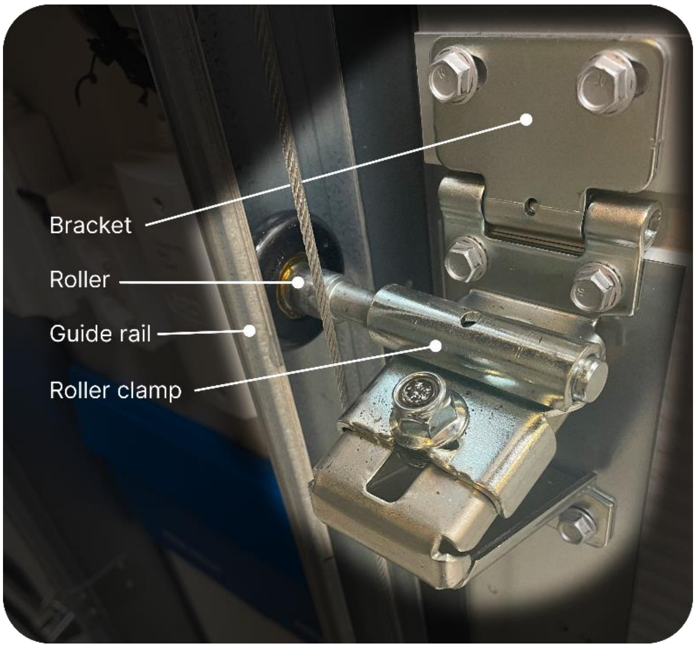



**Figure 2.11 Door leaf and track set interface**

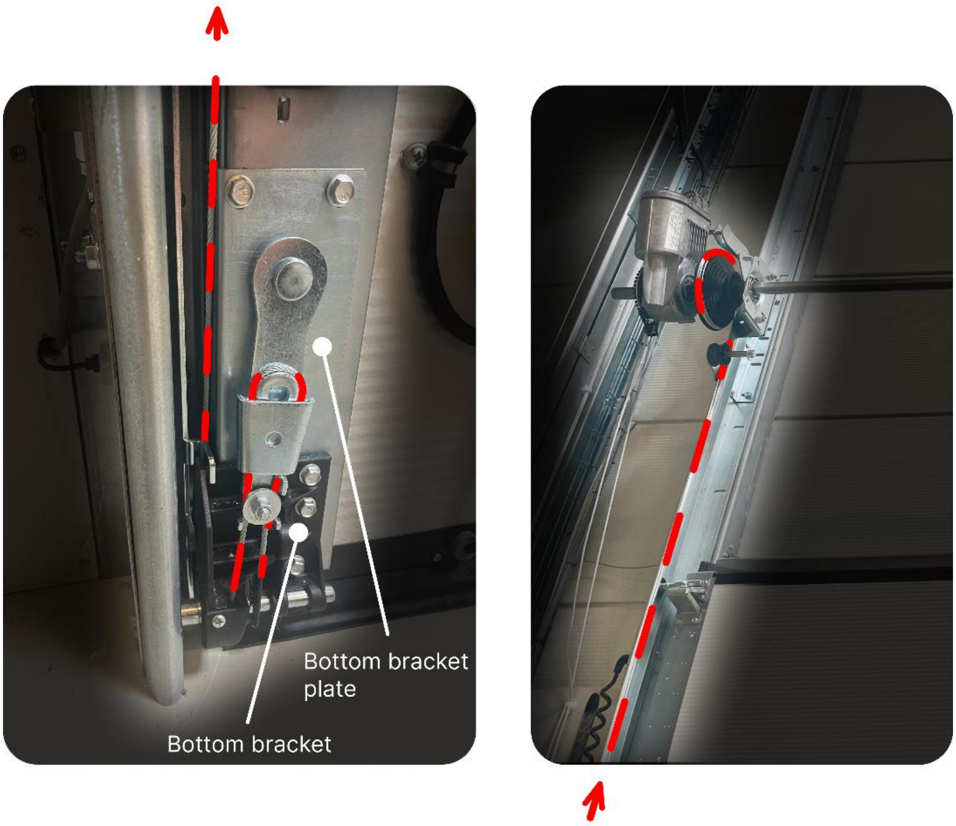



**Figure 2.12 Door cable**

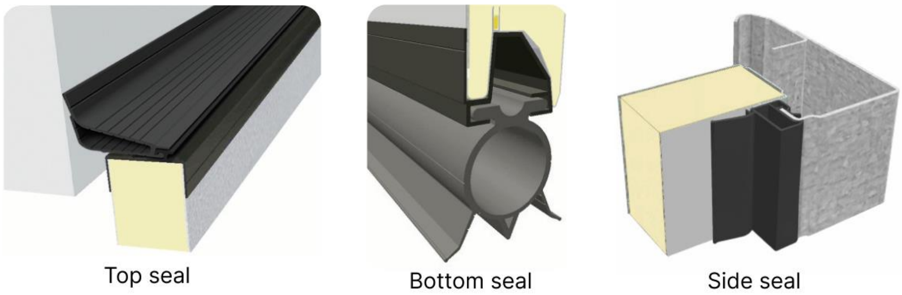



**Figure 2.13 Top, bottom, and side seal**

Two components/aspect that are especially interesting for this project is the “shark fin” design of the panels seen in Figure 2.14, and the endcap, see Figure 2.15. The main purpose of the “shark fin” is to protect from finger trapping when the door leaf curves, which is explained in SS-EN 12604:2017, see also Figure 2.14.

The main purposes of the endcap are:

- To protect the open edges of the panel regarding fire resistance, sharp edges, and aesthetics.
- To provide more material for the bolts to thread into when fastening the brackets to the panels.
- Added strength in holding the panel together.

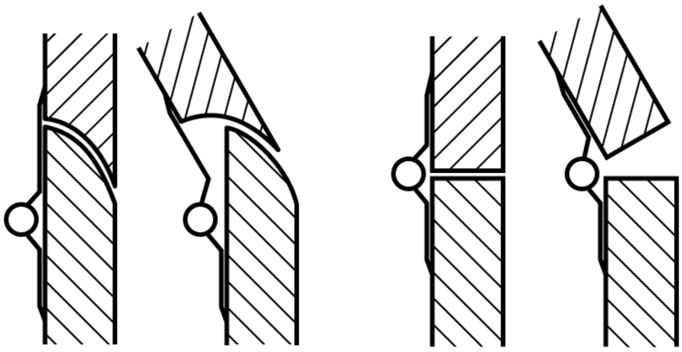


**Figure 2.14 Finger protection vs. no finger protection**

**Figure 2.15 Endcap**

### 2.4.2 Manufacturing

The manufacturing process for the 42 mm panels can be summarized into the following steps,

1. Rolling steel sheets, the skin and support strips
2. Roll bending the sheets into the desired shape
3. Mixing and injecting the PUR foam between the skin sheets
4. Hot melt glue the steel skin together
5. Heating to cure the foam
6. Sawing the continuous panel into sections

A simplified illustration of the process is shown in Figure 2.16 and a cross section of the panel can be seen in Figure 2.17.

All sealings; top, bottom and side, are manufactured through plastic extrusion.

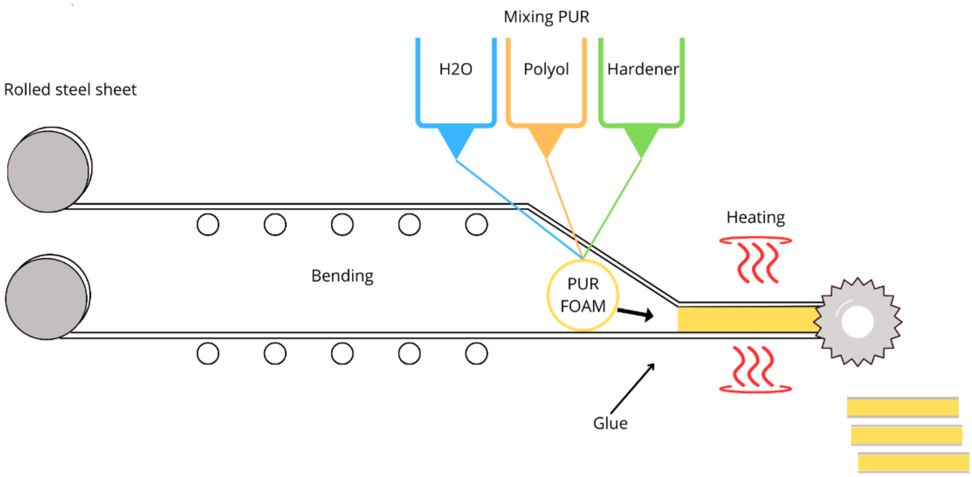



**Figure 2.16 Manufacturing of a 42 mm panel**

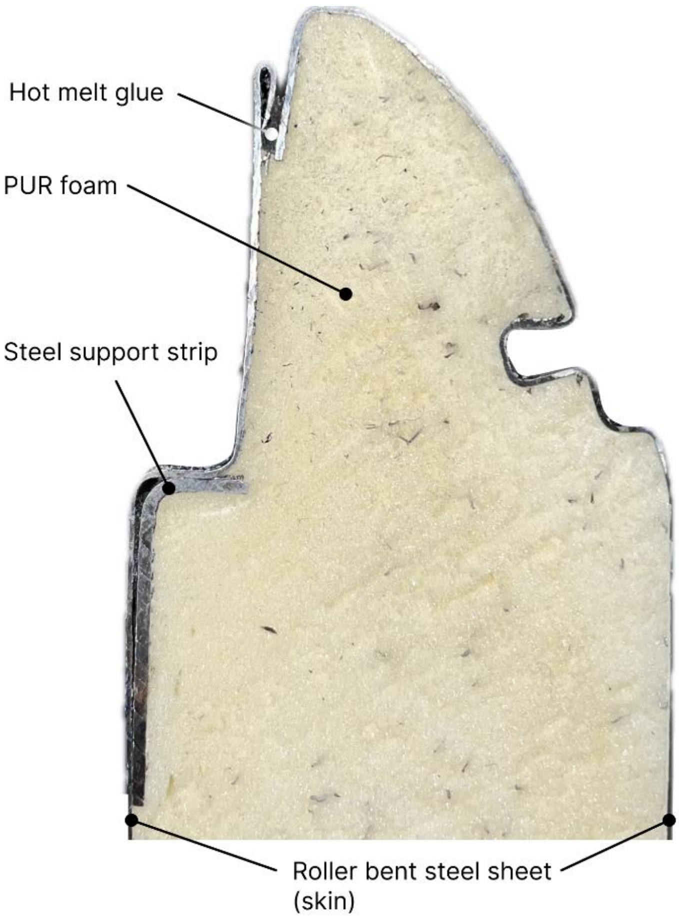



**Figure 2.17 Cross-section of 42 mm panel male part**

## 2.5 Standards

In the following section European standards that are used in the project are presented.

### 2.5.1 SS-EN 12428

**"Industrial commercial and garage doors – Thermal Transmittance – Requirements for the calculation"**

This standard provides a method for calculating the thermal transmittance (Q) of industrial doors in a closed position.

Relevant information from the standard was:

- The principal heat flow in a section is assumed to be perpendicular to a plane parallel to the internal and external surfaces.
- Surrounding floor and walls are seen as adiabatic and therefore has no effect on the thermal transmittance.
- The linear thermal transmittance of connections between the door panel and surrounding construction, or between panels, is determined by assessing the additional heat flow in comparison to the one-dimensional heat flow through the door panel

[3]

### 2.5.2 SS-EN ISO 10077-2:2017

**"Thermal performance on windows, doors and shutters – Calculation of thermal transmittance"**

This standard specifies how to do thermal calculations on windows, doors, and shutters.

Relevant information from the standard was:

- Two methods exist for calculating the heat transfers through cavities
  - The radiosity method
  - The single equivalent thermal conductivity method.
- The single equivalent method was applied indirectly in the project when simulations were done in Flixo.

- For cavities the emissivity value of the surrounding surfaces, a value of 0,9 was used.
- Air cavities are considered unventilated if they are fully enclosed or connected to either the exterior or interior by a narrow slit no wider than 2 mm, regardless of the cavity's orientation in relation to the direction of heat flow. Otherwise, the cavity should be classified as ventilated or slightly ventilated.

[11]

### 2.5.3 SS-EN 12424

**"Industrial, commercial and garage doors and gates – Resistance to wind load – Classification"**

This standard explains the classification for wind load of closed doors. Where a test specimen is assigned to a specific class based on what wind load it can withstand. The required wind load for each class can be found in Table 2.2. Other relevant information for the project was:

- The door leaf shall remain in position when a peak load of 1.25 times greater than the reference wind load is applied. Permanent deformations of door components are allowed during the application of the load.
- The wind load is defined as differential pressure of one side of the fully closed door to the other.

**Table 2.2 Wind load classes**

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

[12]

### 2.5.4 SS-EN 12444

**"Industrial, commercial and garage doors and gates – Resistance to wind load – Testing and calculation."**

This standard explains the test and calculation procedure used to evaluate the wind class of a specimen.

Relevant information for the project was:

- The testing principle involves applying a pressure differential across the test specimen to ascertain failure. Full-size specimens must be tested. In cases where conducting full-scale testing is impractical or uneconomical, sections of door assemblies should be tested for calculating a result for an entire door assembly.
- An evenly distributed load or pressure can be applied to the surface in several ways, including but not limited to:
  a) Using an air – pressurized chamber, where precautions must be taken to eliminate all air leakage on the product and its attachment to the support structure.
  b) Placing bags filled with sand or water across the surface of the test sample
  c) Placing air–pressurized bags that cover the entire surface between the test sample and a fixed rigid surface, such as the floor and the surface of the test sample

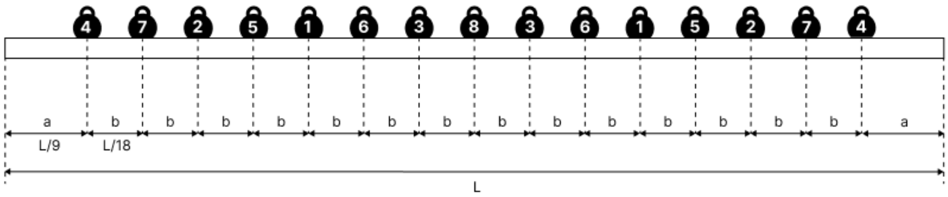



**Figure 2.18 Wind load theoretical setup**

[13]

### 2.5.5 SS-EN 12604:2017

**“Industrial, commercial and garage doors and gates – Mechanical aspects – Requirements and test methods”**

This standard gives design suggestions and provides design requirements for industrial, commercial and garage doors. It was primarily used to understand the requirements of the finger protection design. In addition, when testing is carried out instead of calculation, the door and its components should have the minimum safety factor before yield of 1,1 [14].

