Bachelor thesis

Total cost of production and evaluation of production scenarios for INDU-ZERO

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Smart Renovation Factory
by INDU-ZERO

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North Sea Region
INDU-ZERO
European Regional Development Fund
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Title Page

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Pre-face

You have in front of you the bachelor thesis for the research ‘**Total cost of production and evaluation of production scenarios for INDU-ZERO**’. This research has been carried out for the completion of the study ‘Industrial Engineering and Management’ at the Saxion University of Applied Science in Enschede, the Netherlands. The assignment was published by Gerard Salemink and the INDU-ZERO project commissioned by the European Union and was carried out in the period from February 2021 to July 2021.

The target group for this graduation paper are all people associated with the INDU-ZERO project, people who are responsible for assessing the paper as well as people who are interested in production processes and the future of the housing market.

First of all, I would like to thank Gerard Salemink and the INDU-ZERO project group for offering this assignment and the possibility to work within such an ambitious European project. Furthermore, I would like to thank my graduation supervisor Jacques Bazen for the pleasant guidance and support during my graduation period.

I would also like to thank Mrs. Astrid Hoogveld as the examinator for assessing my deliverables for this graduation thesis. Finally, I would like to thank all respondents of the research taking the time and providing information.

A personal reflection on the semester is added to the appendix I. In this reflection, the challenges faced during the research and lessons learned are mentioned. It helps to understand why certain decisions throughout the semester were made.

Now I wish you a pleasant reading.

Samuel Efkemann

Gronau (Germany),

Monday, 14th June 2021

Reader’s guide

This thesis is composed of nine themed chapters. Each chapter starts with a list of the most important terms used in each chapter. Due to the technological nature of the production process, there are some technical terms used in this research. Defining them at the beginning of each chapter makes it more understandable for people not involved with the project.

The paper begins with an introduction of the project INDU-ZERO, the project rationale, their products and clients and project structure.

Chapter two is concerned with the define-phase of the DMADV-model. In here, the first three sub-questions are answered. The production process is visualized in a flow-chart in sub-chapter 2.1. The scope of the calculations is described in sub-chapter 2.2 and a stakeholder analysis is given in chapter 2.3. At the end of chapter two, a conclusion is added.

The third chapter is concerned with the measure-phase and the associated production cost calculations. In sub-chapter 3.1, the archetype dwellings that form the base of the calculations are stated. Sub-chapter 3.2 is concerned with the calculation of the production costs. The results of the chapter are concluded in sub-chapter 3.3.

Chapter four includes all findings regarding the analyze-phase. Sub-chapter 4.1 starts with an overview of the biggest cost elements and potential cost savings of the production process based on findings in chapter 3. It then continues with a multi-criteria analysis which is stated in sub-chapter 4.2. The conclusion of the chapter is presented in sub-chapter 4.3.

The results of the analyze phase are then translated into a design in chapter five. In sub-chapter 5.1, an evaluation of the optimal scenario is stated. The optimal choice is described in sub-chapter 5.2. The conclusion of the chapter is stated in chapter 5.3.

The sixth chapter answers all questions regarding the verify-phase of the DMADV-model. In sub-chapter 6.1, a step-by-step plan for verifying the results as well as insights for the completion of the project are given.

In chapter seven, all conclusions made earlier per chapter are summarized into one chapter. In here, the central question is being answered.

Chapter eight is concerned with recommendations made based on the conclusions in chapter seven.

In chapter nine, an implementation plan including the background of the research, conditions and an approach for the implementation activities is added.

In the end, the bibliography with all sources used for the study is mentioned and finally, the appendix with all background information is added to this plan of approach.

Abstract

Background research

The INDU-ZERO project is focusing on the development of a blueprint for a smart factory that produces retrofitting packages. One essential part of this is the development of the production process. The goal of this research is to calculate production costs and evaluate different production scenarios. The outcome of this research is a detailed production cost calculation as well as recommendations on which production scenario to choose.

Objective and central question

This aim of this bachelor thesis is double edged: First, the future production costs of the INDU-ZERO production process need to be calculated. Second, four different production scenarios need to be theoretically compared and empirically checked. The central question of the research is 'In what way can the cost structure of the production process be designed in order to realize a 50% cost reduction of the production costs as compared to the current average price in the market, without compromising on quality and production speed, while avoiding high risk situations?'. The objective of the research is to conduct a design-oriented study to calculate the designated production costs of the future product by developing a tool that fits with the INDU-ZERO project. These findings should provide valid production costs calculations which show that a cost reduction of 50% is feasible.

To answer the central question, a process model was chosen to structure the research. The main process model used is the DMADV-model which describes the five research phases **D**efine, **M**easure, **A**nalyze, **D**esign, **V**erify. It is commonly used when new processes are developed and innovation is taking place. Each phase was the base for one chapter. To find the right information, different research methods were used during the research: literature research, semi-structured interviews and personal communication.

Approach

At the start of the research, the scope of the research had to be determined. Within the project INDU-ZERO, there are five different work packages. This research is located in the third work package: co-creative development of a smart factory. Within the work-package, the research is focusing on the production process.

In chapter one an introduction to the project is given. This includes a project description, the products, the problem analysis (including central- and sub-questions), the theoretical framework and research design. The research design describes the scope of the research as well as a justification of research activities.

In the first phase of the DMADV-model, the production process is described. This includes every production step from the delivery of materials to the final quality check. This is followed by a list of cost-elements which are going to be relevant in the calculation of the production cost. This covers labor cost, material cost, energy cost, waste cost and machinery cost. In the following, the four production scenarios 'thermobonding', 'gluing', 'HD-EPS only' and 'current panel' are described. The gluing scenario forms the base for the next sub-chapter. The stakeholder analysis, including all relevant parties concerned with the INDU-ZERO project, is presented afterwards.

In this chapter, the results of production cost calculations are stated. At first, the archetype dwellings with standard measurements are added. These form the base for further calculations. For each cost-element, the costs are calculated which leads to a detailed cost-structure. The results of the calculations show that material costs are the biggest cost element. The second highest expense are the cost for machinery acquisition and system integration. These are followed by labor costs, energy costs and waste costs.

In the third part of the research, the base for an evaluation of all four production scenarios is done. This is done with the help of a multi-criteria analysis (MCA). The MCA is filled in based on interviews done with four main stakeholders. The criteria to compare the scenarios and the attached weight-factors per criterion were determined in the interviews. The average weight-factors have led to the following order of criteria: easy to assemble, product costs, production costs, quality, quantity, environmental impact, tact time, lifetime product, robustness, flexible building factory, fire safety and maintenance. After letting all respondents fill in the MCA based in a list of classification, total MCA-scores per scenario could be calculated. This has led to the following order of scenarios: 1. HD-EPS only; 2. gluing; 3. thermobonding; current panel.

After analyzing the results from the interviews and calculating the total MCA-score per scenario, the four production scenarios are evaluated in the design-phase. At first, each criterion is evaluated individually based on the results from the MCA. This leads to an optimal choice of scenarios. The optimal choice then is divided into short and medium-/long-term choices. For the short-term, gluing is the optimal choice. On the medium-/long term, thermobonding portrays the best option. HD-EPS-only is not the optimal choice mainly because the technology is not tested and ready for practice yet. The current panel is no option because it does not fit with the concept of a smart factory.

The last phase of the DMADV-model is concerned with verifying all results from the research. In here, a step-by-step plan is given how the results from the research can be verified and completed in the future. The steps are: 1. Prove product and process suitability; 2. Set up monitoring, carry out tests and piloting; 3. Create process documentation; 4. Submit and complete project.

All the information gathered in each chapter are summed up in the conclusions. The conclusion answers the central question. In order to achieve a 50% cost reduction compared to the current market price of a retrofitting package, other costs need to be calculated first. The main cost savings are not achieved by savings in material costs as the prices for raw materials are increasing currently. The focus needs to be on the labor cost savings due to the automation of the process. The second part of the central question is answered by evaluating the four production scenarios. The result is that scenario 2 'gluing' is the option to choose in the short-term. Scenario 1 'thermobonding' and 3 'HD-EPS only' are options for the medium-/ long term.

Based on the conclusions, the recommendations are given. In total there are six recommendations given: 1. choose scenario 'gluing' as main production method, 2. keep design practices' Design for Manufacturing' and 'Design for Assembly' in mind, 3. calculate precise production costs of the roof; 4. calculate labor cost of other departments than production, 5. focus more on the costs caused by machinery, 6. Do a follow-up study regarding circularity of the factory and products.

At the very end of this thesis, an implementation plan is added. This plan is a guide for the members of the INDU-ZERO project and aims to help putting the results of the research into practice and show what further research needs to be done. In here, the conditions for implementation, the approach and a management plan including an activity planning are mentioned. The conditions required are the availability of expertise, employees, resources and testing locations. The approach includes the 'four-ball model' which answers four main questions: 1. Why do things need to change?; 2. What do the current and future situations look like?, 3. How do you structure the process of change in order to reality the desired situation?; 4. Who is involved in the process of change and what are their respective roles?. After the four questions are answered, a potential follow-up study is presented. The management plan presented at the end includes a detailed activity planning and short information regarding the aftercare of the implementation.

The main chapters are followed by the appendix where a reflection on the semester and additional background information for the research is given.

1. Introduction

Definition of terms

Smart factory	“The smart factory is at the center of Industry 4.0 and describes a production environment that organizes itself. The production facilities and the logistics systems are part of the production environment. Humans no longer have to intervene in the actual production process” *(Torsten Klanitz, 2021)*.
Energetic retrofitting	In the context of housing renovation, energetic retrofitting refers to the modernization of a building to minimize energy consumption for heating, hot water and ventilation *(Ausbau + Fassade, 2021)*.
Business case	“A business case is a scenario for assessing an investment under strategic, economic and other aspects. From the client’s point of view, a project is also an investment. The business case of a project describes how and in what period of time the results benefit the company” *(Angermeier, 2018)*.

This research was carried out for the INDU-ZERO project group. Sub-chapter 1.1 gives insights in the goals and structure of the INDU-ZERO project. In the following, the project rationale (1.1.1), products (1.1.2) and projects structure (1.1.3) are further explained. In sub-chapter 1.2, a problem analysis is done. This includes the cause of the research (1.2.1), a description of the problem situation (1.2.2), the objective (1.2.3) and central question (1.2.4) of the research and finally, the research’s sub-questions are stated (1.2.5). In addition to that, the theoretical framework is explained in sub-chapter 1.3 including the literature research (1.3.1) as well as the theory and models used for carrying out the research (1.3.2). Lastly, the research design is stated in sub-chapter 1.4. In here, a justification of research activities (1.4.1), evaluation of reliability and validity (1.4.2) and evaluation of sources used for the research (1.4.3) were done.

1.1 INDU-ZERO

The so called INDU-ZERO project was co-founded by the Interreg North Sea Region (NSR) Programme 2014-2020. Interreg, or as it is officially called ‘European Territorial Cooperation’ is part of the structural and investment policy of the European Union. It supports cross-border cooperation between regions and cities regarding traffic, labor market and environmental protection *(Bundesinstitut für Bau,- Stadt- und Raumforschung (BBSR), 2012)*.

The NSR covers Denmark, Norway and the coastal regions of Germany, the Netherlands, Belgium, Sweden and Great Britain. The main characteristics of the region are its highly developed economic power, infrastructure, qualified workforce and the efficient management of environmental risks *(Interreg North Sea Region, 2020)*. In total, the NSR contains around 22 million houses built between 1950-1985. These alone cause 79 million tons of CO2-emission annually *(European Regional Development Fund, 2018)*.

The INDU-ZERO project in particular started in 2018 and will run until October 2021. It focusses on the development of a business case including a blueprint for an innovative ‘smart factory’. This factory should be able to produce 15.000 retrofitting packages for half of the current average price. The knowledge of 14 organizations from six countries is bundled to design the blueprint able to produce ‘net zero energy’ retrofitting packages for existing houses. This approach can be applied to houses and apartments build between 1950 and 1985. The total budget for the project is around 4.4 million euros.

Another important aspect to mention is the general structure within the project. It is divided into five different work packages (WP): 1. Project Management, 2. Communication, 3. Co-creative development of a smart factory, 4. Testing and piloting components of the manufacturing innovation, 5. Showcasing and encouraging adoption. The Saxion University of Applied Sciences is working within the third WP: Co-creating development of a smart factory. The aim of WP3 is to design a blueprint (including a business case) for a smart factory suitable for manufacturing retrofitting packages for renovation towards energy-neutrality

(Krämer, 2018). This is the environment this research focused on as well. A more detailed description of all WP is added to the appendix II.

The business case includes a business plan with the following information:

Break-even calculation	Production costs, engineering and scanning costs, capital costs, operating costs, logistics equipment, costs for mounting, costs for logistics to construction site and a total cost of ownership
Business model canvas and value propositions	Demand and market potential, letter of intent, product/market combinations, competitor analysis, number of jobs and an analysis of the CO2-footprint
Target groups INDU-ZERO factory	1. Product's buyer, 2. Investors, 3. Main supplier's, 4. Financier, 5. Government

Information about clients and competitors of the INDU-ZERO project is added to the appendix III.

1.1.1 Project rationale

As the INDU-ZERO is not a typical organization but a multinational project, the 'mission and vision' differ from what it would look like for a company. It is called the 'project rationale' and explains why the project must go ahead. In this case, the project rationale of INDU-ZERO is described as follows:

The project rationale of INDU-ZERO is to design a factory blueprint, based on the concept of the 'smart factory' (commonly known as Industry 4.0) with the capacity to manufacture retrofitting packages suitable for all NSR countries at a high volume of 15.000 packages per year at 50% lower cost *(Interreg North Sea Region, 2020)*. The vision is the achievement of sustainable and energy self-sufficient houses in NSR countries that will meet the targets of the Paris Agreement *(Interreg North Sea Region, 2020)*. Currently, the methods to energetically renovate the existing housing stock are too slow and too expensive. Without innovations, the 2050 goals will not be met.

1.1.2 Products

The INDU-Zero smart factory will focus on the production of three main products:

1. **Façade elements**, 2. **Long façade elements** (up to 12m), 3. **Roof elements**

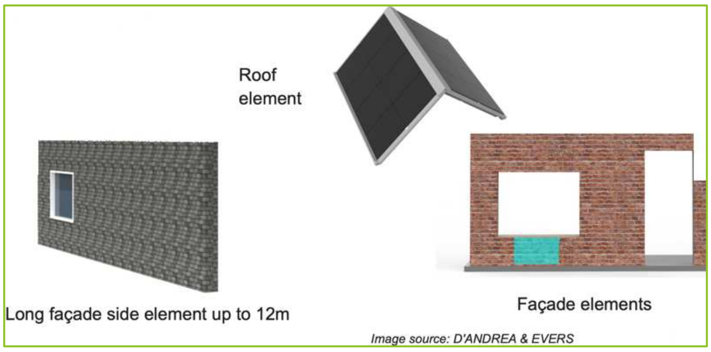


Image source: D'ANDREA & EVERS

Figure 1.1 - Products

These three products will not be produced following the concept of a standard, non-individualized mass-production. The future factory will be able to produce elements based on a mass-customization method. This means, that the individual wants and needs of house owners can be fulfilled and customization of elements is possible. A visual representation of the product-archetypes can be seen in figure 1.1.

All products will be manufactured in one factory. The idea is to have two production lines responsible for the production of façade elements and one additionally for the roof elements.

This has been visualized and the outcome is added to the appendix IV.

1.1.3 Project Structure

INDU-ZERO is a ‘triple-helix-style’ consortium of entities which represent the industry, the government and knowledge institutions *(Etzkowitz & Leydesdorff, 1995)*. This is a transnational collaboration which provides the necessary knowledge and expertise to deliver a blueprint for a smart factory. All of the participating organizations were divided throughout the five different work packages, based on their skills and responsibilities. For the most part, the individual partners focus on their main responsibilities within one work package but due to the size of the project, a lot of collaboration happens. This leads to ‘blurring borders’ between the work packages. The project structure of all participating organizations is stated below. There is no weighting in the order of the organizations. For contact information about the specific project partners, please have a look at the appendix V.