### 2.5.6 SS-EN 13501-1:2019

**“Fire classification of construction products and building elements –Part 1: Classification using data from reaction to fire tests.”**

This standard explains the fire classifications of construction products based on fire test. It also present different classes and their criteria. Conducting the tests outlined in the standard falls outside the scope of the project. However, checking current classifications on AA’s doors and ensuring that any potential changes align with those classifications was done. The current classifications of the 42 mm panel are:

- C – fire class (read standard)
- d0 – no flaming droplets
- s3 – no limitation of smoke production

[15]

### 2.5.7 Air permeability, Water resistance

European standards regarding air permeability, SS-EN 12426 [16], and water resistance, SS-EN 12489 [17], are not used in this project as they require physical testing in a controlled environment which is out of this project’s scope.

If the company chooses to further develop the final concept, then physical testing must be done, answering to the standards above.

# 3 Method

*In this section a brief introduction is given to the design methodology used in this project.*

## 3.1 Planning

The project plan describing the activities and the duration of the activities can be found in *Appendix F*. The duration of the activities were based on the duration of the project and estimations on their duration in relation to each other, based on previous experience.

## 3.2 Design process

This project mainly follows the Axiomatic design process, with some additional design methods where it was deemed necessary, mainly from U&E. The AD method is thoroughly explained in *2 Theory*. The planned activities will be briefly described in the following chapter and represented graphically in Figure 3.1.

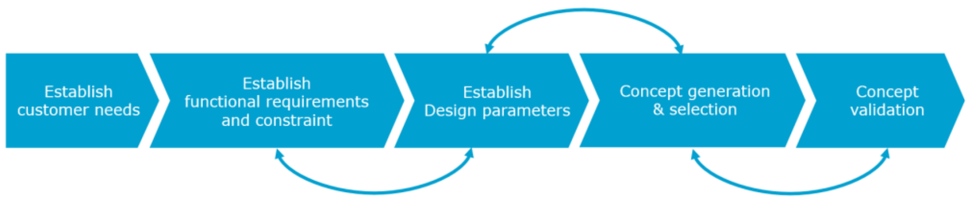



**Figure 3.1 Design process flow chart**

### 3.2.1 Establish customer needs

To fully understand the need and specifications of our problem, a stakeholder analysis will be done to establish the customer needs acting in the customer domain. The stakeholder analysis consists of meetings with experienced people, competitor analysis and literature studies.

### 3.2.2 Establish FRs and Cs

Once the customer needs are set, the next step is to establish the functional requirements (FRs) and the constraints (Cs). To ensure that the FRs cover all the requirements, the current solution will initially be investigated to map all the functions. Where a customer need can't be solved by a FR, a C will have to be set.

### 3.2.3 Establish DPs

The establishment of the design parameters (DPs) will be done through translating the FRs in an iterative process going back and forth from the functional to the physical domain until every FR can be solved by a DP. This will be done by decomposing the FRs that cannot be solved by a DP into lower-level FR. The current solution will be studied and used to set DPs where it is deemed necessary.

### 3.2.4 FR-DP Matrix

When the FRs and DPs are set, a design matrix is made to evaluate the design. If the matrix does not achieve a diagonal form the matrix will be rearranged to achieve a triangular form if possible.

### 3.2.5 Concept generation

The concept generation shall be accomplished through generating concepts from the DPs, where the different DPs will act as individual concept instead of combining them.

### 3.2.6 Concept selection

To determine which concepts to further develop, the concepts will be evaluated in a concept screening matrix based on relevant criteria. From the results of the screening matrix, a joint decision with the supervisors at AA will be made.

### 3.2.7 Validation of concepts

When the final concepts have been chosen, they will be further developed. The further developing will consist of prototyping, simulation, and physical testing. Finally, the concepts will be validated in terms of manufacturability, cost, and their environmental impact.

# 4 Concept development

## 4.1 Stakeholder needs

The project aims to reduce the overall U-value of the door, denoted as $U_D$. While this objective is clear, a stakeholder analysis was conducted to comprehensively identify all needs and limitations in the customer domain. The methods for identifying these were meetings with experienced people, competitor analysis and literature studies.

Initially a meeting with the product manager for industrial OHSD at AA took place to further discuss the background of the project with the aim to clarify all the requirements. A summary of this meeting can be found in *Appendix A*.

To gain insight into what a potential customer might base their decisions on when choosing industrial doors, it was decided to have a meeting with an architect who has experience in designing logistics centers. Questions such as what requirements they have on the industrial door and what makes them choose a certain supplier was asked. A key insight was that BREEAM, a building standard for sustainability, dictates the criteria for carbon footprint of a building. It is a standard that most new buildings in Sweden have to fulfill, which makes lowering the U-value of every component of the building, including its industrial doors, essential [18]. A summary of the meeting can be found in *Appendix C*.

Additionally, a meeting with a salesperson at AA was held, to gain knowledge in the most common sizes, add-ons, what customer usually asks for, what U-value they usually request and where AA falls short on the market. Further information of the meeting can be found in *Appendix D*.

The stakeholder analysis served to gain insights into the entirety of the problem and to take the desires of both the client and the customer into account. This resulted in the needs and limitations that can be found in Table 4.1.

**Table 4.1 Stakeholder needs**

| ***No.*** | ***Needs*** | ***Stakeholder*** |
|---|---|---|
| 1 | *Lower the U-Value without drastically increasing the price* | AA, Customer |
| 2 | *Fit with other parts in current system* | AA |
| 3 | *Work with the most common configuration* | AA |
| 4 | *Environmental & ethical material (Reach)* | AA, Customer |
| 5 | *Easy to manufacture* | AA |
| 6 | *Meet the standards (see chapter* Standards*)* | AA |

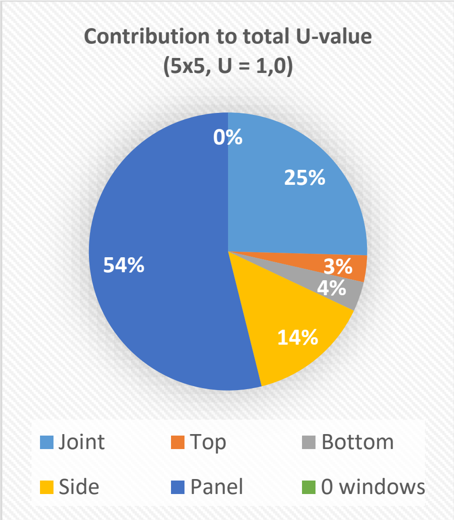
These desires and needs were subsequently translated into FRs and Cs, which will be further explored in the following chapters.

## 4.2 Breaking down the problem

The authors were given access to an Excel sheet that calculates the $U_D$ of different configurations of AA's OHSD. From this sheet the contribution to $U_D$ of every aspect of the door could be determined. The aspects were divided as follows:

- Horizontal joint between panels (joint)
- Top sealing (top)
- Bottom sealing (bottom)
- Side construction/sealing (side)
- Panel
- Windows

From the excel sheet a pie chart was created showing each aspect's percentual contribution to the $U_D$ which can be seen in Figure 4.1. It was decided to have the benchmark configurations, 5x5 m without windows and 3x3 m with a single row of double layered acrylic window (DARP). The choice 5x5 m aligns with the industry standard benchmark dimension, while the 3x3 m with a single row of DARP reflects the most common dimension. As illustrated in Figure 4.1, the influence of each aspects varies depending on the dimensions of the door.



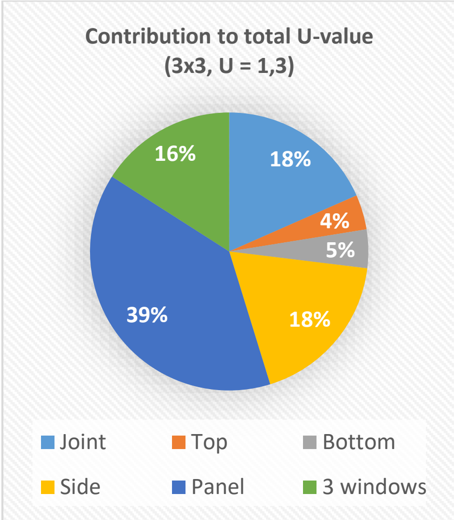




**Figure 4.1 Contribution to total U-value of two different configurations of the 42 mm door**

Based on the most impactful aspects, the chosen ones to focus on and set up FR's for were the joint, the side and the panel.

## 4.3 Establish functional requirements

It was decided to break down a potential solution based on the three most influential aspects. The establishment of FRs was carried out individually for the side sealing, while for the joint and panel, it was determined to set the FRs collectively, as they are heavily dependent of each other.

Initially, the main FRs for the side sealing were established by examining the current solution and defining the essential FRs required to address its current task while taking the stakeholder desires into account. During the investigation of the current side sealing, it was discovered that it had a cold bridge, as the endcap was in direct contact with the outer steel skin and the inside climate, see Figure 4.2. For the side sealing there were only two main FRs, where one of them could not be achieved by one DP which resulted in breaking it down into three lower level FRs. The FRs for the side sealing can be found in Table 4.2.

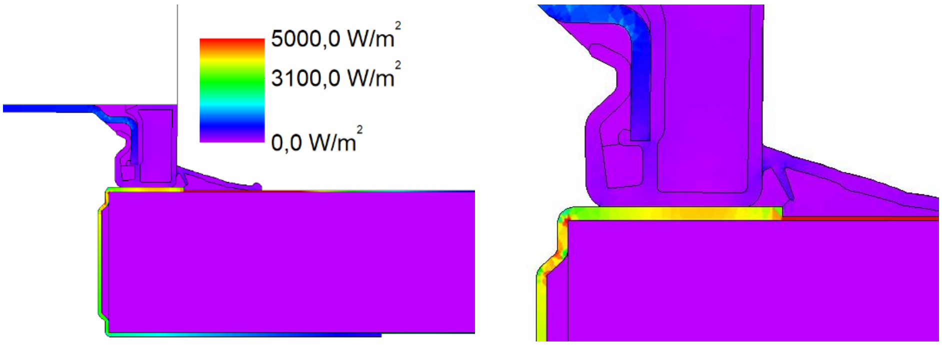



**Figure 4.2 Cold bridge through the endcap**

**Table 4.2 Side sealing FRs**

| ***FR*** | ***Description*** |
|---|---|
| **1** | **Break cold bridge** |
| 1.1 | Break rail cold bridge |
| 1.2 | Break endcap cold bridge |
| 1.3 | Prevent air flow in gaps |
| **2** | **Integrable with current system** |

As mentioned earlier, the FRs for the joint and panel were decided to be addressed together. The main FRs for both were established accordingly. Once the main FRs were set, they were further elaborated through zigzagging back and forth between the functional and physical domain into lower-level FRs achievable for the DPs to satisfy. Decomposing the main FRs for the joint and panel resulted in the identification of the following lower-level FRs. Unlike the side sealing the panel joint construction had more main FRs that required breaking down. The FRs for the panel joint can be found in Table 4.3.

**Table 4.3 Panel Joint FRs**

| *FR* | *Description* |
|---|---|
| **1** | **Divide inside from outside** |
| 1.1 | Thermally divide inside from outside |
| 1.2 | Break cold bridge |
| 1.3 | Physically divide inside from outside |
| 1.4 | Prevent airflow between units |
| **2** | **Integrable with current system** |
| 2.1 | Possible to attach guide wheels |
| 2.2 | Integrable with bottom wheel/wire plate |
| **3** | **Connectable with other panels** |
| 3.1 | Top and bottom of panel connectable |
| 3.2 | Allow tilting in one direction |
| 3.3 | Distribute forces that occur when tilting |
| 3.4 | Connect with other panels physically |

The Cs were derived from the customer needs and specifications in the customer domain. These were the needs that could not be translated to FRs, as they were more associated with design specifications rather than functions. See Table 4.4 for side construction constraints and Table 4.5 for panel & joint constraints.

**Table 4.4 Side construction Cs**

| *C* | *Description* |
|---|---|
| 1 | Finger trapping safe |
| 2 | Ψ-value < $0{,}366\ W/mK$ (Current solution) |
| 3 | Similar cost of current 42 mm door |
| 4 | Follow standards for an industrial door, see *2.5* Standards |

**Table 4.5 Panel & Joint Cs**

| *C* | *Description* |
|---|---|
| 1 | Finger trapping safe |
| 2 | Ψ-value < $0{,}146\ W/mK$ (Current solution) |
| 3 | Similar cost of current 42 mm door |
| 4 | Follow standards for an industrial door, see *2.5* Standards |
| 5 | Maintain manufacturing method for panel |
| 6 | Sealing invisible from outside |
| 7 | Panel U-value < 0,549 $W/m^2K$ (Current solution) |
| 8 | Withstand forces that occur when closed |

## 4.4 Establish design parameters

After establishing the FRs, the next step was to select DPs that address to the lowest-level FRs. The approach to this was to come up with DPs that were uncoupled to the greatest extent. Multiple DPs were generated for some FRs, while part of the current solution was maintained for others.

For the side construction multiple DPs were generated for various FRs and they are found in Table 4.6.

**Table 4.6 Side construction DPs**

| ***No.*** | ***FR*** | ***Existing*** | ***DP 1*** | ***DP 2*** |
|---|---|---|---|---|
| 1 | Break cold bridge | | | |
| 1.1 | Break rail cold bridge | Hollow PP profile | Foam filled PP profile | Hollow PP profile |
| 1.2 | Break endcap cold bridge | - | Plastic endcap | An insert between endcap and panel |
| 1.3 | Prevent air flow in gaps | TPE flap | Multiple flaps | Increased width of air pocket |
| 2 | Integrable with current system | Click connection to rail | Attached as endcap | |

For the panel & joint only a few DPs were generated. This is because the existing DPs for some FRs were self-evident and could not be developed much further within the project scope. The DPs can be found in Table 4.7.

**Table 4.7 Panel & Joint DPs**

| *No.* | *FR* | *Existing* | *DP 1* | *DP 2* | *DP 3* |
|---|---|---|---|---|---|
| **1** | Divide inside from outside | | | | |
| 1.1 | Thermally divide inside from outside | Foam | Increased thickness | Aerogel | Insulating Patches |
| 1.2 | Break cold bridge | Glue | Plastic shark fin | Slit | Extended slit |
| 1.3 | Physically divide inside from outside | Steel sheet | Fiberglass skin | | |
| 1.4 | Prevent airflow between units | TPE Sealing | | | |
| **2** | Integrable with current system | | | | |
| 2.1 | Possible to attach brackets | Support steel piece | | | |
| 2.2 | Integrable with bottom bracket | Bottom bracket - support steel plate | | | |
| **3** | Connectable with other panels | | | | |
| 3.1 | Top and bottom of panel connectable | Shark fin geometry | | | |
| 3.2 | Allow tilting in one direction | Hinge | | | |
| 3.3 | Distribute forces that occur when tilting | Bracket & hinges | | | |
| 3.4 | Connect with other panels physically | Bracket & hinges | | | |

## 4.5 Mapping

The design matrix for the current design of the side seal is visible in Table 4.8. From this it became evident that a design parameter was missing for FR1.2, which led to two DP proposals that would leave an uncoupled matrix. For the rest of the DPs, the authors proposed new DPs that would further lower the ψ-value.