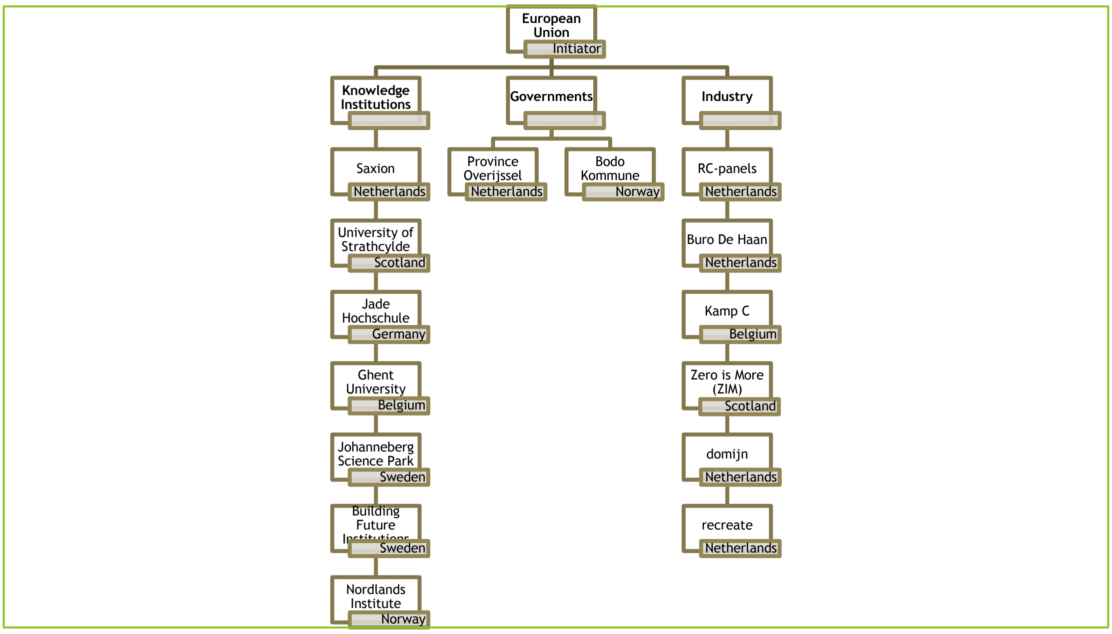


Figure 1.2 - Project Structure INDU-ZERO

1.2 Problem analysis

1.2.1 Cause of research

External developments

An external development causing this research is the development of the housing market. It has changed and will continue to do so in the future since the Paris climate agreement in 2015. All houses within the EU need to be CO2-neutral by 2050. Since massive demolishing of old houses and building energy efficient houses new is not a feasible solution a solution needs to be found for the already existing ones. This is due to both the available construction capacity as well as the importance of circular economy design principles. One part of a solution is the smart factory that is going to be the result of the INDU-ZERO project.

In the Netherlands alone, more than three million houses have to be renovated before 2050. That equals around 1000 houses per week. That is much more than the speed at which retrofitting is currently going (~ 100 weekly). Due to the traditional nature of the retrofitting process, it’s not possible to make the current process faster without innovations of the market.

Internal developments

The fundament for this research is the goal formulated for the INDU-ZERO project: reducing production costs of mass customizable façade- and roof elements by 50%. To be able to realize such an ambitious goal, a lot of calculations need to be done and an automized new production process needs to be set up. Another internal development causing this research is the lack of clarity regarding the underlying components of the cost structure of the production process. Considering the mass-customization approach, it is crucial to choose an archetype dwelling for further calculations. Otherwise, it is not possible to make reliable calculations that help investors get an impression of what to expect from the smart factory. Choosing an archetype as well as detailed calculations regarding the production process and cost-price have not been done yet. Furthermore, there are different production scenarios known within the project group. They have not been compared to one another nor has an in-depth research taken place.

1.2.2 Problem Situation

The problem is that energetic renovation costs too much nowadays. INDU-ZERO's overall goal is to bring innovation to the market by developing a blueprint and business case for an automated smart factory that is able to produce retrofitting packages for half of the current price. Therefore, the product cost needs to be cut by 50%. The reason behind this research can be divided into two parts: 1. proof that such an ambitious cost-reduction is feasible; 2. compare four scenarios for the production process in order to choose the right process design.

To bring more clarity to the problem, a detailed written draft of the problem analysis based on the 6W-formula is added to the appendix VI.

The expected current average price of a retrofitting package is estimated to be around 80.000-120.000€. It is not only that these figures are not very precise, but there is no reliable break-down of these numbers available. Given the very fragmented nature of the building supply chain, with a lot of contractors and sub-contractors and little cooperation within the supply chain, it is very difficult to find out the different components (materials, logistics, labor etc.) that the final price is made up of. Amongst other things, the research focusses on the achievability to produce for half of the current average price in the market.

The last important thing to mention in regard to the problem situation is the different production scenarios that need to be compared. At the moment, there are four main scenarios for the production process. The starting point for all scenarios is this main material used to produce the elements: EPS, commonly known as Styrofoam. The four production scenarios are: 1. Thermobonding EPS, 2. Gluing EPS only, 3. High Density EPS only, 4. Current panel.

At the time this research was done, the machine developers mainly had knowledge regarding the gluing scenario. They started developing machines for this scenario. The INDU-ZERO project group still has no detailed production cost price calculation for this scenario. That is the reason why the production cost of scenario 'gluing EPS' also have to be calculated. Other partners of the project have mentioned a need to also look at other production scenarios. This is what the second part of the research is about.

A multi-criteria analysis (MCA) is done to compare the four possible production scenarios. The criteria for the MCA were determined through interviews with experts. Based on the results, recommendations regarding the design and costs of the production process can be made.

The objective as well as the central- and sub-questions were formulated based on the problem analysis.

1.2.3 Objective

In this sub-chapter, the objective of the research is stated. It is formulated based on the SMART-method which is the acronym for **S**pecific, **M**easurable, **A**chievable, **R**easonable and **T**ime-bound. The exact definition of the model is added to the appendix VII.

SMART-Objective

Conducting a design-oriented study commissioned by Gerard Salemink and the INDU-ZERO initiative to calculate the designated production costs of the future product by developing a tool that fits with the INDU-ZERO project. These findings should provide valid production costs calculations which show that a cost reduction of 50% is feasible. At the moment there are different scenarios for the production process and those need to be evaluated and compared to one another. The research started on February 8, 2021 and the final product must be submitted to the INDU-ZERO project group and Saxion University of Applied Sciences before June 1, 2021.

1.2.4 Central question

This chapter contains the central question of the research. This is a crucial part since it shows in which direction this research is oriented. Thus, the base for the research. To answer the central question, further sub-questions are required. These are stated in sub-chapter 1.2.5 and will give insight in the process of gathering and analyzing information for the research.

The central question for this research is the following:

“In what way can the cost structure of the production process be designed in order to realize a 50% cost reduction of the production costs as compared to the current average price in the market, without compromising on quality and production speed, while avoiding high risk situations?”

1.2.5 Sub-questions

The below mentioned sub-questions are derived from the central question. All answers to the sub-questions will ultimately answer the central question. The sub-questions are structured according to the DMADV-model which is explained in chapter 2 regarding the theoretical framework.

1 **Define**
    1.1 What do the scenarios of the INDU-ZERO production process look like?
    1.2 What are the most important aspects in the calculation of the production costs?
    1.3 Who are the stakeholders?

2 **Measure**
    2.1 What does the production cost structure of the INDU-ZERO production process look like?

3 **Analyze**
    3.1 What are the biggest cost elements in the calculation of the production costs?
    3.2 Which factors other than production costs should be taken into consideration when choosing the optimal scenario?
    3.3 How should the different factors of the MCA be weighed in order to be able to select the optimal scenario?
4 **Design**
    4.1 What is the most suitable production scenario?
5 **Verify**
    5.1 In reality, is it feasible to produce for half of the current average production costs?
    5.2 Has the right scenario been chosen for the design of the production process?

1.3 Theoretical framework

In this sub-chapter, the theoretical background of the research including the literature research, theory and models used for the research and a demarcation of the projects scope is presented.

1.3.1 Literature research

Relevant previous studies within the INDU-ZERO project

To understand the importance of the research in the project and what already has been worked on, it was important to read through the work other students have delivered before joining the project. One main research that was comparable to this one contains four main topics: total cost of ownership (TCOO), competitor analysis, product-market combinations and an analysis of the Dutch and West-German demand. The analysis of the Dutch housing market was used for this thesis especially. It was written by four students from the Saxion University and will be published on INDU-ZERO's website by the end of June, 2021. This underlines the reliability of the source further.

Research methods

According to the theory of Jan Leen and Jef Mertens, the research is a mixture of quantitative and qualitative data collection methods *(Leen & Mertens, 2017)*. A lot of figures and numbers need to be gathered and the end result of the data-collecting for the production costs is therefore going to be numeric. The MCA is mainly qualitative since different non-numeric criteria are the base for the analysis. The end results are recommendations regarding the optimal scenario choice, which mostly build on the qualitative characteristics of this research. The quantitative characteristic appeared in the calculation of production costs as one of the aspects of the MCA.

The main methods used to receive the right information about future costs and the criteria for choosing the optimal scenario are the following:

1. Literature research

The literature research was necessary to get the right information about potential calculation tools and definitions of important terms. This includes detailed information about production costs calculation, different production technologies as well as definitions of terms used for the research.

2. Semi-structured interviews

Interviews were essential for the outcome of this research. As there are a lot of partners from different countries who are participating in the project, a lot of different people can provide information regarding the production process. Especially for determining criteria, weights and ratings per scenario for the MCA, interviews with stakeholders were inevitable. In case of the costs regarding the production process and machines, the partners working for the University of Strathclyde in Scotland, a product developer at Bureau de Haan from the Netherlands, production partners from the industry and research assistants from the Saxion University in the Netherlands provided valuable information. Other questions regarding the bill of material and archetype houses were answered by the responsible at the Jade Hochschule in Germany. The interviews were 'half-structured'. The most essential questions for further progress have been prepared before the interview began and throughout the interview, questions were added or left out.

Apart from interviews, regular meetings with the project partners were essential to this project as well. Due to the project's size, meetings on a regular basis are inevitable. In these meetings, important information about the progress and problems are shared. Relevant figures and information are presented frequently in these meetings.

3. Analysis of existing material/documents

There is a SharePoint available published by the Province Overijssel where access is granted to people who are directly involved in the project. In here, all documents from the past three years are uploaded. These documents form the base of other researches (including this one) as a lot of relevant information is already collected while other parts are still missing. The SharePoint is not available to people outside the project. Most of the information in there was gathered from other sources as well. Wherever possible, the original source was named.

A better overview of how the research methods were used in order to get the right information per sub-question is stated in a table about data collection in appendix VIII.

1.3.2 Theory & models

In this sub-chapter, the important models used for the research are presented. The base process-model is DMADV which is explained below. The different models used in this research are described below.

DMADV

The DMADV-model is an improvement model used to develop new processes or products. It consists of five phases: **D**efine, **M**easure, **A**nalyze, **D**esign, **V**erify. Each of the five phases builds on the previous one. In the define-phase, the customer wants and needs must be identified in order to have a thorough impression of the overall problem situation. The measure-phase aims to collect data and information about the problem situation identified in the define-phase. The results gathered in the measure-phase are, amongst other things, being analyzed with the help of different models in the analyze-phase. In the design-phase, the development of an implementation plan is an essential activity to bring the results from the analyze-phase into practically applicable activities. The last phase is called the verify-phase since the outcome of all earlier phases before must be approved. It shows whether or not the recommendations and implementations made earlier are feasible or not *(Rana Majumdar, 2014)*.

Mendelow's matrix

The Mendelow matrix analyses stakeholder groups based on the power and interest they have on a project. The power is defined as the ability to influence the organization strategy or projects. The interest a stakeholder has shows how interested they are in the organization or project succeeding *(Eriksen-Coats, 2021)*.

Relatively speaking, some stakeholders have more power than others and some more interest, even if it does not seem like it in the first place. A director for example is more likely to have high interest and high power in the succeeding of his/her organization, whereas the government only has high power but less interest *(Eriksen-Coats, 2021)*.

Multi criteria analysis (MCA)

The multi-criteria analysis (MCA) or multi-criteria decision analysis (MCDA) can be applied in both the private and public sector and is an approach/technique that helps in the process of decision making. It provides a classification of options from most to least preferred and also gives different weights to the options to choose from. By applying the MCA, a complex problem can be broken into manageable pieces and different aspects *(Department for Communities and Local Government, 2009)*.

1.4 Research design

In this sub-chapter, a demarcation of the research is presented. To underline this, a justification of research activities as well as the reliability and validity of the research are discussed. In the end, an evaluation of the sources used for the research is given.

1.4.1 Demarcation

The research had to be demarcated, otherwise it would not have been possible to do it in the period of five months.

The research DID focus on:

1. The research focused on the production process of INDU-ZERO. This includes everything from the delivery of the EPS plates to the production line to the last production step (quality check).
2. The first half of the research focused on the calculation of future production costs for the INDU-ZERO production process. The second half focused on the evaluation of four different production scenarios.
3. The research was done within the third work package (WP3) as stated in chapter 1.1.
4. The primary language used throughout the project was English. All deliverables were written in English as well.

The research DID NOT focus on:

5. The research did not focus on any other departments other than the production. Other departments are scanning (3D scanning of buildings to build a digital twin), engineering, inbound logistics, marketing, sales, warehousing, outbound logistics, on-site mounting.

1.4.2 Table of data collection

The complete table of data collection including the way of collecting and analyzing data and the results is added to the appendix VIII.

1.4.3 Justification of research activities

As the whole INDU-ZERO project, including this research, is aiming for the development of a smart factory blueprint, the research is design-oriented *(Leen & Mertens, 2017)*. The processes for the smart factory need to be developed and therefore, precise production cost calculations and evaluations of production scenarios of the future production process need to be done.

The main process-model used for the research is DMADV. It is a common tool used for the development of new processes. The main difference of this model when compared to the DMAIC (Define, Measure, Analyze, Improve, Control) model, are the Design- and Verify-phase. While DMAIC focuses on the improvement of already existing processes, DMADV is used for creating new ones. That’s why this model is used to structure the whole research and sub-questions.

1.4.4 Reliability and validity

Reliability refers to the consistency of a measure which means whether or not the research can be repeated under the same conditions or not. Validity describes the accuracy of a measure which means whether or not the outcomes of a research really do represent what they are supposed to measure *(Saxion University, 2018)*.

The reliability of the research, it is judged as high. The project is in the end-phase and needs to be finished by October 7th. Apart from this, it would be theoretically possible to repeat the research under the same conditions, as the current average prices will not change drastically and the desired situation is clear as well. The main point of criticism regarding the reliability of the research is that due to the conceptual nature of the whole project, relatively many estimations need to be made. This can lead to inaccuracies in the research results.

The validity of the research is high as the goal was to develop a tool for the INDU-ZERO project which can be used to calculate the production costs. A calculation-tool needs to be precise and calculate exactly what INDU-ZERO needs to calculate their production costs, otherwise it is not practically applicable. The base for the calculation tool were realistic numbers gathered from the different project partners and external parties (e.g., companies or projects in the same market). The estimated numbers can easily be replaced in the future when reliable facts are available. Based on these numbers and some added assumptions that were filled in, a valid production costs calculation was possible. It will ultimately serve as adjustment for the business case to convince the possible investors to invest in making the smart factory a reality.

1.4.5 Evaluation sources

All sources used in this plan of approach are gathered from (scientifically) relevant sources. The main search engines used are Google Scholar and internal information sources (SharePoint) from the INDU-ZERO project as well as the Saxion online library. The main criteria taken into account for this were based off the criteria from *(Niezink, 2017)*. For each source used in this thesis, the criteria mentioned below apply. Below the criteria are presented.

APA-norm fulfilled?	Yes
Is the source relevant?	Yes
Is the overall quality adequate?	Yes
Is there a reasonable purpose for the source to exist?	Yes
Are the author or publisher knowledgeable and reliable?	Yes
Is the source up to date?	Yes
Is the source objective?	Yes
Is the source precise and accurate?	Yes

2. Define-phase

Definition of terms

EPS	Short for ‘Expanded Polystyrene’. It describes a foam generally known under the brand name ‘Styrofoam’. EPS is based on hydrocarbon styrene which can be processed into plastic. Since the middle of the last century, polystyrene has been expanded into EPS and is used in a variety of ways *(Flamme, 2020)*. EPS is commonly known as Styrofoam.
HD-EPS	Short for ‘High Density Expanded Polystyrene’. Compared to the Standard EPS, HD-EPS has a higher material density and better insulation values.
CNC	Short for ‘Computerized Numerical Control’. The CNC-Programme transfers control commands to a machine. By doing this, a CNC machine can produce various workpieces form different materials at lower cost without needing an employee taking care of the machine. The machine basically takes care of its own regarding the speed, tools etc. *(Cengiz Ay, 2020)*.
Thermobonding	Thermobonding is a technology where two or more plate surfaces are connected or glued without an additional binding material *(Bürkle, 2013)*. The surfaces of two EPS-panels are thermally heated and joined together. The result is a thicker panel with a better insulation value than directly foamed foams of the same thickness. It also results in a greater manufacturing flexibility and shorter retrieval times *(Bachl, 2021)*.
PU Glue	Short for ‘Polyurea glue’. PU glue is an industrial coating and primarily defined by its protective characteristics. The technology of ‘polyurea’ means a specific technology that includes the raw material polyurea, any additions of color or textures as well as the complete technology with pumps, heating system and spraying devices *(Polyureatec, 2008)*.

The second chapter answers following sub-questions:

1.1 What do the scenarios of the INDU-ZERO production process look like?
1.2 What are the most important aspects in the calculation of the production costs?
1.3 Who are the stakeholders?