**Table 4.8 Design matrix for current side seal design**

| ***FR \ DP*** | ***1.1*** | ***1.2*** | ***1.3*** | ***2*** |
|---|---|---|---|---|
| ***1.1*** | *x* | | | |
| ***1.2*** | | | | |
| ***1.3*** | | | *x* | |
| ***2*** | | | | *x* |

The design matrix for the panel & joint design is visible in Table 4.9. It shows a coupled design matrix, but because of the Cs nothing could be done to decouple it. Instead the authors only proposed new DPs that would lower the ψ-value.

**Table 4.9 Design matrix for current panel and joint design**

| *FR \ DP* | *1.1* | *1.2* | *1.3* | *1.4* | *2.1* | *2.2* | *3.1* | *3.2* | *3.3* | *3.4* |
|---|---|---|---|---|---|---|---|---|---|---|
| *1.1* | x | | | | | | | | | |
| *1.2* | | x | x | | | | | | | |
| *1.3* | x | | x | | | | | | | |
| *1.4* | | | | x | | | | | | |
| *2.1* | | | x | | x | x | | | x | |
| *2.2* | | | x | | x | x | | | x | |
| *3.1* | | | | | | | x | | | |
| *3.2* | | | | | | | | x | x | x |
| *3.3* | x | | x | | x | x | | x | x | x |
| *3.4* | | | x | | | | | x | x | x |

## 4.6 Generated concepts

### 4.6.1 Side construction

The generated concepts are derived from the DPs answering to the FRs. The solutions could be implemented independently, and some of them could also be combined with each other creating a combination of concepts. It was decided to split the concepts rather than combining them and having a couple of concepts answering to all the DPs. In Table 4.10 the generated concepts for the side construction are described.

**Table 4.10 Side construction concepts**

| *Concept* | *Description* |
|---|---|
| S1 | Plastic endcap (polypropylene, PP) |
| S2 | Plastic under endcap (PP) |
| S3 | Air pocket in sealing filled with foam |
| S4 | Added flaps on current profile |
| S5 | Making current profile wider by shortening the steel. |
| S6 | Combination of concepts 1,3,4 and 5 |

Concepts S1 and S2 focuses on breaking the cold bridge in the endcap. The idea with concept S3 is to lower the λ-value in the air pocket by inserting foam as it has a lower λ-value than air. Both concept S4 and S5 will increase the amount of unventilated air between inside and outside thus decreasing the Ψ-value. See Figure 4.3 for illustrations of the concepts.

To assess the various concepts derived from the concept generation process, they were evaluated in the software Flixo. Initially, a setup of the current configuration was created, serving as a baseline for evaluation. The Flixo model for the current configuration was made by importing a DFX-file of the current model, assigning materials and adding boundary conditions in accordance with EN-ISO 10077-2. The result matched the current Ψ-value, so the setup was assumed to be correct. Once the baseline was established, the different concepts were implemented individually to observe their isolated impacts on the ψ-value, see Figure 4.3. As most of the concepts could be independently implemented it allowed for making a combination integrating a few of them together. Lastly that combination was tried in Flixo, as seen in Figure 4.4. A material table showing the material and boundary conditions used in the simulations for both the side construction and the panel joint can be found in Figure 4.5.

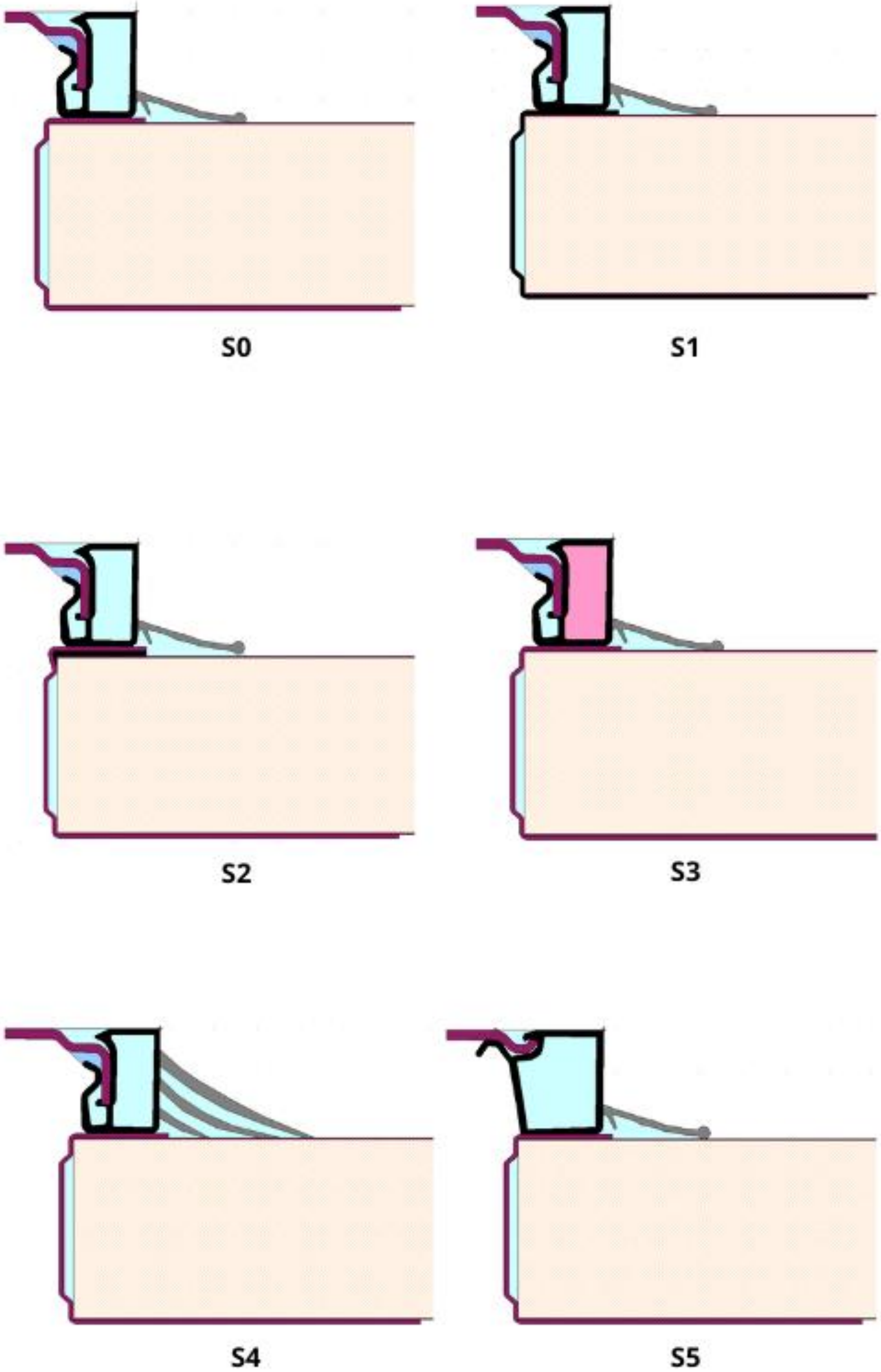



**Figure 4.3 Side construction concepts**

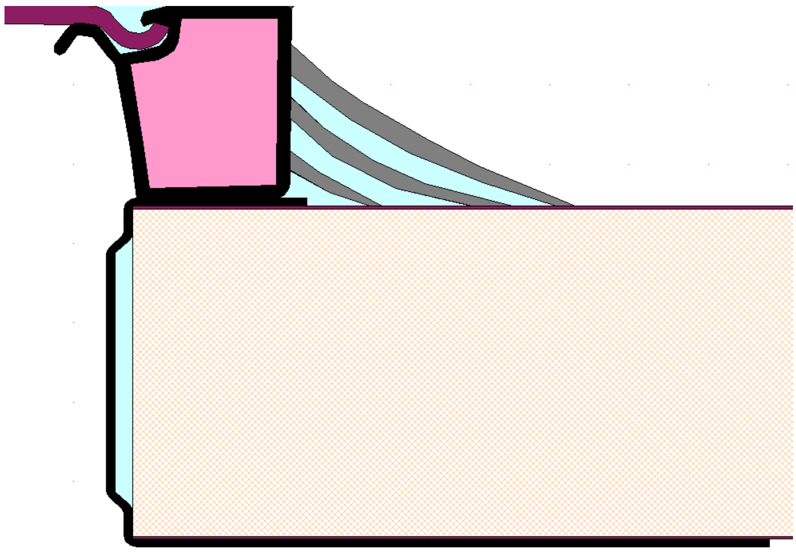


**Figure 4.4 Combination of concept S1, S3, S4, S5**

| Material | λ[W/(m·K)] | ε | μ[-] |
|---|---|---|---|
| ABS (acrylonitrile butadiene styrene) | 0,200 | 0,900 | |
| EPDM (ethylene propylene diene monomer) | 0,250 | 0,900 | |
| EPDM (ethylene propylene diene monomer) (1) | 0,080 | 0,900 | |
| Hot melt glue | 0,130 | 0,900 | 1,000 |
| PP | 0,220 | 0,900 | 1,000 |
| PUR | 0,025 | 0,900 | 1,000 |
| Steel | 50,000 | 0,900 | 100000000,000 |
| TPE | 0,190 | 0,900 | 1,000 |
| Slightly ventilated air cavity * | | | 1,000 |
| Unventilated air cavity * | | | 1,000 |

* EN ISO 10077-2:2017, 6.4.3/anisotrop

| Boundary Condition | q[W/m²] | θ[°C] | R[(m²·K)/W] | ε | φ[%] |
|---|---|---|---|---|---|
| Exterior, frame | | 0,000 | 0,040 | | |
| Interior, frame, normal | | 20,000 | 0,130 | | |
| Interior, frame, reduced | | 20,000 | 0,200 | | |
| Symmetry/Model section | 0,000 | | | | |
| Epsilon 0.9 | | | | 0,900 | |

**Figure 4.5 Material and boundary conditions**

The Ψ-values for the side construction concepts are shown in Table 4.11. Using a PP endcap had the greatest individual impact on the Ψ-value. Combining it with concepts S3, S4 and S5 gave the lowest overall Ψ-value.

**Table 4.11 Ψ-values of evaluated side construction concepts**

| *Concept* | *Concept eva*luated | *Ψ-Value [W/mK]* |
|---|---|---|
| S0 | *Current solution* | 0.364 |
| S1 | *Plastic endcap* | 0.214 |
| S2 | *Plastic under endcap* | 0.338 |
| S3 | *Foam filled* | 0.344 |
| S4 | *Added flaps* | 0.311 |
| S5 | *Wider Seal* | 0.337 |
| S6 | *Combination of S1, S3, S4, S5* | 0.126 |

### 4.6.2 Panel joint construction

For the panel joint construction, the concept generation was done in the same manner as the side construction. The generated concepts for the panel joint construction are presented in Table 4.12.

**Table 4.12 Panel Joint Construction Concepts**

| *Concept* | *Description* |
|---|---|
| J1 | Simple slit |
| J2 | Extended slit, glue removed |
| J3 | Plastic shark fins |

The idea with concept J3 is to break the cold bridge as much as possible by replacing the material of the shark fin from steel to plastic. This concept was also elaborated into a modular design where the panel itself could be manufactured like a top/bottom-symmetric panel and the shark fin male or female part could be attached to either side. This would drastically reduce the cost of manufacturing for the panel since it would require less rollers. This would also be considered a better design regarding AD, since it would not be as coupled. This elaborated modular design was however discarded as it would require redesigning the panel.

Concepts J1 and J2 are simply expanding the cold break by removing steel in the connection. Illustrations of the concepts are presented in Figure 4.6.

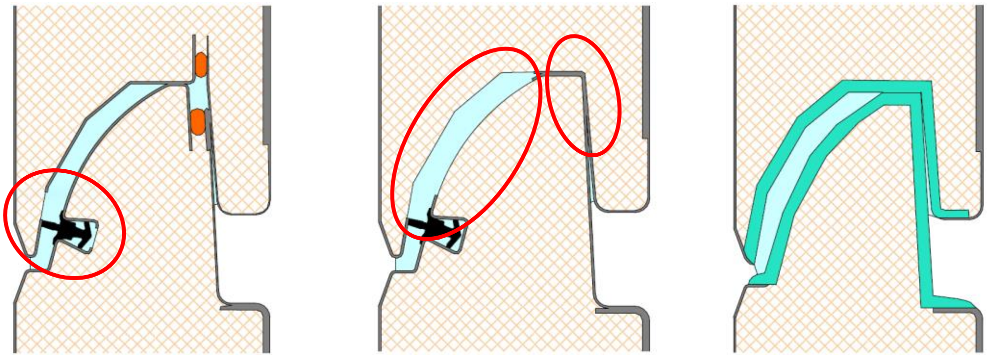


**Figure 4.6 Joint concepts J1, J2 & J3 from left to right**

The extended slit and plastic fins concepts showed the greatest impact, lowering the Ψ-value by 85% respectively 86% compared to the current solution. The Ψ-values for the panel joint construction are found in Table 4.13.

**Table 4.13 Ψ–values of tested panel joint concepts**

| *Concept* | *Description* | *Ψ-Value [W/mK]* |
|---|---|---|
| *J0* | *Current solution* | 0.146 |
| *J1* | *Slit* | 0.105 |
| *J2* | *Extended slit* | 0.022 |
| *J3* | *Plastic fins* | 0.019 |

### 4.6.3 Panel

The concepts for the panel are presented in Table 4.14. This is the aspect with the greatest impact on the $U_D$, but also the most coupled aspect with respect to the rest of the door system.

**Table 4.14 Panel Concepts**

| *Concept* | *Description* |
|---|---|
| P1 | Increased width with maximum 10 mm |
| P2 | Add patches of insulating material on the door leaf's inside |
| P3 | Change skin material to one with lower conductivity (Fiberglass) |
| P4 | Change filling material (Aerogel) |

Concept P1 derived from the fact that the panel thickness could be increased up to 10 mm without affecting the rail system. All that would have to be redesigned within the project scope was the bottom brackets, the endcap, and the shark fin. It would however affect the pass door, the framed sections, and the windows, but as mentioned in Delimitations, this is out of scope. Figure 4.7 shows how the U-value decreases while the thickness increases.

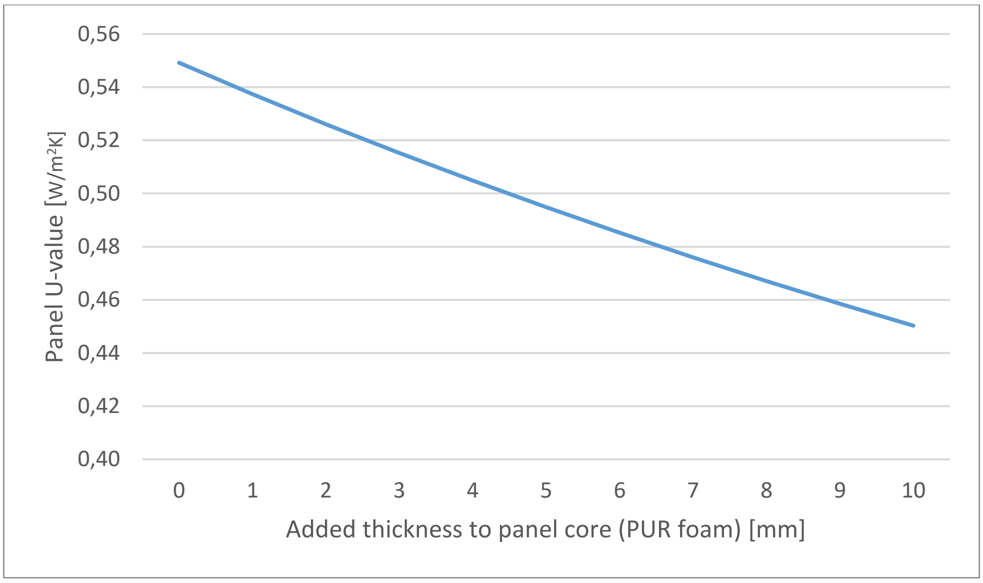



**Figure 4.7 U-value of panel as a function of added core thickness**

Concept P2 is a way of making the panel thicker without changing the manufacturing process. This can be implemented in post-production by attaching these patches when the door is assembled, see Figure 4.8.

**Figure 4.8 Added patches of insulation material**

Concept P3 would require redesigning the entire manufacturing process but could have many positive outcomes in forms of cheaper manufacturing, lighter door leaf and better U-value.

Concept P4 was based on trying to find a better filling material than the PUR foam used today. No material was found that had the same desirable combination of density, λ-value, price and strength. But a study on hybrid core sandwich panels where polyisocyanurate rigid foam (PIR foam) is combined with Aerogel foam showed some potential [19]. Figure 4.9 shows how the U-value of the panel would decrease with the increased ratio of Aerogel foam, which has a λ-value of $\sim 0{,}018 W/mK$. It should be noted that aerogel has significantly higher density than PUR foam and does not expand when solidifying [20], which is a key aspect in the manufacturing process of the panel. So, the only way of implementing this solution would be to insert a block of aerogel into the panel and have the PUR foam expand around it, working like a glue between the metal sheets and the aerogel block.

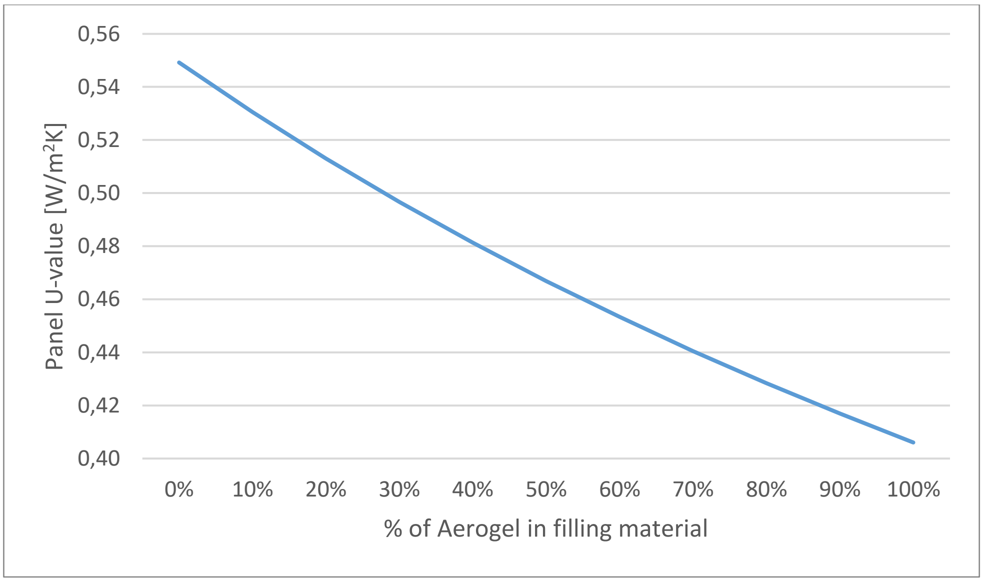



**Figure 4.9 U-value of panel as a function of % of Aerogel in hybrid core**

# 5 Concept selection

A presentation was held at AA for people involved in the project. The developed concepts were presented with the aim to get feedback and to select the most promising concepts moving forward. The concepts that were presented are those found in Table 4.10, Table 4.12 and Table 4.14. This was done to limit the amount of concept for further exploration, as the time limitation of this project did not allow to further iterate each concept.

To decide on which concepts to further develop a combination of the methods *concept screening* and *external decision* were used. The main criteria were improvement in ψ-value and cost, but other criteria, such as manufacturability, environmental impact, aesthetic, ease of implementation were also discussed. See Table 5.1, Table 5.2, and Table 5.3. The concepts set as references were chosen because they represented the median value of most criteria.

**Table 5.1 Concept screening matrix for side seal concepts**

| | Concepts | | | | | |
|---|---|---|---|---|---|---|
| ***Criteria*** | ***S0*** | ***S1*** | ***S2*** | ***S3*** | ***S4*** | ***S5*** |
| ***Cost*** | *0* | + | + | 0 | 0 | 0 |
| ***Ψ gain*** | *0* | + | 0 | 0 | + | 0 |
| ***Ease of implementation*** | *0* | *0* | 0 | 0 | 0 | 0 |
| ***Manufacturability*** | *0* | + | + | 0 | 0 | 0 |
| ***Environmental impact*** | *0* | *0* | - | - | - | - |
| ***Aesthetics*** | *0* | *0* | 0 | 0 | 0 | 0 |
| ***Sum +'s*** | *0* | *3* | 2 | 0 | 1 | 0 |
| ***Sum -'s*** | *0* | *0* | 1 | 1 | 1 | 1 |
| ***Sum 0's*** | *6* | *3* | 3 | 5 | 4 | 5 |
| ***Net Score*** | *0* | *3* | 1 | -1 | 0 | -1 |

**Table 5.2 Concept screening matrix for joint concepts**

| | *Concepts* | | | |
|---|---|---|---|---|
| ***Criteria*** | ***J0*** | ***J1*** | ***J2*** | ***J3*** |
| ***Cost*** | + | *0* | 0 | - |
| ***Ψ gain*** | - | *0* | + | + |
| ***Ease of implementation*** | + | *0* | 0 | - |
| ***Manufacturability*** | + | *0* | 0 | - |
| ***Environmental impact*** | *0* | *0* | + | + |
| ***Aesthetics*** | *0* | *0* | 0 | 0 |
| ***Sum +'s*** | *3* | *0* | 2 | 2 |
| ***Sum -'s*** | *1* | *0* | 0 | 3 |
| ***Sum 0's*** | *2* | *6* | 4 | 1 |
| ***Net Score*** | *2* | *0* | 2 | -1 |

**Table 5.3 Concept screening for panel concepts**

| | *Concepts* | | | | |
|---|---|---|---|---|---|
| ***Criteria*** | ***P0*** | ***P1*** | ***P2*** | ***P3*** | ***P4*** |
| ***Cost*** | + | *0* | + | - | - |
| ***Ψ gain*** | - | *0* | 0 | 0 | 0 |
| ***Ease of implementation*** | + | *0* | + | - | 0 |
| ***Manufacturability*** | + | *0* | + | 0 | 0 |
| ***Environmental impact*** | + | *0* | 0 | + | 0 |
| ***Aesthetics*** | *0* | *0* | - | 0 | 0 |
| ***Sum +'s*** | *4* | *0* | 3 | 1 | 0 |
| ***Sum -'s*** | *1* | *0* | 1 | 2 | 1 |
| ***Sum 0's*** | *1* | *6* | 2 | 3 | 5 |
| ***Net Score*** | *3* | *0* | 2 | -1 | -1 |

The most promising concepts for each aspect based on the screening matrices, were J2 the extended slit, S1 plastic endcap and P2 the insulative patches.

The chosen concepts for further development were J2 the extended slit and the S1 plastic endcap. Additionally, it was decided to expand the "plastic endcap" concept to include any other material than steel, but also the option to remove the endcap entirely. These selected concepts were deemed feasible to test and simulate, aligning well with the scope of the project. The insulative patches scored the best for the panel concepts but was not chosen to further develop as AA thought it would be wise to limit the project to only two concepts, seeing as these could already significantly decrease the U-value without the patches. Hence, priority was given to the extended slit and plastic endcap.

Although concepts 3,4,5 for the side construction showed some potential, they were not selected to further development or combine with the endcap concept. This decision was made as AA had developed a newer version of the side sealing, which they kept secret to prevent influencing the authors ideation process. However, this newer version shared many aspects of the DPs generated for the side sealing.

# 6 Concept validation

*In this section the selected the concepts S1 plastic endcap and J2 extended slit, are holistically validated through physical testing, environmental analysis & cost analysis.*

## 6.1 Wind load test

One of the requirements is resistance to wind load, which must be tested according to EN 12444. AA have different requirements for different widths regarding what wind class the door must fulfill. Doors up to 4250 mm width must fulfill wind class 3, while doors wider than 4250 mm only need to fulfill wind class 2. This makes a 4250 mm wide door the worst-case scenario regarding wind load. There were only 4000 mm wide panels accessible, so these were used for testing. Further information regarding the wind load testing can be found in Appendix G. Four configurations were tested:

1. Current
2. No endcap
3. Slit
4. Slit + no endcap.

Both the deflection when the load was applied, and the resulting residual deflection were measured for each test on the panel's midpoint. The results are illustrated in Figure 6.1 and Figure 6.2. All test configurations could support wind class 4 and yielded at approximately 3300 N / 1100 Pa except the slit configuration, which is explained below.

According to the test results it can be determined that implementing both the slit and removing the endcap will pass the load requirements from wind class 2 and 3.

The slit configuration experienced a gust of wind when wind class 4 was applied, which made the door oscillate and break before the deflection could be measured. The plastic deformation for the current panel design was much higher than the rest. One explanation for this could be that the panel may have been faulty. Another explanation could be fatigue because the load was applied for a longer period of time, as it was the first test and the authors worked at a slower pace. The authors did not have time nor enough panels to do more tests.

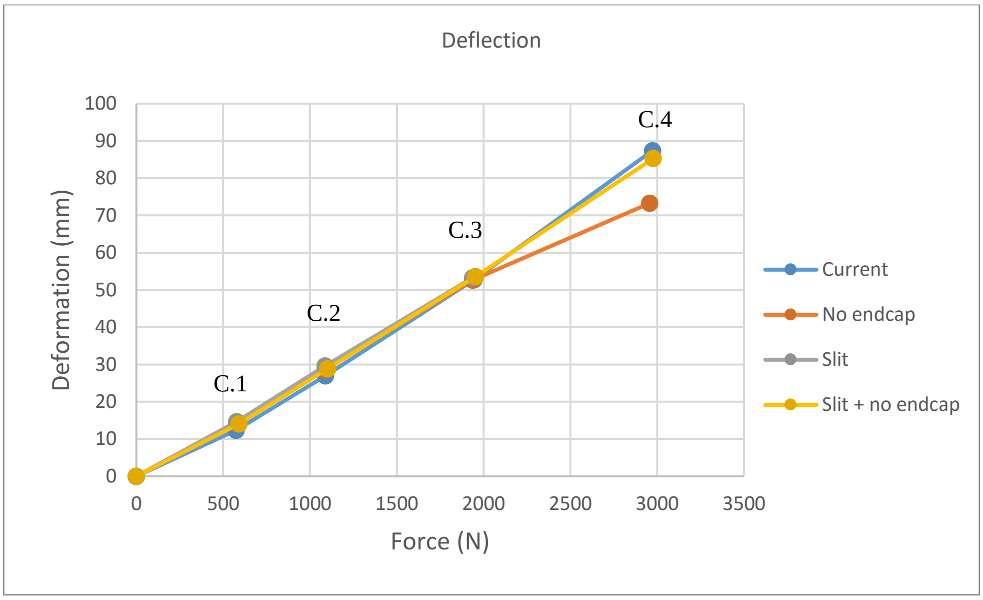



**Figure 6.1 Deflection from weight of the different wind classes**

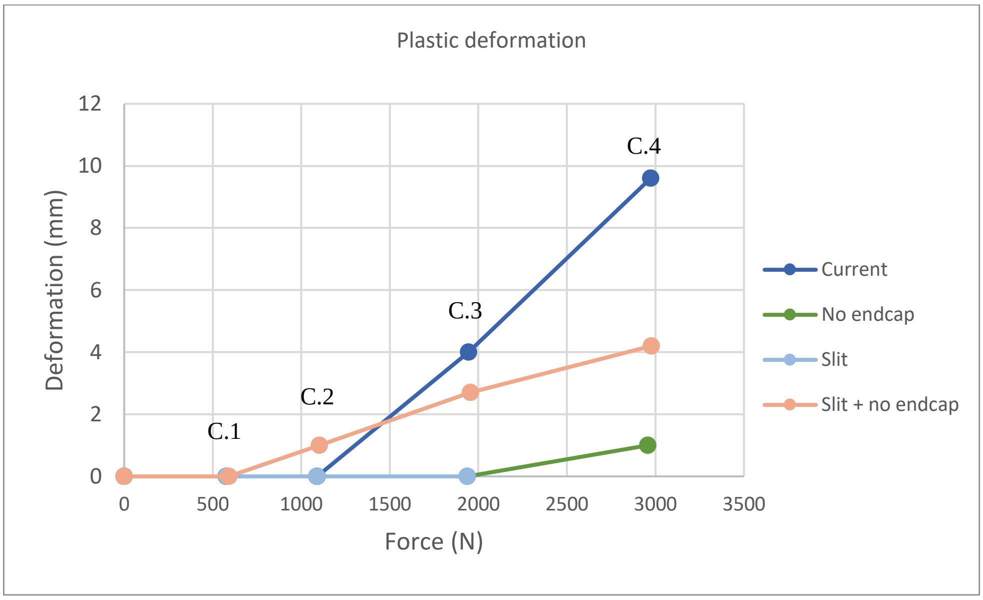



**Figure 6.2 Plastic deformation after the weight of the different wind classes were removed**

## 6.2 Vertical weight test

A panel joint test was done to simulate the compressive load that acts on the panel joint in a closed position. To test the worst-case scenario, it was decided to do it on the bottom panel as that is the panel with the highest load on top of it. The load application and set up can be found in Appendix F. The load that was applied represent the weight of the panels on top and is repeated with different safety factors until failure. Starting with a safety factor of 1,1 according to EN 12604:2017. Between each scenario the load is removed, and the panel is checked for any plastic deformation by checking the cross section with a yardstick. A total of 4 tests were made, one for the current configuration and 3 tests for the extended slit concept. The result is found in Table 6.1.

No test specimens showed any sign of plastic deformation until a load of 1500 N was applied, equaling 9 times the required safety factor. Thus it can be claimed that implementing the changes wont affect the neccesarry structural integrity of the panel from the load acting in a closed position.