This chapter covers the first phase of the DMADV-model: Define. Sub-chapter 2.1 starts with a visualization of the future production process. In the following, the different production scenarios are stated in sub-chapter 2.2. Moreover, the scope of the calculation of the production costs is shown in sub-chapter 2.3. Additionally, a stakeholder analysis is presented in sub-chapter 2.4 and finally, a conclusion of the second chapter is stated.

2.1 Future INDU-ZERO production process

In order to have a better understanding of what the future production process of INDU-ZERO will look like, a flowchart visualizes the different process steps. They are of high importance as the production steps form the base of each scenario and all calculations.

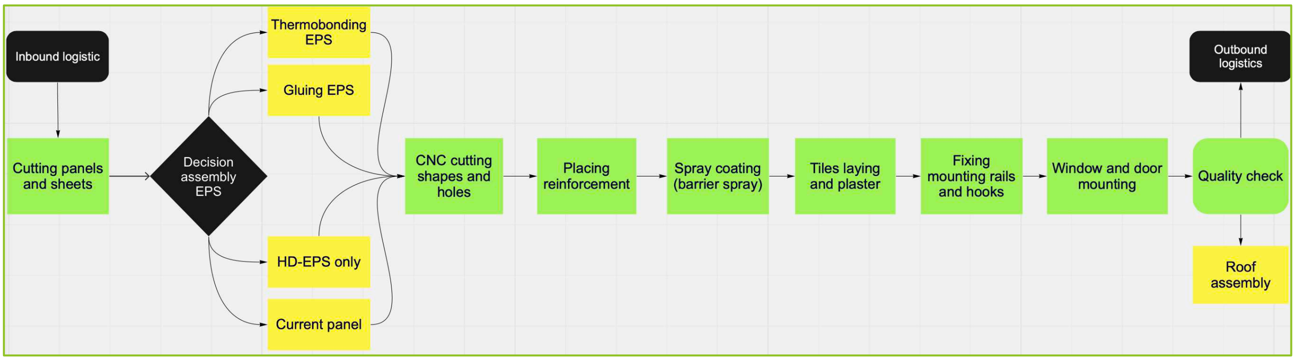


Figure 2.1 - Flowchart production process INDU-ZERO

The process shown in the flowchart (green) are the primary process steps that represent the future production of retrofitting packages.

The production starts with the cutting of panels and sheets. The main materials EPS and HD-EPS are delivered in the form of big blocks that are cut here for the first time. This is where most of the waste is produced. The second process step depends on which scenario is chosen for the assembly of the EPS-blocks. A decision has to be made here and only one out of the four yellow marked sections will be applied in the future production process. The process continues with the cutting of chapes and holes driven by CNC software.

The next action that needs to be taken is the placement of reinforcements. For this purpose, HD-EPS can be used. After reinforcements are placed, a barrier spray is sprayed onto the sides of the panel to insulate. The barrier spray used is based on polyurea which is a certain type of coating system/technology based on a synthetic resin.

The following production step is the laying of tiles. When this is done, corner tiles and plaster are added to the panel.

Hooks and mounting rails are fixed in the next process step. When this is done, the windows and doors are added to the panel. Therefore, screws, windows and doors are needed. When the façade element is finished, a final quality check is done. This is the last production process step in the factory. From there on, the panels are placed into an outbound warehouse where they receive their final curing and can be shipped to the customer.

It is expected that a similar process is used for the manufacturing of the roof but there is no information available regarding the production of the roof. For that reason, the roof is later on taken into account with a total price of production, based on information from a partner from the industry.

2.2 Production scenarios

In order to explain the difference between the scenarios of the production process it is important to understand the root of the different scenarios. The base for all scenarios is the main material used for the façade and roof elements: EPS.

The literal definition of EPS is given in the list of definitions in chapter 1. (HD)-EPS is the base material for all façade and roof elements in the production process of INDU-ZERO and commonly known as Styrofoam. It is used for the insulation of the future houses where the final products are ultimately installed.

EPS is crucial for the production process as it is the base for all products and starting point in the production process. After cutting the panels and sheets in the first production steps, a decision has to be made between the different scenarios for the assembly of the EPS plates. The four main scenarios for the production process are the following:

1. Thermobonding EPS only
2. Gluing EPS only
3. High Density EPS only
4. Current panel of RC-Panel

Scenario 1: Thermobonding EPS

Thermobonding is a technology where two or more plate surfaces are connected or glued without an additional binding material *(Bürkle, 2013)*. The surfaces of two EPS-panels are thermally heated and joined together. The result is a thicker panel with better insulation values than directly foamed plates of the same thickness. It also results in a greater manufacturing flexibility and shorter retrieval times *(Bachl, 2021)*.

The thermobonded façade consists of five layers: 1. High Density EPS (HD-EPS); 2. Standard EPS; 3. HD-EPS; 4. Mortar; 5. Stone strips. The side finish of the plate would also be made out of HD-EPS.

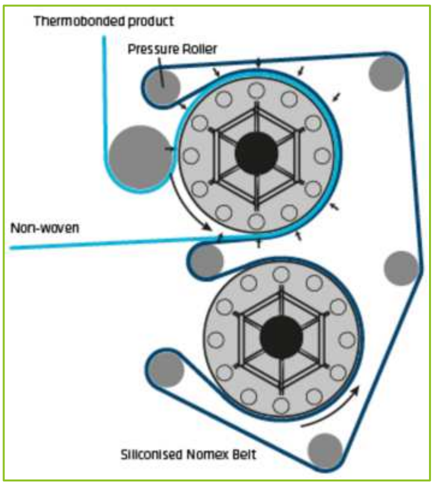


Figure 2.3 - Thermobonding procedure (Klieverik, 2021)

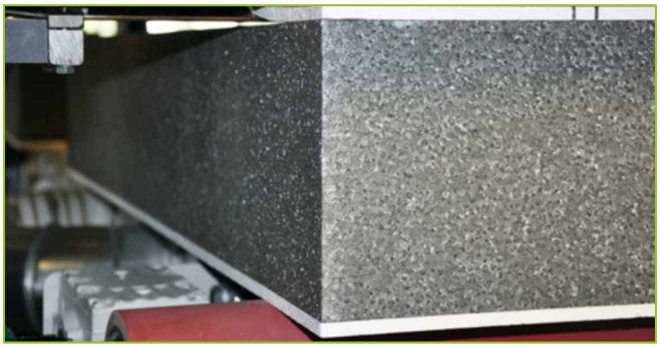


Figure 2.2 - Thermobonded EPS-panel

The technical drawing on the left shows a common thermobonding process. The unprocessed EPS-panel gets tugged between two barrels. It then gets thermally heated and the second material (HD-EPS) is joined with the standard EPS-plate by using a pressure roller and heat. The semi-fabricated product then continues to a second barrel where the same process is repeated on the other side of the EPS-plate. The result is a thicker thermobonded panel with three layers of material, without the need of an extra binding material. This technique even leads to a greater manufacturing flexibility *(Bachl, 2020)*. A visualization representation of the finished product is presented in figure 2.2. The black material shows the standard EPS. The two layers on top and bottom of the standard EPS panel shows the standard EPS plates.

Scenario 2: Gluing EPS

The second scenario "gluing EPS" differs from the first scenario mainly due to the use of a binding material. A polyurea-glue (PU-glue) is added in between the EPS-plates. The consequence is a higher amount of material that is required. Additionally, the dimensions of the panel increase and the environmental impact is bigger due to the use of glue.

For the second scenario, the different layers of EPS are connected with a glue. It then consists of a total of seven layers: 1. HD-EPS; 2. Glue PU; 3. Standard EPS; 4. PU Glue; 5. HD-EPS; 6. Mortar; 7. Stone strips. The side finish of the plate would also be made out of HD-EPS. Figure 2.4 shows the build-up of the panel (left). On the right, it shows a test sample without decoration. The picture shows two panels on top of each other. Two thin HD-EPS plates (black) are glued on both sides of the thicker standard EPS plate (grey).

Figure 2.4 - Build up panel & test sample glued EPS (without decoration)

Scenario 3: High Density EPS

The third scenario 'HD-EPS' only uses high density EPS plates for the insulation of the facade and roof elements. It therefore consists of just three layers: 1. HD-EPS; 2. Mortar; 3. Stone strips.

The third possible production scenario is to only use High Density EPS for the façade elements. HD EPS has the advantage of being very easy to assemble as it does not need any outer skin or aperture liners. It just scores low for product cost and environmental impact due to the fifteen times as much raw polystyrene beads that it is produced from. The main visual difference of HD-EPS to standard EPS panels is that standard EPS panels have a common thickness of 20cm, while HD-EPS is only 3cm thick. Standard EPS panels have a thickness of 20cm, while HD-EPS is only 3cm thick.