**Table 6.1 Result Vertical test**

| *Safety factor* | *Force (N)* | *Current* | *Extended Slit 1* | *Extended Slit 2* | *Extended Slit 3* |
|---|---|---|---|---|---|
| *1,1* | 166 | Small non-plastic deformation. | Small non-plastic deformation. | Small non-plastic deformation. | Small non-plastic deformation. |
| *3,3* | 500 | ---\|\|--- | ---\|\|--- | ---\|\|--- | ---\|\|--- |
| *5,3* | 800 | ---\|\|--- | ---\|\|--- | ---\|\|--- | ---\|\|--- |
| *6,6* | 1000 | Small non-plastic deformation. Finger protection gap closed. | Small non-plastic deformation. Finger protection gap closed. | Small non-plastic deformation | Small non-plastic deformation. Finger protection gap closed. |
| *9,9* | 1500 | Significant non-plastic deformation. | Significant non-plastic deformation. | Small non-plastic deformation. Finger protection gap closed | Plastic deformation. |
| *13,3* | 2000 | Plastic deformation. | Plastic deformation. | Plastic deformation | Failure. |
| *15,3* | 2300 | Failure. | Failure. | Failure | - |

## 6.3 Material research

While the conducted structural tests showed promising result of removing the endcap completely, this was not deemed viable as it needs to meet other ISO standards and aesthetically leaving the panel's sides open did not align with AA. The main concern being that there should be some fire-retardant barrier covering the foam. Hence, a fire-retardant material should be applied to the endcap. In addition to this the material should be

- Lightweight
- Low λ-value
- Cost effective
- Suitable for mass production

It was decided not to investigate the possibility of manufacturing the endcap in wood due to the profile's geometry. Instead, a comparison of polymers was conducted, especially considering fire resistance. The industry standard for fire resistance in polymers is UL 94, which is a test method that describes how a certain sized polymer acts when exposed to a flame [21]. The classifications are retrieved from UL's website:

**HB:** Horizontal burning. For test specimen < 3 mm, the burning rate must be ≤ 75 mm / min

**V2:** Vertical burning. burning stops within 30 seconds. Allows burning droplets

**V1:** Vertical burning. burning stops within 30 seconds. Does not allow burning droplets

**V0:** Vertical burning. burning stops within 10 seconds. Does not allow burning droplets [22]

There is no direct way of translating the fire class in EN 13501 [15] to the UL 94 classifications, but V0 and V1 comes closest to the current panel classification of C-s3,d0. The compared polymers are presented in Table 6.2.

**Table 6.2 Material table of polymers [23]**

| ***Polymer*** | ***Abbrv.*** | ***λ (W/mk)*** | ***ρ (g/cm³)*** | ***E (GPa)*** | ***σˢ (Mpa)*** | ***Cost (€/kg)*** | ***Fire rating[b]*** |
|---|---|---|---|---|---|---|---|
| Polyvinyl Chloride | PVC | 0,16 | 1,4 | 3,7 | 47 | - | V-0 |
| Polyvinylidene fluoride | PVDF | 0,12 | 1,8 | 1,1 | 49 | 15[c] | V-0 |
| Polytetrafloureten | PTFE | 0,24 | 2,2 | 0,45 | 25 | - | V-0 |
| Polyether ether ketone | PEEK | 0,25 | 1,3 | 4 | 97 | - | V-0 |
| Polycarbonate | PC | 0,2 | 1,2 | 2,3 | 66 | - | V-2 |
| Acrylonitrile Butadiene Styrene | ABS | 0,23 | 1,1 | 2 | 41 | - | HB |
| Polypropylene | PP | 0,15 | 0,91 | 1,4 | 36 | - | HB |
| Polyamide 6 glass fiber 30% | PA6-GF 30 | <0,25 | 1,4 | 9 | 150 | 1,8[c] | V0[c] |
| POLYblend 83 FR[a] | PC/ABS | 0,215* | 1,2 | 2,15 | 70 | 5,9 | V0[a] |
| POLYFfill PP 150NH[a] | Pf-PP | 0,15* | 1,06 | 1,4 | 24 | 5,5 | V0[a] |

Notes:
[a] [24]
[b] [25]
[c] (AA supplier - Flexiforce)
*Data taken from standard polymer

If a fire rating of V1 is needed to pass the requirements from SS EN 13501-1 then all non V1 and V0-rated polymers are disregarded. Additionally, PVC is not an option due to AAs policy regarding microplastics. With this, six alternatives were relevant: PVDF, PTFE, PEEK, PA6-GF 30, POLYblend 83 FR and POLYfill PP 150 NH. PEEK was ruled out due to its high cost and PTFE due to high processing temperature. Of the four remaining options, the two most promising alternatives were the PA6-GF 30 due to its low cost and the POLYfill PP 150NH due to a good combination of low conductivity, low density, and average cost.

If not taking the fire classification into account the most suitable option would be PP, having appropriate conductivity for good thermal isolation and low density while being one of the cheapest polymers.

The cost was difficult to compare as it differs depending on the supplier. Therefore, it was compared in the end between the most promising alternatives.

## 6.4 Manufacturing and cost

### 6.4.1 Extended slit

To validate the implementation of the extended slit concept it was investigated if it was possible to manufacture in a cost-efficient way. The authors had two ideas of how to implement the concept. The first one being, removing the metal strip by post processing the panel, see Figure 6.3. Implementing this into the current panel manufacturing method would be though as the foam must harden before the steel can be removed. The second alternative would be changing the rolling forms to achieve the wanted break already in the production, having the inner skin extend further. The cross section would look like Figure 6.4.

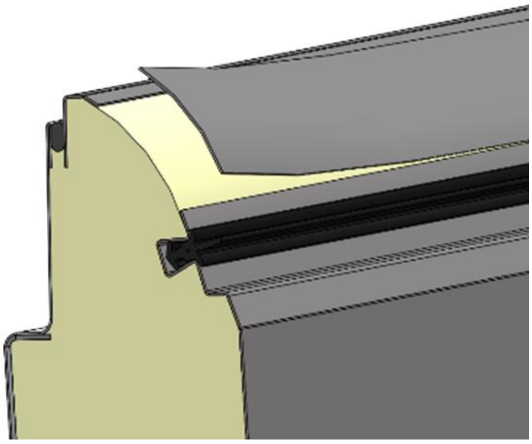


**Figure 6.3 Post processing of slit**

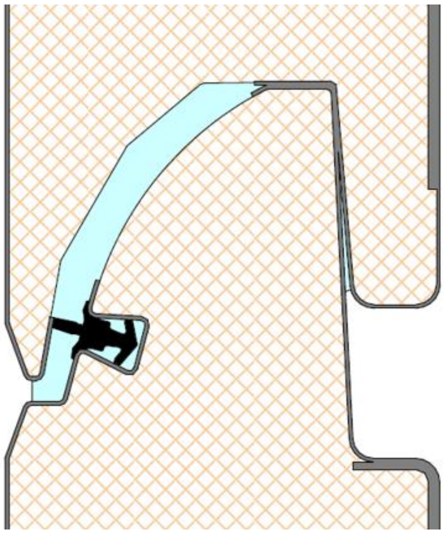


**Figure 6.4 Changing roll bending forms to create slit**

As it was desired by AA to just have an alternative to the 42 mm door with a better U-value and not replacing the original, changing the rolling forms was not a viable option to move forward with.

Therefore, it was chosen to investigate how the post processing alternative would be executed in the optimal way. The team contacted manufacturing engineers at AA. Having had previous experience of needing to remove a metal strip they had concluded that using a "*shear cutter*" Figure 6.5, was the optimal way after having tried different methods such as milling and sawing. The tool is relatively cheap and easy to implement, with the downsides of having a fixed slit width of about 5 mm, and the fact that the cutter also must remove some of foam in the cutting process.

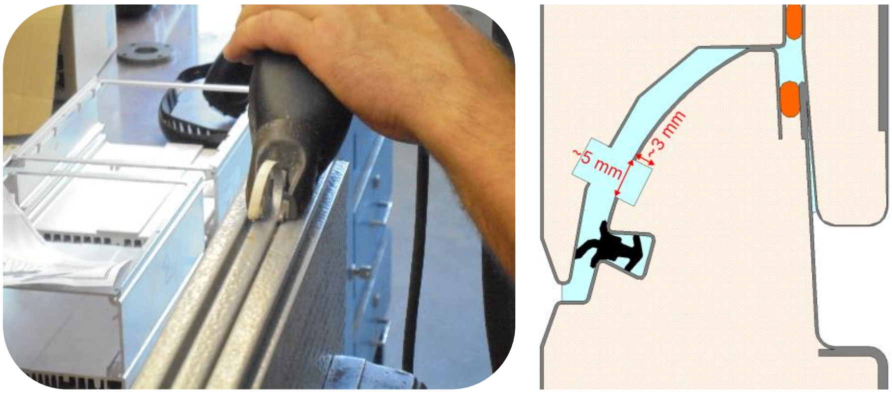



**Figure 6.5 Shear cutter used on another AA panel (left). Shear cutter's effect on 42 mm panel (right)**

The same engineers had documented the labor cost of executing the cut for a complete 4x4 door. As it was a different door with different panels the cost was used as a benchmark for estimating the cost of implementing it on the 42 mm panels. The resulting values are found in Table 6.3.

**Table 6.3 Cost of implementing the slit**

| *Door size* | *Slit cost / door cost* |
|---|---|
| 3x3 | 1,19 % |
| 4x4 | 1,66 % |
| 5x5 | 1,87 % |

Post processing the panel this way, a shear cutter is needed. In addition to this, to make the process semi-automated a jig is needed to be built.

### 6.4.2 Plastic Endcap

Possible ways of manufacturing the endcap are through extrusion, injection molding or heat bending. For large volume manufacturing and with the simple geometry of the endcap, extrusion is the optimal choice as this is more cost effective for large scale production.

Several variations for the endcap geometry were created. The main function of the endcap is to cover the foam. As the screws that goes into the hinges already exist, they are used to attach the endcap as well. Therefore, a simple geometry is kept. The difference in the variations is how to achieve the gap that allows for the tolerance of the panel width, the extrusion concept can be found in Figure 6.6.

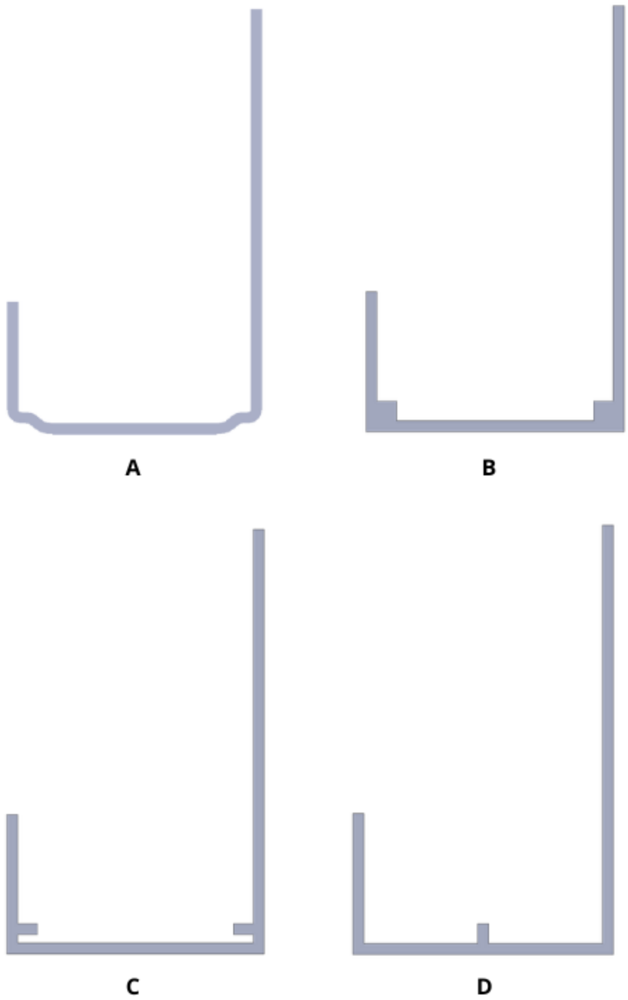



**Figure 6.6 Extrusion concepts**

Having a uniform wall thickness of the extruded profile is important so that the flow of plastic is the same and that it will cool down at equal speed. Therefore, concept B is disregarded. Concept D achieves the gap through an extra bit of material in the middle, this is not desirable as it will only rest against the foam, creating a risk that the foam gets deformed. Leaving concept, A and C as viable options. Where option A is preferably due to a smaller number of sharp corners.

The detail will have to be post processed, to create holes and remove some material required, allowing for tolerances required in the panel's width. This will increase the manufacturing cost.

To get an estimation of the manufacturing cost the team contacted Flexiforce, who is a current supplier for AA. Flexiforce gave a cost estimation for manufacturing the part without taking the tooling cost into account. The estimation was done for mass producing the part in an amount resembling the potential sale volume. According to Flexiforce the tooling cost would be around 55,000€.

For manufacturing the part in PA6-GF30, the cost was estimated by Flexiforce to 3,84€ /endcap. Based on this an estimate was made for Pf-PP by extrapolating the cost of PA6-GF30 through the difference in material cost. The cost was estimated to 4,4€ /endcap. Comparing to the current steel endcap, this will lead to a decrease in cost.

## 6.5 Environmental comparison

Greenhouse gases play a crucial role in warming the Earth by absorbing energy and reducing the rate at which the energy escapes into space, effectively acting as an insulating blanket. However, not all greenhouse gases have the same impact. Two key differences between the gasses are their ability to absorb energy, and how long they remain in the atmosphere. [26]

To allow for comparison between different gases, the concept of Global Warming Potential (GWP) was introduced. GWP measures the amount of energy that the emissions of 1 ton of gas will absorb over a specified timeframe compared to 1 ton of carbon dioxide (CO2) emissions. A higher GWP indicates a greater warming effect relative to CO2 over that period. This standardized metric allow analyst to add up to add up emissions estimates of different gases. Additionally, policymakers can utilize GWPs to assess emissions reduction opportunities across sectors and gases, providing a measure for comparison. [26]

GWP can also be used to compare the emission of greenhouse gasses emitted during production of different products and materials. This is applied to compare the environmental impact per kg of different materials, see Table 6.4.

**Table 6.4 Endcap GWP comparison, 3x3 door**

| ***Material*** | ***Abbrv.*** | ***ρ (g/cm3)*** | ***Endcap Weight (kg)*** | ***Endcap pieces*** | ***GWP/kg [a]*** | ***Total GWP*** |
|---|---|---|---|---|---|---|
| Steel | - | 7,8 | 0,575 | 11 | 2,11 | 13,4 |
| Polypropylene | PP | 0,91 | 0,14 | 11 | 3,48 | 5,4 |
| Polyamide 6 glass fiber 30% | PA6-GF 30 | 1,4 | 0.21 | 11 | 8,1 | 18,7 |
| POLYFfill PP 150NHa | Pf-PP | 1,06 | 0,16 | 11 | 4,05[b] | 7,3 |

[a] (ASSA ABLOY, n,d.)
[b] Assumed to be the same GWP/kg as regular PP.

For the V0-classed options, the Pf-PP has a significantly lower GWP than the PA6-GF30. Based on this in addition to the cost price, the team proposes to go forward with the Pf-PP polymer for the endcap. This should be seen as a recommendation and not a final decision on material, leaving it open for further investigation, either by other thesis workers or by AA.

# 7 Final results

*In this section the proposed solution is presented through the final design, manufacturing proposal, cost, and an environmental impact.*

## 7.1 Final design

Models of the proposed design can be seen in Figure 7.1 and Figure 7.2. This design does not negatively affect structural integrity or fire resistance, see *6 Concept validation*. No changes have been made that will affect air permeability. The ψ-values and $U_D$ for the final design were simulated with the proposed material and manufacturing method and can be seen below.

**ψ-values:**

| | | |
|---|---|---|
| Joint: | 0,061 $W/mK$ | (58,2% lower) |
| Side: | 0,196 $W/mK$ | (46,4% lower) |

**$U_D$:**

| | | |
|---|---|---|
| 3x3 m, one row DARP: | 1,06 $W/m^2K$ | (18,5% lower) |
| 5x5 m, no windows: | 0,81 $W/m^2K$ | (19% lower) |

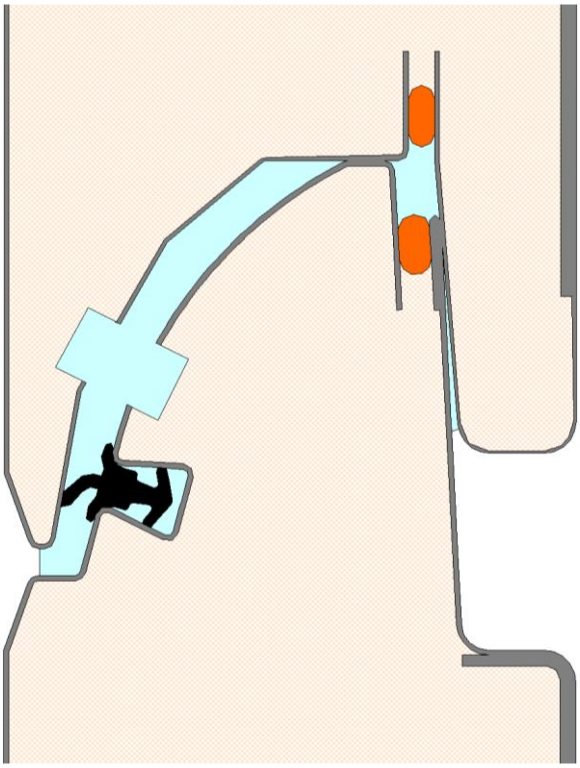


**Figure 7.1 Final design of joint, post processed by a shear-cutter**

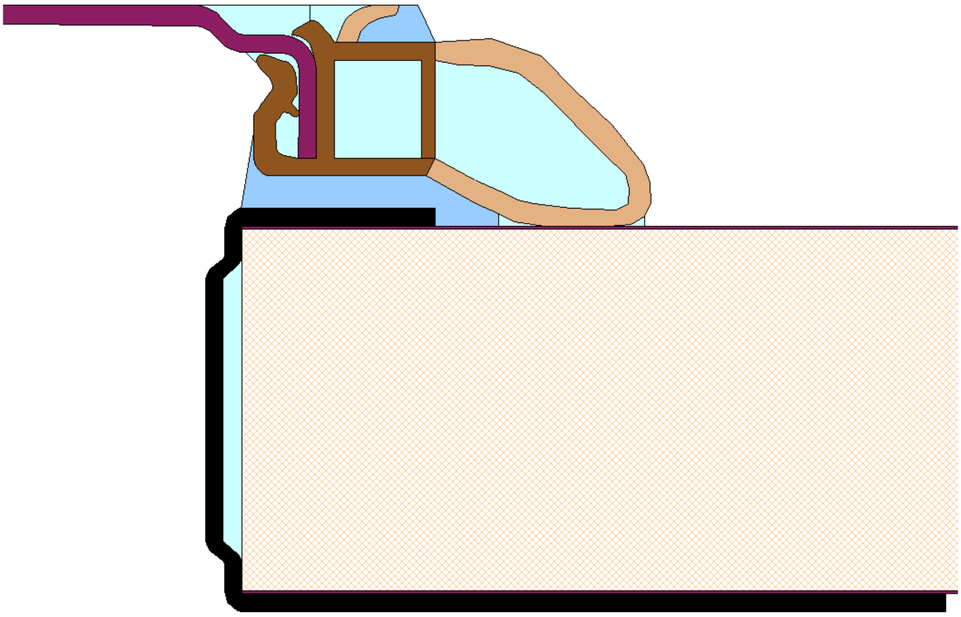


**Figure 7.2 Final design of side with Pf-PP endcap and AA's new side sealing**

## 7.2 Manufacturing and cost

The extended slit will be manufactured through post processing the panel joint. After the panels have been cut to size, they are manually placed and fastened in a jig where a shear cutter can cut a 5 mm strip along the length of the panel as seen in Figure 2.4.

The endcaps will be manufactured through extrusion in Pf-PP and postprocessed by punching.

Implementing both of the concepts will result in an increased cost of about 1%. Where the implementation of the slit will see a 1,5% increase meanwhile switching to an endcap in Pf-PP will decrease the cost slightly, estimated to be 0,5%. For comparison, the 82 mm door has a ~30% higher cost than the 42 mm door.

## 7.3 Environmental impact

When up and running, the proposed design will affect heat flow and energy consumption of the motor as the door leaf is lighter. According to EDSF [27], the proposed design will save 4,68% energy per door over a period of 5 years. See Appendix J for specifications.

Regarding manufacturing, it is difficult to calculate the exact impact. But the slit is manufactured with a simple hand tool, and producing a plastic detail compared to a steel one generally requires less energy. The GWP contribution for manufacturing the endcap in Pf-PP is 46% lower compared to the current steel one, see Table 6.4.

# 8 Discussion

## 8.1 Result

Comparing the stakeholder needs in Table 4.1 and FRs in Table 4.2 and Table 4.3 with the design proposal, it conveys a rather successful product development process. The design is easily implementable, reduces the $U_D$ with ~19% while only increasing the overall cost with ~1% without introducing any unwanted side effects such as reduced fire safety, reduced mechanical strength, negative environmental effect etc. For comparison, the 82 mm door has 54% lower $U_D$ and ~30% higher cost. In addition, the proposed design will save 4,68% energy per door over a 5-year period, as well as only generating half of the GWP compared to the current one. These are positive results considering how far along the product development process the authors have come. However, this should merely be seen as a proof of concept as a lot of further testing and validation is required to ensure all phases of this solutions lifecycle are verified, from manufacturing to usage to end-of-life management.

The results from the physical testing puzzled the authors as removing material and components did not seem to impact structural integrity. Although an open profile is generally known to be significantly weaker than a closed one, this difference was not evident in the test results. The authors concluded that these design changes could be implemented without affecting structural integrity under static conditions. However, they might impact integrity under dynamic loads, which would become evident through full life cycle testing as proposed below.

Other than lowering the U-value, this solution has been heavily influenced by the need of easy implementation and manufacturability. However, for some of the generated concepts the authors tried not to consider this to get a few “out-of-the-box”-ideas. E.g. the modular panel design mentioned in *3.2.5 Concept generation* would have been very interesting to further develop, especially if it could be combined with replacing the skin material with something other than steel. In addition, this would decrease the amount of material not getting used due to the symmetry of the panel, which allows one panel to be used for either top or bottom pieces.

Another out of the box idea was to lower the pressure in the panel. As lowering the pressure for porous material such as the PUR foam would lead to a decrease in the material’s $\lambda$-value [28]. This idea was disregarded as it would be incredible hard to implement as well as being economically viable. However, in the future this concept could be interesting for certain applications were alternating the λ-value would be useful.

One interesting finding was that the endcap does not serve a significant structural purpose and could most likely be replaced by something far cheaper and lighter. Yet most competitors still use them. This could be because historically endcaps were structurally essential, but improvements in the quality of other components, such as the PUR foam, have reduced the structural contribution required from the endcaps.

When investigating what affected the $U_D$, it was found that thermal bridges and ψ-value played a greater role than expected. Typically, a thermal bridge is the primary factor contributing to increased Q. It was also found that increasing the width of a thermal break will significantly decrease Q, as illustrated in Figure 2.4. This principle was applied to the extended slit concept, maximizing the benefit from the thermal break while keeping the manufacturing method in mind.

Lastly, it should be mentioned that the work of this project has contributed towards reaching some of the goals for the 2030 agenda for sustainable development:

*"Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation"*

The goal of this project was to produce a design solution that would make an already existing product more well insulated.

*"Goal 12. Ensure sustainable consumption and production patterns"*

By making the industrial door more well insulated, less energy is required for heating/cooling in the building where the doors are installed.

*"Goal 13. Take urgent action to combat climate change and its impacts"*

Less greenhouse gases in the form of steel production and less energy used for heating/cooling [29].

## 8.2 Method

All methods presented were applied in the project. However, some methods were only applied to a certain extent, mainly the FR-DP matrix decoupling. It was tried on the current panel joint solution first. Due to the number of coupled DPs in the current design that could not be altered due to Cs, it was chosen to only use the mapping to illustrate the different DPs effect on multiple FRs

One thing that took longer than expected was the material research/selection. Due to the large number of different polymers and variants, it was challenging to know what type of polymers would fit the requirements. Different sources displayed different specifications for what seemed like the same polymer. This made the comparison of data cumbersome.  In addition, the response time from plastic suppliers and manufacturers delayed the work further.

Overall AD was a useful process to follow, sharing many fundamental aspects of other design processes, such as establishing customer needs and setting design requirements. What was especially useful with AD was the importance of establishing clear, useful, and independent FRs in a solution neutral environment. This really forces the designer to find the heart of the matter. Some parts of AD were less useful. E.g. the mathematical models that quantify the information content seemed too much work compared to what would be gained. Instead, it was chosen to implement a scoring matrix for evaluating the DPs.

If the authors were to use AD again, it would be very helpful to get continuous supervision from an expert AD user. The authors have to the best of their abilities tried to implement the theory and interpret the many examples available. But it is challenging trying something for the first time without any guidance.
As mentioned above, this project has tried to prove a concept. So, for AA to take this design to market, further testing and verification should be conducted. These include:

- Full life cycle test of about 200.000 cycles with regular checkups
- Wind load test on a full 5500x5500 mm door
- Fire safety test
- Humidity test
- Test thermal expansion and contraction, especially if outside is colored black.

## 8.3 Limitations

- More tests on each configuration of the wind load test would have been desirable, especially since the data on plastic deformation of the current configuration did not seem logical. But there was no time nor panels for this.
- The authors would have wanted to test multiple 4250 mm and 5500 mm wide panels for wind load. But this was not possible as these sizes were not available on site.
- A full or partial life cycle test (50.000-200.000 cycles) of the concepts implemented on a door would have been desirable, but there was no time for this.

## 8.4 Future work

As mentioned above, this project has tried to prove a concept. So, for AA to take this design to market, further testing and verification should be conducted. These include:

- Full life cycle test of about 200.000 cycles with regular checkups
- Wind load test on a full 5500x5500 mm door
- Fire safety test
- Humidity test
- Test thermal expansion and contraction, especially if outside is colored black.

# 9 Conclusion

## 9.1 Project overview

In the broadest sense, the authors set out to find a design solution that would be easy and cost effective to implement on the most common configurations of ASSA ABLOY’s 42 mm overhead sectional industrial door to lower its U-value, and such a solution was found. Resulting in two concepts, one being a slit in the shark fin profile and the other a polymer endcap. Combined they offer a good alternative to the existing doors of ASSA ABLOY, the 42 and 82 mm.

The project was a systematically carried out with the help of the axiomatic design methodology accompanied by some of Ulrich & Eppinger methods. The combination of methods complemented each other well, mainly in the area of concept selection where axiomatic design was overly complicated.

## 9.2 Contribution to the advancement of knowledge

In the field of mechanical engineering with industrial design, this project has shown the importance of working in a solution neutral environment to formulate FRs for a problem, and that the most obvious solution might not be the best one. Additionally, it was a lesson in designing seemingly small and unnoticeable changes that had significant impact.

It has let AD make an entrance to the world of design science within Lund University and will hopefully inspire other designers to put AD into practice.

Regarding the technical aspect of this project, it may stand as a guideline on how to design for thermal insulation applications. The key takeaway being the importance of excluding or breaking thermal bridges to the largest possible extent, as this has a much greater impact on heat flow than one might think.

# 10 References


[1] ASSA ABLOY, "ASSA ABLOY Entrance Systems, Overhead sectional doors," ASSA ABLOY, [Online]. Available: https://www.assaabloyentrance.com/uk/en/solutions/products/commercial-and-industrial-doors/overhead-sectional-doors. [Accessed 10 May 2024].

[2] D. A. Snow, Plant Engineer's Reference Book, Butterworth-Heinemann, 2003.

[3] SS-EN 12428, "Industrial, commercial and garage doors – Thermal transmittance – Requirements for the calculation," SIS, 2013.

[4] N. P. Suh, The Principles of Design, Oxford University Press, 1990.

[5] N. Pyo Suh, M. Cavique and J. T. Foley, Design Engineering and Science, Cham: Springer Nature Switzerland, 2021.

[6] M. Nordlund, T. Lee and K. Sang-Gook, "Axiomatic Design: 30 Years After," in *IMECE2015*, Houston, 2015.

[7] W. Li, Z. Song and C. Suh, Principles of Innovative Design Thinking, Higher Education Press, 2022.

[8] M. A. Mabrok, M. Efatmaneshnik and M. Ryan, "Including Non-Functional Requirements in the," IEEE, 2015.

[9] M. K. Thompson, "Improving the requirements process in Axiomatic Design Theory," *CIRP Journal of Manufacturing Science and Technology*, no. 62, pp. 115-118, 2013.

[10] K. T. Ulrich and S. D. Eppinger, Product Design and Development, Sixth Edition, New York: McGraw-Hill Education, 2016.

[11] SS-EN ISO 10077-2:2017, "Thermal performance on windows, doors and shutters – Calculation of thermal transmittance," SIS, 2017.

[12] SS-EN 12424, "Industrial, commercial and garage doors and gates – Resistance to wind load – Classification," SIS, 2000.

[13] SS-EN 12444, "Industrial, commercial and garage doors and gates – Resistance to wind load – Testing and calculation," SIS, 2001.

[14] SS-EN 12604:2017, "Industrial, commercial and garage doors and gates – Mechanical aspects – Requirements and test methods," SIS, 2017.

[15] SS-EN 13501-1:2019, "Fire classification of construction products and building elements –Part 1: Classification using data from reaction to fire tests," SIS, 2019.