Scenario 4: Current panel

The fourth scenario describes the current panel that is produced by the one of the project partners. The traditional process requires a lot of handwork. Furthermore, the traditional panel consists of more layers and uses other materials such as glass fiber polyester or OSB-wood plates. Both factors have an effect on the production costs.

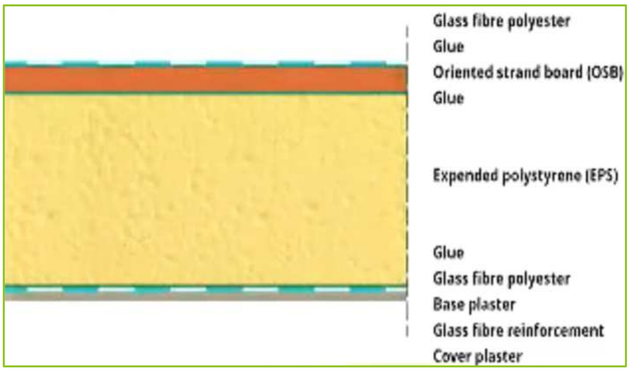


Figure 2.5 - Visualization current panel (without decoration)

The traditional panel consists of a total of 12 layers. 1. Glass fiber polyester; 2. PU Glue; 3. OSB wood; 4. PU Glue; 5. Standard EPS; 6. PU Glue; 7. Glass fiber polyester; 8. Base plaster; 9. Glass fiber reinforcement; 10. Cover plaster; 11. Mortar; 12. Stone strips. Below, a visualization of the current panel from RC-Panel is stated.

2.3 Scope of the calculation

This sub-chapter aims to sum up the most important aspects for the calculation of the future production costs of the INDU-ZERO production process. Therefore, the literature research as well as the information shared by different partners are an essential source of information. All calculations were done in Excel. The datasheets will be added to this report as an appendix. The most important results are written down in this report.

In order to be able to make precise cost calculations, it had to be clear which aspects are relevant for the calculation of the production costs. Therefore, different cost elements were chosen:

1. Labor costs

Labor costs are a big cost element for the smart factory of INDU-ZERO. For the calculation of the labor costs, the number and roles of employees are essential. Based on this information, average salary cost in the Netherlands for each group of employees can be taken into consideration. For the production, there are two main groups of employees: production staff (for instance machinery control, assembly, placing panels) and production management (for instance production manager, process manager, line managers).

2. Material costs

The material costs are essential for the calculation of INDU-ZERO's production costs as they build the foundation for all products. A majority of materials used for the production of each dwelling type remains the same. Especially the quantity of main materials such as EPS, HD-EPS and glue varies per scenario. Material costs are expected to be the highest cost factor in the production.

3. Machinery cost

The costs for machinery are essential to the smart factory. Based on personal communication with partners from the Strathclyde University, it became clear that the costs caused by machinery are only partly known (Strathclyde, personal communication, March 29, 2021). Considering that the research needed to be finished by the end of May 2021, only acquisition costs and system integration costs were taken into consideration. Acquisition costs are the costs caused by the investment in the machinery. System integration costs cover costs such as software licenses, legal fees, setting up a local network and any other expenses regarding the integration of the production process. System integration costs are usually, with respect to any acquisition, multiple times higher. According to partners from the Strathclyde University, maintenance costs for machinery (cleaning, wear and tear of tools, checking technology) cannot be calculated precisely enough to make realistic assumptions yet (Strathclyde, personal communication, March 29, 2021). Nevertheless, maintenance costs for machinery need to be taken into account as an extra expense when listing all cost-elements of the production cost.

4. Energy costs

Energy costs are often underestimated but especially in case of a smart factory they are of high importance. For the most part, the production process is working autonomously according to the industry 4.0 approach. Workers need to place different materials in the production line but other than that the rest is done by autonomous machines. All these machines need electricity in order to function properly. This leads to significant energy costs and consumption caused by the production.

5. Waste costs

Waste costs are taken into consideration as well. By cutting and assembling the different panels in order to fulfill the individual customer wants and needs, waste is produced. Disposing waste costs money. The material disposed costs money too. The amount of money spend on waste can be limited by reusing or recycling. These are questions that need to be answered in order to estimate the amount of waste and attached costs caused by it.

2.4 Stakeholder analysis

In this sub-chapter, the stakeholders for the project are being identified by means of a stakeholder analysis. The model used for this is the 'Mendelow stakeholder matrix' which shows the different roles of the stakeholders as well their interest and influence on the project.

The background information regarding the theory about the stakeholder matrix listed below is based off a literature research.

- The role of the 'influencer' (top left corner) describes a stakeholder that has a lot of influence on the project but little interest in the research behind it. These stakeholders need to be kept satisfied.
- The position of the 'key player' (top right corner) describes the most important stakeholder as they have a great deal of power but at the same time major interest in the project. These stakeholders need to be spoiled.
- The 'viewer' (bottom left corner) is a group of stakeholders that has little influence and interest in the project. They need to be monitored.
- The 'interested party' describes the stakeholders that have little influence on the project but at the same time do have major interest in the research. They must be informed regularly *(Saxion University, 2018)*.

When looking at just the factory blueprint, it is beneficial for a total of four target groups:

1. Housing cooperation's and large homeowners who need a sustainable housing stock by 2050
2. Industries and suppliers who want to play a role in the energy transition and the renewing of the construction sector
3. Investors who want to create a role in creating a new economy

4. Local, regional and European governments who have committed to climate targets and want to play a progressive role in facilitating the renovations and by doing so, reducing the CO2-emissions *(Interreg North Sea Region, 2020)*

For this research, the business case is the main environment. Therefore, the stakeholders who are linked to the business case are essential.

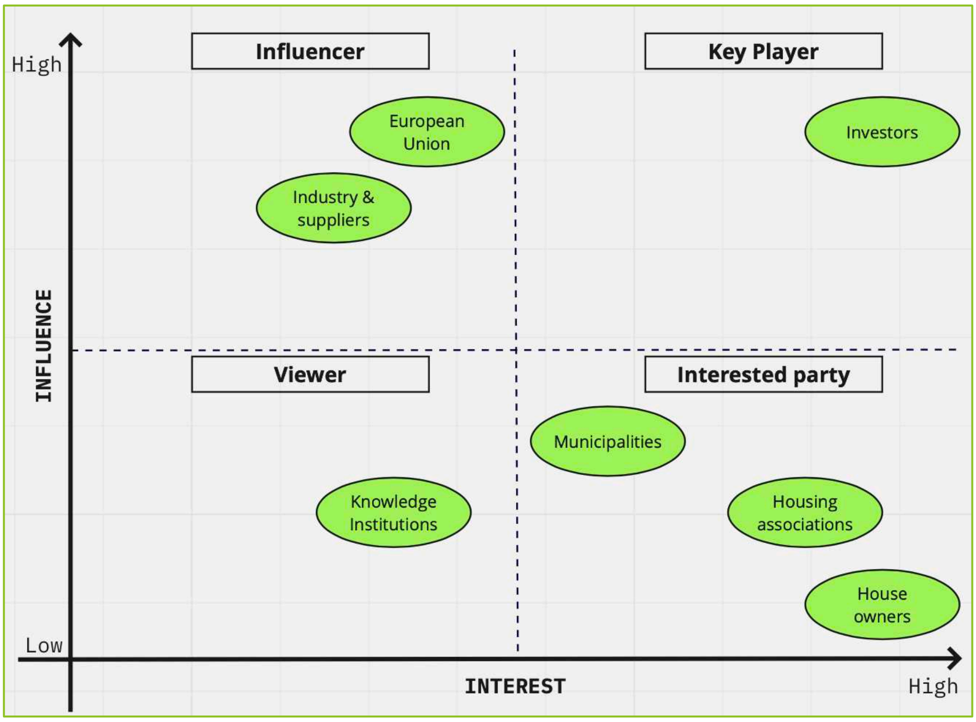


Figure 2.6 - Stakeholder matrix business case INDU-ZERO

The matrix shows that the investors are the key players in the context of the business case. Without the investors, the factory cannot be built and put into reality. It would lead to a failing of the project. Considering that the investors need to invest a large amount of money (expected: 200 million euro), their interest in a succeeding of the project is definitely high.

The role of the influencer is filled by the European Union (EU) as well as the industry and suppliers. As the initiator of the INDU-ZERO project, the influence of the EU on the project is tremendously. They are the ones who subsidized the project from the beginning. When the project is finished, they are the governmental institution responsible for fitting regulations for the smart factory. Yet, their interest in the finished business-case is lower compared to the investors, as they do not have the financial risks. The industry and suppliers have a high influence on the project because the business case is highly dependent on them fulfilling their part in the supply chain. Both parties (the EU and industry) have a lower interest compared to the investors as it is not their main responsibility to keep the factory running.