[16] SS-EN 12426, "Industrial, commercial and garage doors and gates – Air permeability – Classification," SIS, 2000.

[17] SS-EN 12489, "Industrial, commercial and garage doors and gates – Resistance to water penetration – Test method," SIS, 2000.

[18] Sweden Green Building Council, "SGBC," [Online]. Available: https://www.sgbc.se/certifiering/breeam-se/. [Accessed 22 Febuary 2024].

[19] R. Studzinski, "Optimal design of sanwdich panels with hybrid core," *Journal of Sandwich Structures and Materials*, vol. 21, no. 7, pp. 2181-2193, 2019.

[20] N. Diascorn, S. Calas, H. Sallée, P. Achard and A. Rigacci, "Polyurethane aerogels synthesis for thermal insulation – textural, thermal and mechanical properties," *The Journal of Supercritical Fluids*, no. 106, p. 7684, 2015.

[21] UL 94, "Tests for Flammability of Plastic Materials for Parts in Devices and Appliances," 2023.

[22] UL Solutions, "Combustion (Fire) Tests for Plastics," UL Solutions, [Online]. Available: https://www.ul.com/services/combustion-fire-tests-plastics#:~:text=UL%2094%20also%20describes%20a,flames%20once%20it%20becomes%20ignited.. [Accessed 15 May 2024].

[23] "MakeItFrom," [Online]. Available: https://www.makeitfrom.com/material-group/Thermoplastic. [Accessed 13 May 2024].

[24] "polykemi," 2024. [Online]. Available: https://www.polykemi.se/. [Accessed 13 May 2024].

[25] "Direct Plastics," Direct Plastics Limited, 25 July 2019. [Online]. Available: https://www.directplastics.co.uk/news/post/fire-ratings-of-engineering-plastics. [Accessed 13 May 2024].

[26] "United States Enviromental Protection Agency," 27 March 2024. [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#:~:text=The%20Global%20Warming%20Potential%20(GWP,carbon%20dioxide%20(CO2).. [Accessed 8 May 2024].

[27] European Door and Shutter Federation, "EDSF," [Online]. Available: https://calculator.edsfdoorenergy.com/steps.html. [Accessed 22 Febuary 2024].

[28] A. Berge, C.-E. Hagentoft, P. Wahlgren and B. Adl-Zarrabi, "Effect from a Variable U-Value in Adaptive Building Components with Controlled Internal Air Pressure," in *IBPC*, Turin, 2015.

[29] United Nations - Department of Economic and Social Affairs, "Transforming our world: the 2030 Agenda for Sustainable Development," [Online]. Available: https://sdgs.un.org/2030agenda. [Accessed 14 May 2024].

# Appendix A Meeting with AA's OHSD product manager

A meeting was held with the product manager of the OHSD who gave important insight to the reasoning behind why this project arose and what competitors can offer. These insights are listed below:

- EDSF.com (European Door and Shutter Federation) offers an online tool that can calculate the energy consumption of a door based on location, average use, type of door, U-value etc. which could be very useful for this project.
- A PowerPoint showing competitors and their corresponding doors with U-values and other parameters was shown.
- A design proposal was given; to increase the cold gap between the out- and inside metal sheet. Today it is a small amount of hotmelt glue.
- AA offers two OHSD today; the 42 mm (U-value: 1,0) and the 82 mm (U-value: 0,46). They would like to offer something in between, regarding U-value, through modifications of the 42 mm. It is not viable to introduce a new door on the market, e.g. a 62 mm, as the demand does not justify it.
- The one aspect that should not be modified trough redesign is thickness (42 mm) as this would affect the rail system and a whole new product would have to be created. Everything else (material, sealing, endcaps, sectional geometry) can be considered.

# Appendix B Meetings with AA product development engineers

Multiple meetings were held with the product development engineers who provided the team with technical insight to the OHSD which are listed below:

- General information about the OHSD's regarding function and insulation, manufacturing processes, load point demonstration, see Figure B.10.1 Force distribution of current panel design (left) and old panel design (right)Figure B.10.1.
- Access to previous Q simulations in Flixo.
- Access to a U-value calculator spreadsheet that shows how the U-value changes depending on size and configuration.
- U-value reports from SP, RISE and IFT Rosenheim of the 42 mm and 82 mm doors with all the different configurations. Official λ-values of all materials used in AA's doors can be found in these reports.

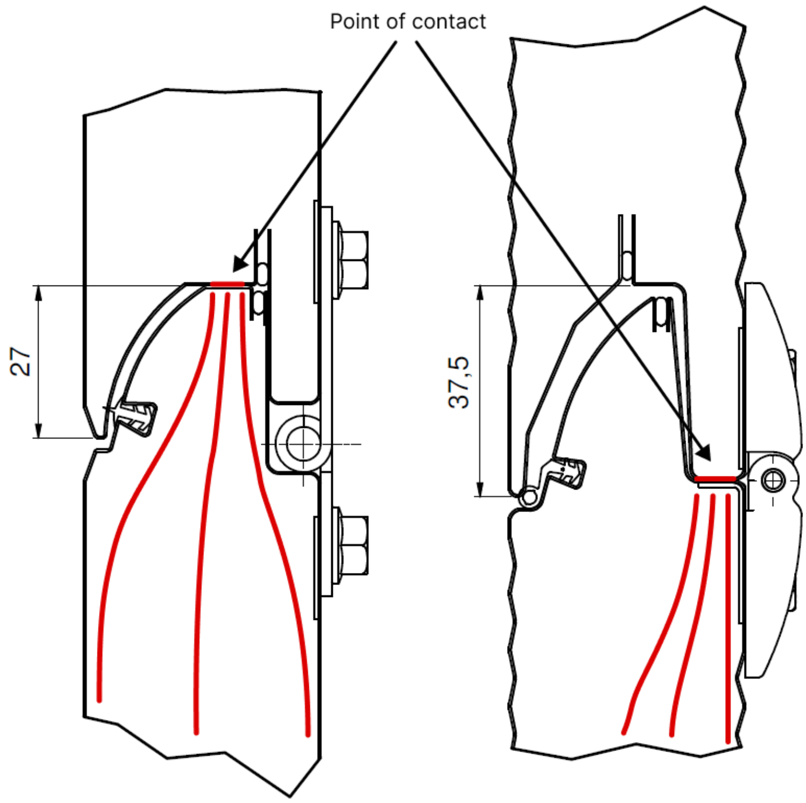



**Figure B.10.1 Force distribution of current panel design (left) and old panel design (right)**

# Appendix C Meeting with an architect from Sweco

A meeting was held with an architect from Sweco who had been involved in several projects regarding distribution centers where OHSD's were to be installed. They gave insights to an architect's thinking in such a project:

- Many factors are considered; size, requirements, preferences, safety certifications, environmental certifications (BREEAM)
- Regarding energy loss, comprehensive lifetime analysis [27] is rarely considered. The U-value is what is important.
- Brand reputation is very important as you rarely search the market for new brands with new products, even though they might be better and/or cheaper.

# Appendix D Meeting with AA salesperson

A meeting was held with a salesperson from AA who has many years of experience inside the company. They gave insights to what is important when selling the OHSD's and what role U-value plays in the process:

- Architects and contractors usually don't consider that the marketing U-value of any OHSD is based on a 5x5 m door without any windows, as this is industry standard. Most OHSD's are in the realm om 3x3 m with at least one row of windows, and this will significantly increase the U-value.
- Air permeability and lifetime analysis [27] is rarely considered or discussed.
- Sales price for a 3x3,6 m 82 mm door with one row of windows is approximately 45% higher than the equivalent 42 mm door.
- Roughly 90% of all OHSD sold are 42 mm doors with one row of windows.
- 82 mm doors are mostly bought for keeping the cold in rather than out (freezer warehouses for food or fresh goods).
- Most customers buy the OHSD's for logistics and distribution centers.
- In Sweden AA has a big market share, much thanks to a strong brand. In the rest of Europe there are a lot of other strong brands with similar products, so the chance of even giving an offer is much smaller.
- In this business, customer relations are a key factor.
- A small improvement in U-value without a significant impact on price would be favorable.

# Appendix E Meeting with AA manufacturing engineers

Meetings were held with two experienced manufacturing engineers at AA. The meetings were held with the aim to get insight into how to manufacture the concepts in the best way possible and what aspects are needed to consider.

- A similar project on another insulated door in AA's catalogue, where they needed to remove a small slit concluded that a "*Shear cutter"* mounted on a jig that holds the panel in place was optimal. This was after trying other methods such as, milling and sawing. The steel needed to be cut is 0,4 mm.
- Their "*shear cutter*" did 5mm wide slit.
- Hard to implement in the manufacturing process due to limited space and its effect on the PUR foam as it would not have completely hardened. Must be processed manually after the panels are cut. (The 82 mm panels are treated in the same manner)
- Started off by doing it completely by hand before they moved onto a semi-automatic solution but still needed someone to observe. An estimated cost of 88 euro to post process the slit for all the panels in 4x4 door, with a panel height of 200mm, mainly labor cost.

# Appendix F Panel joint weight test

The current configuration was tested once followed by three test specimens with the "extended slit". Material and equipment needed and the steps to conduct the test are explained in detail below. The panel joint tested corresponds to the lowest panel joint between the bottom panel and the one above. The load levels are based on the "real life weight" on top of the bottom panel corresponding to 10 panels.

**Material**

- Panel (at least 1200 mm wide)
- Wooden placeholder top and bottom

**Equipment**

- Circular saw.
- Hydraulic press machine.
- Force measuring device.
- Weight scale
- Ruler
- Safety equipment (glasses, gloves, mouth guard)

**Steps**

1. Cut panel to 300 mm width and then in half to get a top and a bottom piece.
2. Put the panels in each wooden support.
3. Place them in the hydraulic press with force measuring device in between, see Figure F.
4. Apply compressive load in sequences and look for deformation.

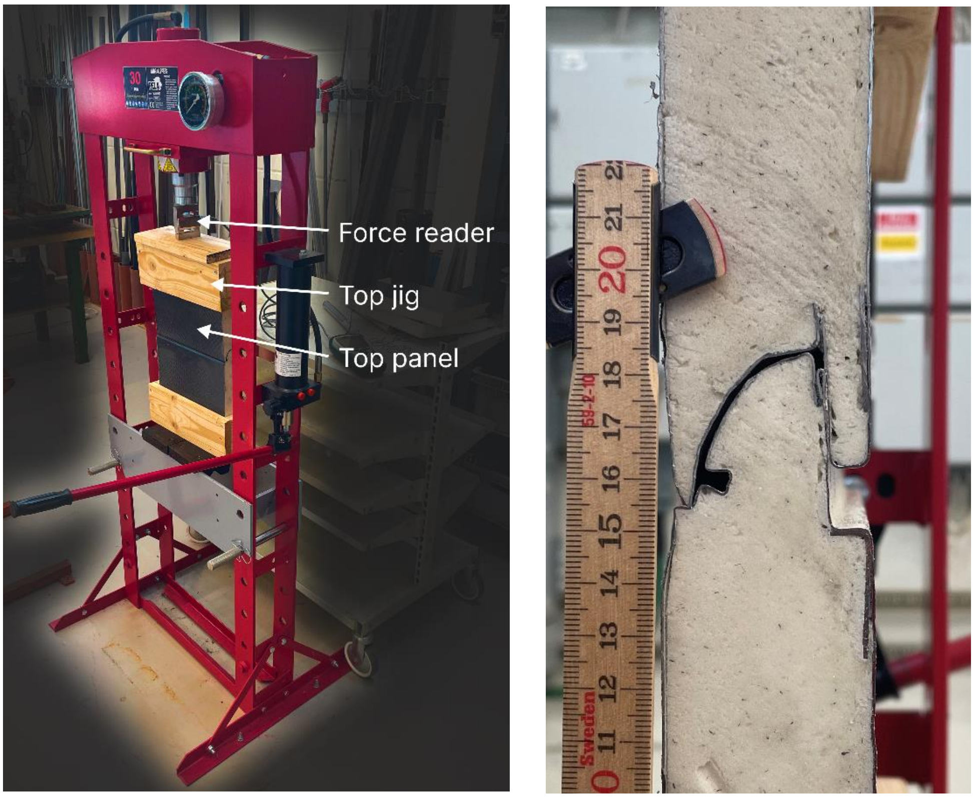



**Figure F.1 Panel joint weight test setup**

# Appendix G Panel wind load test

A recurring section of the 42 mm door was tested for wind load in accordance with SS EN 12424 and SS EN 12444. Four configurations were tested:

5. Current
6. No endcap
7. Extended Slit
8. Extended Slit + no endcap.

All configurations were tested with a load corresponding to a specific wind load class. The deflection was measured before, during and after the load was applied to compare deflection and plastic deformation.

**Material:**

- 8x 4 m panels
- Misc items: wheels, brackets, screws, endcaps
- OSB sheet, 0,7 x 4,0-meter
- Weights up to 400 kg, sets of ~9 kg and ~4 kg
- Styrofoam to facilitate cutting the panels.

**Equipment:**

- Circular Saw
- Safety equipment (glasses, gloves, mouth guard)
- 2x Support
- Measuring pole
- Weight scale

**Steps:**

1. Cut the panel so the total height is 685 mm.
2. Assemble the panels, Bracket roller, screws etc.
3. Place the assembled panel between two supports.
4. Place the measuring pole in the middle.
5. Start test, follow wind load standard EN 12444
6. Repeat for the other configurations

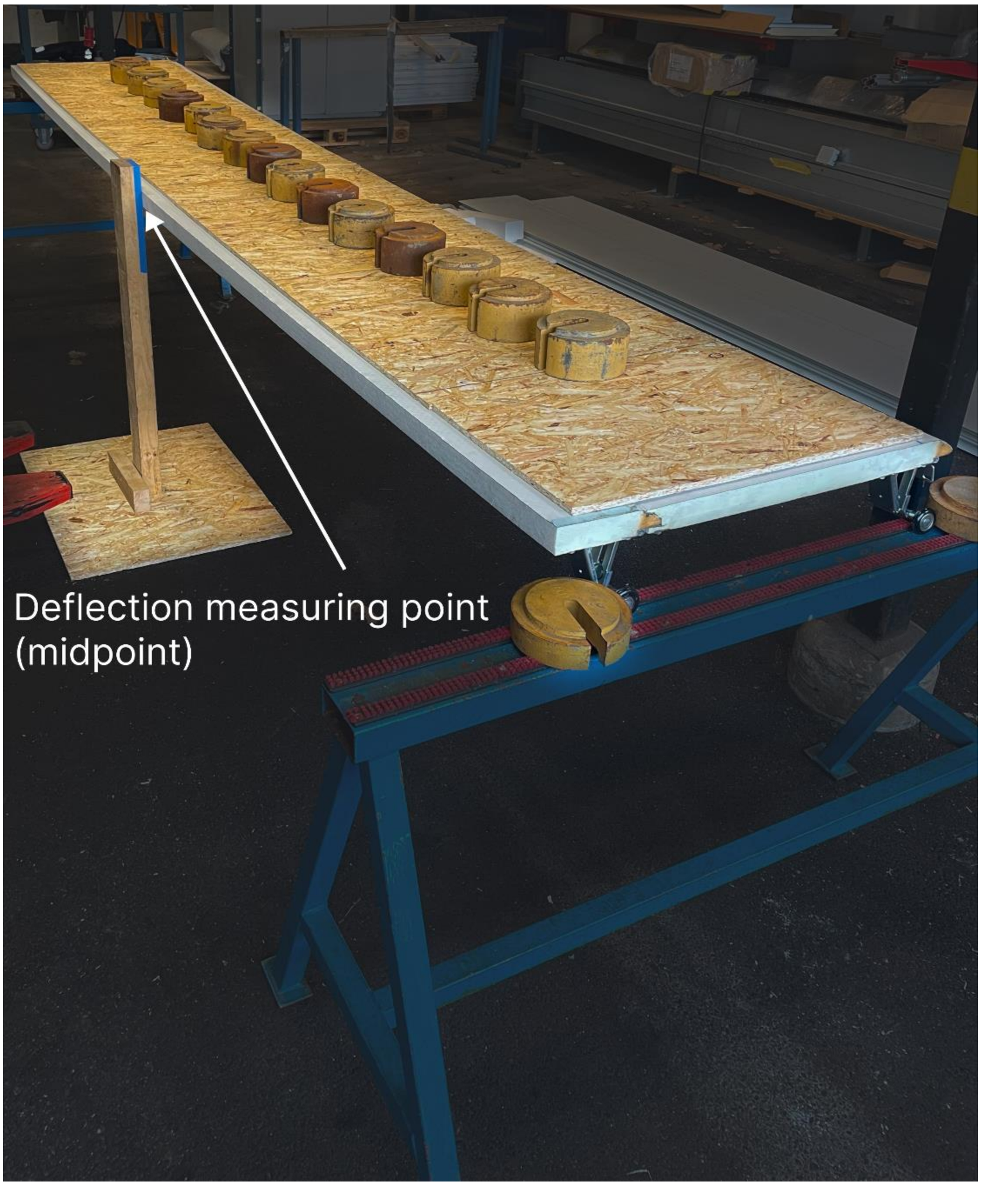



**Figure G.1 Wind load real setup**

# Appendix H Project plan and work distribution

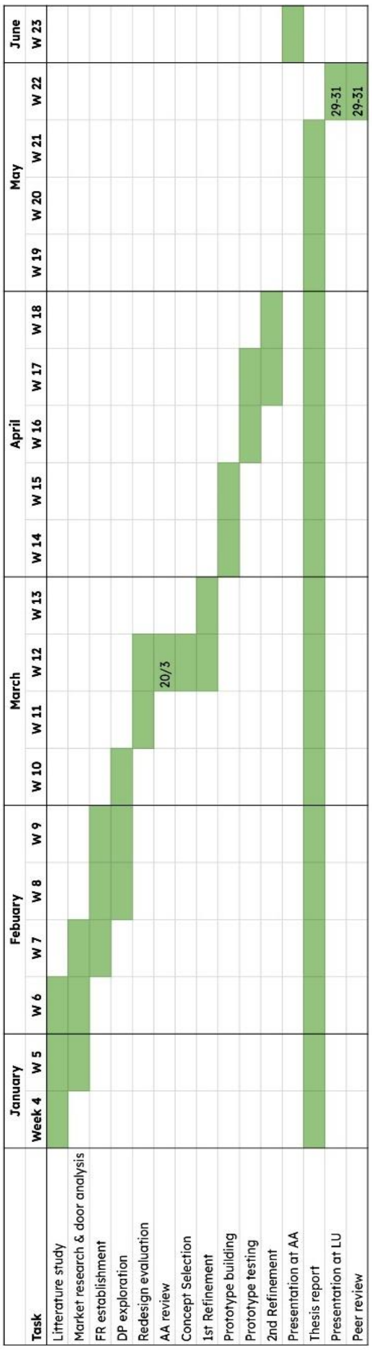


**Table I.1 Division of task between the authors**

| *Task* | *Daniel* | *Oskar* |
|---|---|---|
| AD research | 60 % | 40 % |
| Flixo simulations | 60 % | 40 % |
| Material research | 30 % | 70% |
| Physical testing | 50 % | 50 % |
| Concept generation | 50 % | 50 % |
| Project report writing | 50 % | 50 % |

# Appendix I 42 mm door product datasheet

*This appendix provides a shortened product datasheet of the 42 mm door, which contains all necessary public information that explains the product. For the full datasheet, visit: www.assaabloyentrance.com*

Product datasheet
Overhead sectional door
ASSA ABLOY OH1042P

ASSA ABLOY
Entrance Systems

Experience a safer
and more open world

# Technical facts

## Features

| | |
|---|---|
| Max size: (W x H) | 8000 x 6000 mm (larger sizes available on request) |
| Panel thickness: | 42 mm |
| Panel material: | Diamond grid steel or aluminium |
| Filling: | CFC-free polyurethane, flame retardant DIN 4102-B2 |
| Weight: | Steel: 13 kg/m$^2$<br>Alu: 10 kg/m2 |
| Color outside: | 14 standard RAL colors |
| Color inside: | RAL 9002 |
| Track types: | Standard: SL<br>Optional: HL, LL, VL, SLL, HHL |
| Windows: | Optional: DARP, TARP, DAOP, ALRB, ALBS, Framed section |
| Passdoor: | Optional: In door leaf with low threshold and standard threshold |
| Electrical operation: | Optional: Automated operation, Access control, Safety functions |

## Performance

| | | |
|---|---|---|
| Opening/closing speed: | CDM9: 0,25 m/s<br>CDM9 HD: 0,18 m/s<br>CDM9 2H: opening 0,5 m/s, closing 0,25 m/s | |
| Life time expectations: | Door: 200.000 door cycles or 10 years, when service/replacement program has been performed<br>Springs: 20.000 door cycles | |
| Resistance to wind load, EN 12424 | Insulated panel sections | Class 3 (DLW ≤ 4250)<br>Class 2 (4250 < DLW)<br>(Higher classes on request) |
| | Framed sections | Class 3 (DLW ≤ 3650)<br>Class 2 (3650 < DLW)<br>(Higher classes on request) |
| Thermal transmittance, EN12428 | 1,0 W/(m$^2$K) Steel door, full panel<br>1,1 W/(m$^2$K) Aluminium door, full panel<br>(Door surface 5000 x 5000 mm, no passdoor)<br>Thermal calculations on exact door sizes and configurations are available on request | |
| Resistance to Water penetration, EN12425 | Class 3<br>(no passdoor) | |
| Air permeability, EN12426 | Class 3<br>(no passdoor) | |
| Acoustic insulation, EN ISO 10140-2 | R - 25 dB<br>(no passdoor) | |

# 1. Description

## 1.1 General

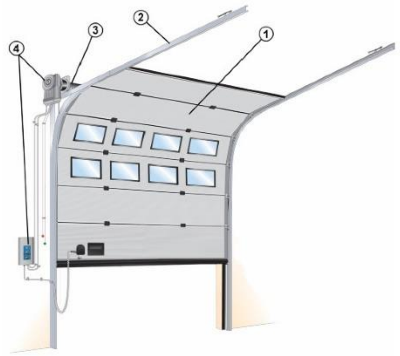
The ASSA ABLOY OH1042P overhead sectional door, with it's modern, clean design, is one of the most stable and well-insulated overhead doors on the market.

It is an overhead sectional door, suitable for all types of buildings, with regard to both function and appearance. High flexibility makes it possible to install this door in almost every type of building.

The door slides up under the roof when opened, allowing free space around the door opening and leaving the door opening completely free.

The door is made of insulated panels. These panels are designed without thermal bridge to provide minimal thermal transmittance, which reduces energy cost.

The ASSA ABLOY OH1042P overhead sectional door has been designed to meet all operational and safety requirements in the European Directives and the standards issued by the European Standardization Committee, CEN.




The door has 4 primary parts:

1) Door leaf
2) Track set
3) Balancing system
4) Operating system

## 1.2 Dimensions

### 1.2.1 Daylight width and daylight height

The standard ASSA ABLOY OH1042P overhead sectional door is delivered in the following size range:

| | Daylight width | Daylight height |
|---|---|---|
| Min.: | 1200 mm | 1936 mm |
| Max.: | 8000 mm | 6000 mm |

Door leaf >550kg, the door will be delivered with 3" track set.

On request available up to 10.000 x 6000 mm.

### 1.2.2 Section sizes

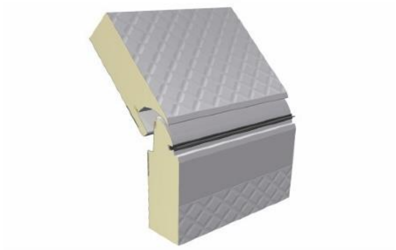
| | |
|---|---|
| Section height: | 545 mm |
| Top section height: | 275 - 820 mm trimcut |
| Thickness: | 42 mm |

The door leaf height is achieved by trimcutting the top section.

## 1.3 Door leaf

### 1.3.1 Construction

The ASSA ABLOY OH1042P overhead sectional door leaf has horizontal sections, connected together with hinges. The outer hinges of each section have rollers that run in the tracks. The horizontal sections are insulated panels designed without thermal bridges for optimal insulation. The panels are filled with water blown CFC-free polyurethane.



### 1.3.4 Colors

The RAL-colors are as close as possible to the official RAL HR collection. Max. deviation is 1,0 ΔE (RAL 7016 excluded).

Pre-coated range:

| |
|---|
| RAL 1021 |
| RAL 3000 |
| RAL 5003 |
| RAL 5010 |
| RAL 6005 |
| RAL 7016 |
| RAL 7021 |
| RAL 7024 |
| RAL 8017 |
| RAL 9002 |
| RAL 9005 |
| RAL 9006 |
| RAL 9007 |
| RAL 9010 |

#### 1.3.4.1 Pre-coated colors

**Steel**
- Outside color: The steel panel is available in the 14 standard RAL colors.
- Inside color: RAL 9002 - Grey white.

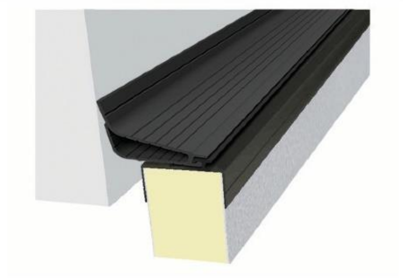
**Aluminium**
- Outside color: The aluminium panel is available in 3 standard colors: RAL 9006 Aluminium, RAL 5010 - Gentian blue, RAL 9010 - Pure white.
- Inside color: Clear polyester.

### 1.3.5 Seals

The door is equipped with well designed seals on all sides that gives the door its excellent sealing abilities.

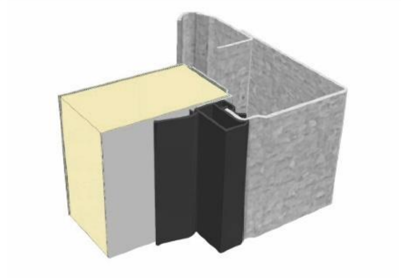
#### 1.3.5.1 Top seal

Installed on the top panel to seal the gap between the panel and the wall. The double lip EPDM rubber top seal is mounted in an ABS adapter profile for optimal insulation and tightness.



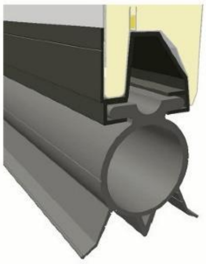
#### 1.3.5.2 Side seal

Installed on the track set to close the gap between the tracks and the door leaf. The double lip side seal design with insulation chambers ensures an optimal insulation and sealing.



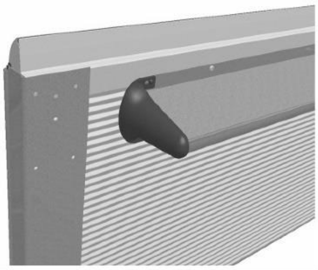
#### 1.3.5.3 Bottom seal

Installed on the bottom edge of the bottom panel, to act as a barrier as well as a shock absorber. The flexible EPDM rubber material and the O-shape provides continuous pressure on the floor, ensuring maximum sealing. The bottom seal is mounted in an ABS adapter for optimal insulation and reduced risk of condensation.



### 1.3.6 Wind reinforcement truss

Wider door panels and panels with windows are reinforced with metal profiles that act as trusses. These trusses reduce bending of the panel caused by wind loads or when the door leaf is in the horizontal position and is bending under its own weight.



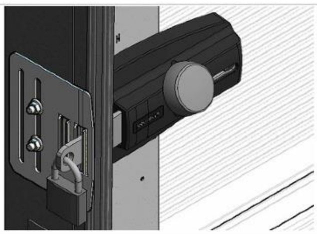
### 1.3.7 Handle

For manual operation, every ASSA ABLOY OH1042P overhead sectional door is provided with a solid, easy to grip and step-on handle, finished with the ASSA ABLOY logo.


### 1.3.8 Lock bolt

A standard ASSA ABLOY OH1042P overhead sectional door is equipped with a lock bolt. The lock bolt locks the door from the inside, without the use of a key. The lock bolt has a hole in the latch, to allow the use of a 12mm padlock.

The lock bolt is not visible from the outside.



# Appendix J Door energy calculation

*Door energy calculation from EDSF.com comparing the final design with current solution.*

Door Energy Calculator
European Door and Shutter Federation e.V.

| RESULTS | CASE 1 | CASE 2 | CASE 3 |
|---|---|---|---|
| Location | Gothemburg | Gothemburg | |
| Building (Vol.) | 40000 m³ | 40000 m³ | |
| Door application | Industrial | Industrial | |
| Door type | Overhead Sectional | Overhead Sectional | |
| Door size (W x H) | 3 x 3 m | 3 x 3 m | |
| Glass area | 10 % | 10 % | |
| Cycle time | 48 s | 48 s | |
| Mean cycle speed | 0.33 m/s | 0.33 m/s | |
| Number of cycles | 1500 | 1500 | |
| U-Value | 1.1 W/m²K | 0.89 W/m²K | |
| Air permeability | 6 m³/m²h | 6 m³/m²h | |
| Solar factor g-value | 0.75 | 0.75 | |
| Energy losses heating season | 4899 kWh | 4680 kWh | |
| Energy losses cooling season | 0 kWh | 0 kWh | |
| Total energy losses | 4899 kWh | 4680 kWh | |
| EDSF Energy Classi cation | T1 C T2 E T3 F | T1 C T2 E T3 F | |


Important

These results of energy losses through the doors are illustrative and they are shown only for comparison purposes. The calculation is based on EDSF research and standards and carried out on buildings with a parallelepiped shape without interior divisions. The overall losses in buildings in real environments are influenced by a lot of factors that must be taken into consideration for an accurate calculation. For more information, please go to www.edsfdoorenergy.com.