The viewers are the knowledge institutions. Their role is to help develop the business case and project in general, but when the project is finished, their interest and influence is lower compared to the other stakeholders as they have no active role once the business case is completed.

The last group of stakeholders, the interested parties, are the housing associations, house owners and local government. The house owners and housing associations are the ones who have a high interest in the outcome of the project as it would mean cost reduction and the ability to renovate significantly more houses before the deadline of 2050. They are the ones who buy the final product but have no big impact on the outcome of the project INDU-ZERO.

2.5 Sub-conclusion chapter 2

Based on the results from sub-chapter 2.1 it became clear that the majority of process steps from the future production process have been determined already. The choice regarding the production process has to be made in the assembly of the EPS-panels. This is the second process step in the production.

The flowchart shown in sub-chapter 2.1 shows the production of façade elements. It consists of nine main process steps. The manufacturing process of roof-elements is expected to look similar for the most part but there is still no clarity within the project group. This is why it was decided to contact a partner company and ask for a total price of their roof. The total price of a standard roof (including solar panels) was then used for the calculation of production costs. This is seen as a maximum price.

Apart from the fourth scenario which is the current way of manufacturing a façade element, the choice can be made between three new production scenarios: thermobonding, gluing or HD-EPS only.

What these scenarios look like is explained in sub-chapter 2.2. In the following, the first sub-question 'what do the scenarios of the INDU-ZERO production process look like?' is answered. The gluing scenario is the one where most research has been done for. The main difference compared to the new technology 'thermobonding' is that the EPS plates are joined together with a glue instead of thermal heating of the EPS-plates. The third scenario 'HD-EPS only' is the only scenario where no standard EPS is used. Only HD-EPS is used which makes the whole panel a lot more expensive.

The results of sub-chapter 2.3 answer the second sub-question 'What are the most important aspects in the calculation of the production costs?'. The relevant cost-elements for the calculation of the production costs are labor costs, material costs, investment cost, energy costs and waste costs. Due to the innovative nature of the project, some values regarding the production costs are expected to be estimations done by experts. This is a common method used in the developing of new processes.

Sub-chapter 2.4 shows who the stakeholders of the INDU-ZERO project are. Therefore, a stakeholder matrix was used as the main tool. Four categories of stakeholders including their interest and influence on the project have been determined: Viewer (Knowledge institutions), Influencer (Industry and suppliers, EU), Key player (Investors), Interested party (municipalities, housing associations, house owners). The main source of information for this research will be the viewers, interested parties and influencers. The investors will be determined once the project is finished.

3. Measure-phase

Definition of terms

BOM	Short for 'bill of material'. The bill of material includes all materials used in the manufacturing process of a product.
Density per m3	The density per cubic meter describes the kilogram per cubic meter needed for the respective material. It is a unit derived from the International System of Units (SI), commonly known as the metric system *(National Institute of Standards and Technology , 2021)*.
System Integration costs	System integration costs are the costs caused by creating a "complex information system that may include designing or building a customized architecture or application, integrating it with new or existing hardware, packaged and custom software, and communications" *(Gartner, 2021)*.
Acquisition cost	"Acquisition costs are expenses that are incurred in order to acquire an asset and to put it in an operational state" *(Weber, 2020)*

The third chapter answers the following sub-question:

2.1 What does the production cost structure of the INDU-ZERO production process look like?

This chapter covers the second phase of the DMADV-model: Measure. In sub-chapter 3.1, the archetype dwellings that form the base of the calculations are stated. In the following, the results of the calculation of future production costs are added to sub-chapter 3.2. Finally, a conclusion of the third chapter is stated in sub-chapter 3.3.

3.1 Archetype dwellings

For the INDU-ZERO business case as well as the calculation of production costs, choosing archetype-dwellings is of high importance. It is crucial to use them as a starting point for further calculations as the products of the smart factory ultimately differ almost every time. This is due to the fact that existing houses are (slightly) different from one another, but the foreseen mass-customization concept makes small differences between dwellings possible for very limited changes in cost price. A majority of dwellings has individual measurements and is produced to meet the individual customer wants and needs. Researchers from the Saxion and Jade University have chosen three archetype-dwellings which are used in this study. The selection was made based on three criteria:

1. Degree of representativeness for the building stock in the North-Sea-Region (NSR)
2. Feasibility for large scale production
3. Consistency with respect to floor area and overall design

Below, the relevant dimensions of each archetype dwelling are listed.

Table 3.1 - Dimensions archetype dwellings

	Semi-detached (m2)	Terraced (m2)	Apartment (m2)
Floor	60	52	71
Roof (tilted)	65.2	65.5	-
Roof (flat)	14	-	20
Façade	170	110	125
Glass (single)	6.7	4.3	1.3
Glass (double)	24.6	21.3	16.8

1. Semi-detached dwelling (1965-1974)

Figure 3.1 - Semi-detached dwelling

The main characteristic of a semi-detached dwelling is that, compared to terraced dwellings, it is placed on corners. It may also conclude the final dwelling in a series of terraced dwellings. A semi-detached dwelling built in the Netherlands between 1965-1974 is more representative of its time as it matches the floor area of terraced dwellings build around the same time. Usually, semi-detached dwellings are bigger than terraced ones and have a larger floor area. Furthermore, semi-detached dwellings have one more side element compared to terraced ones and the roof can be either tilted or flat. Below, the most important dimensions regarding the façade- and roof elements are listed up. With around 142.000 houses in the Netherland alone, semi-detached homes represent a market share of 2.1% from the Dutch housing stock *(Ministerie voor Binnenlandse Zaken en Koninkrijkrelaties, 2011).*

2. *Terraced dwelling (1965-1974)*

Figure 3.2 - Terraced dwelling

Terraced houses are houses in a row of similar houses and are joined by a common boundary. Though joined, each house has its own side walls, boundary walls and roof. The main difference of a terraced dwelling compared to semi-detached ones is that terraced houses have a smaller floor space and therefore smaller façade elements. With a total of 654.000 homes, terraced houses built between 1965-1974 represent around 10% of the Dutch housing market *(Ministerie voor Binnenlandse Zaken en Koninkrijkrelaties, 2011).*

3. *Gallery apartment block (1965-1974)*

Figure 3.3 - Gallery apartment block

A typical gallery apartment built between 1965-1974 consists of four dwellings in one apartment block. The biggest difference compared to semi-detached and terraced dwellings is that one roof is shared by four apartments and that there is one shared entrance for all apartments. Furthermore, the floor space of an apartment dwelling is slightly bigger than the floor space of a terraced dwelling and smaller than a semi-detached dwelling. With 208.000 homes, 3.2% of the Dutch housing stock are represented by gallery apartments built between 1965-1974 *(Ministerie voor Binnenlandse Zaken en Koninkrijkrelaties, 2011).*

Important to mention is the fact that the INDU-ZERO smart factory will be able to produce elements for similar houses as well. These houses can be built before 1965 and after 1974 too. For calculations and other research activities it was important to choose archetype-dwellings that have relatively high market shares as a starting point in order to increase the validity and reliability of this study.

Table 3.2 - Key figures dwellings

Type	m2 facade	m2 roof	Number of façade elements	Number of roof elements
Semi-detached	170	65	7	3
Terraced	110	66	5	3
Apartment	125	20	5	1

For all three dwelling types, the dimensions in table 3.2 were taken into account for further calculations. The values were determined in a discussion with a partner from the Jade University who has detailed insights in logistics and warehouse calculations. Therefore, he has a collection of all measurements regarding the final product that is applied to the dwelling.

3.2 Calculation production cost

This sub-chapter will answer sub-question 2a: "What does the production cost structure of the different scenarios of the INDU-ZERO production process look like?".

The production costs are structured according to the cost elements mentioned in chapter two: labor cost, material cost, energy cost, waste cost, machinery cost. The results of each cost element and the final production costs per dwelling are presented below. Detailed insights in the calculations are added to the appendix IX and can be found in an external Excel sheet named 'production cost INDU-ZERO'.

Labor cost

For the calculation of labor costs caused by the production process, different cost elements were chosen. In order to calculate labor costs, general information about the number of working days, shifts, employees per shift and the different roles of production staff had to be collected. The staff then was classified in two segments: production staff and production management. Production staff includes everyone working actively in the production hall such as machinery control operator or employees responsible for placing the EPS correctly. Production management includes employees such as production manager, line leader or manufacturing engineer. A list of all roles of the production staff used for the calculation is added to the appendix IXa.

Table 3.3 - Overview labor cost

Overview labor costs	
Number of working days	220
Total number production workers	209
Production staff	181
Production management	28
Average salary staff	2.665,00€
Average salary management	4.608,50€
Labor costs annually	7.336.836,00€
Costs per dwelling	**489,12€**

The number of working days determined is 220. This is based on the Dutch average of 250 working days minus 30 days for vacation. The number of shifts for the majority of production staff is set to be 3 x 8 hours, five days a week. Considering that the in- and outbound trucks are only arriving and departing throughout the day, some employees such as warehouse manager, production manager or manufacturing engineers are not required in the night shifts. The factory is expected to produce at a lower tact time throughout the night shifts. The total number of production staff is expected to be around 181 workers, the total for production management staff 28 workers.

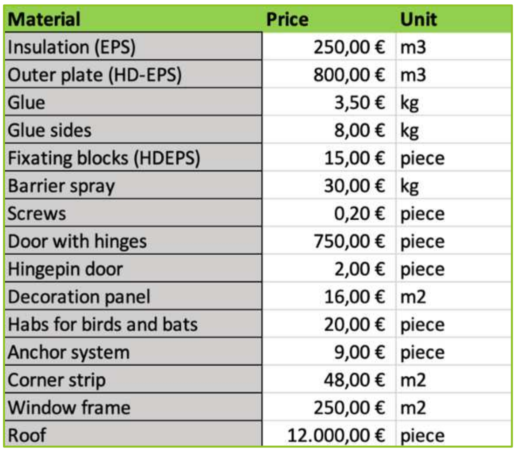
Based on information about the number of working days, employees and roles in the production, the Dutch average salary for production staff as well as an average of all salaries from higher qualified staff were determined through a literature research. The average salary for an employee of the production staff is 2050€, the average salary for the higher qualified staff 3.545€ *(Berenschot, 2017)*. By adding 30% of ancillary wage cost that companies have to pay for in the Netherlands, the total monthly cost increase to about 2.665€ for production staff and 4.608€ for production management staff. By multiplying the total number of workers with the annual salary of the respective staff group, the total annual labor costs for the production result in 7.336.836€. This equals 489,12€ per dwelling.

Material cost

The material costs are essential when calculating the production costs for INDU-ZERO's smart factory. Due to the technical nature of the process, some materials may seem unknown for laymen's terms. The literal definitions of technical terms are stated in the beginning of the chapter.

The starting point for the calculation of the material costs is the bill of material (BOM). The BOM for the production process of INDU-ZERO includes the materials discussed on the next page:

Table 3.4 - Bill of material (BOM)



Material	Price	Unit
Insulation (EPS)	250,00 €	m3
Outer plate (HD-EPS)	800,00 €	m3
Glue	3,50 €	kg
Glue sides	8,00 €	kg
Fixating blocks (HDEPS)	15,00 €	piece
Barrier spray	30,00 €	kg
Screws	0,20 €	piece
Door with hinges	750,00 €	piece
Hingepin door	2,00 €	piece
Decoration panel	16,00 €	m2
Habs for birds and bats	20,00 €	piece
Anchor system	9,00 €	piece
Corner strip	48,00 €	m2
Window frame	250,00 €	m2
Roof	12.000,00 €	piece

An example of each material is pictured and added to appendix XVI. The prices for EPS, HD-EPS and glue were determined in close cooperation with the project leader (project leader, personal communication, May 5, 2021). The price of the roof is a standard price for a roof including materials, PV-panels and labor cost from one of INDU-ZERO's partners (industry partner, personal communication, May 20, 2021). In the calculations, this price is seen as a maximum. All other costs were determined in close cooperation with Bureau de Haan (personal communication, May 18, 2021). For more insights in calculations, please have a look at appendix IX or the attached Excel-sheet 'production cost INDU-ZERO'. The archetypes mentioned in chapter 3.3 are used to calculate the costs as they differ for each archetype. Each dwelling needs a different amount of material during the production. The amount of material used multiplied by the single price of the material equals the price for the material per dwelling. The amount spend on all materials results in a total price per dwelling. The calculations lead to the following material costs:

Table 3.5 - Overview material costs

Overview material costs	
Semi-detached	*24.912,84€*
Terraced	*22.390,88€*
Apartment	*21.219,04€*
Number of dwellings annually	*15.000* *(3000 semi-detached;7500 terraced; 4500 apartment)*
Average annual cost	*338.155.800,00€*
Average per dwelling *(338.155.800,00€/15000)*	***22.543,72€***

The material costs for semi-detached dwellings are the highest at the moment. Terraced dwellings are the second most expensive and the material costs for apartment dwellings are the lowest. Based on the market shares of each dwelling type mentioned in chapter 3.1, the following spread was chosen: 50% of the packages produced are for terraced-, 30% are for apartment- and 20% are for semi-detached houses. This equals 7500 terraced-, 4500 apartment- and 3000 semi-detached-packages. This leads to total average annual material costs for producing 15.000 retrofitting packages of 338.155.800,00€. This results in an average price per dwelling of **22.543,72€.**

Energy cost

Energy costs are the least researched cost element. The main reason for that is that not all machines are fully designed and developed yet nor are there detailed calculations regarding the energy costs. According to a professor at the Strathclyde University, the expected energy costs each month are caused by electricity, water and gas (Strathclyde, personal communication, April 6, 2021). Electricity and water are mainly caused by the machines, gas is used for warming of the factory building and the machines. The outcome of his research is stated below.

Table 3.6 - Energy costs

Energy	*Costs*
Electricity	*133.000€*
Water	*20.200€*
Gas	*17.300€*
Total monthly	*170.500€*
Total annually (x12)	*2.046.000€*
Per dwelling	***136.40€***

The medium-term goal of the INDU-ZERO smart factory is to be energy neutral and off-grid. Based on personal communication with the project leader it appears that this goal is not achievable simultaneously to the factory's building or shortly after (project leader, personal communication, March 12, 2021). That's why it is chosen to calculate with the before mentioned energy costs. Over a period of 5-10 years, the company should be able to go mostly off-grid and supply itself with energy. One method to achieve energy-neutrality that is discussed already is placing PV-panels on top of the factory building.

Waste cost

For the calculation of waste costs, the estimation is that 5% of the main materials used in the manufacturing process of the façade- and roof elements needs to be disposed. This value is based on an estimation done by the responsible CNC-machine designer at the University of Strathclyde. The common unit used for the calculation of waste disposal is cubic meters (m^3).

For the calculation of the expected waste costs, a decision has been made on the materials that produce by far the biggest waste in the production process, mainly due to the CNC-cutting process. This has led to the following list of materials:

1. EPS
2. HD-EPS

For each material the dimensions of one piece, pieces produced annually, 5% offcut of all pieces and the annual waste have been calculated and taken into consideration. All numbers were calculated for each dwelling type. These calculations are added to appendix IXd. Based on these numbers, the monthly waste was calculated.

Table 3.7 - Monthly waste

Waste (m3) monthly	Semi-detached	Terraced	Apartment
EPS	25	20	15
HD-EPS	15,3	11,7	9,9
Total per dwelling	40,3	31,7	24,9
Total waste monthly (m3)	96,9		

Figure 3.4 - Example press container (Perscontainerhuren, 2021)

The average press container has a volume of 25 cubic meters *(Perscontainerhuren, 2021)*. By dividing the total waste monthly by the size of the container, the number of containers per month results in: 96,9/25 = 3,88. This equals four full container loads each month. In figure 3.4 a press container is pictured.

Costs for waste collection are calculated according to a market-based rate, although the prices can still be negotiated further with long-term contracts. The rental costs per container are quantified with 375 euros a month. These are considered as fixed costs for waste collection. Transport costs are 150 euro per container. The costs for 1 ton of industrial waste are 175 euros. The transport cost as well as costs per ton of waste are considered as variable costs for waste collection.

For the calculation of total costs for waste collection, the amount of waste in tons per month had to be calculated. For that, the total waste per month mentioned in table 3.7 has been multiplied by the respective density per m^3 per material. The material density of EPS and HD-EPS is listed in table 3.8 *(geofoamintl, 2021)*:

Table 3.8 - Material density per m3

Material	Material density in tons per cubic meter (t/m^3)
EPS	*0,046 t/m^3*
HD-EPS	*0,048 t/m^3*

This leads to a total waste per month of 4.53 tons. By multiplying this amount with the cost per ton of waste (175€) and adding the mathematical product of transport costs (150€) and number of containers (4) per month, the total variable costs of 1.392,96€ result. Adding variable and fixed costs for waste collection result in **total monthly cost for waste collection of 1.767€.** This equals 1.41€ per dwelling.

Apart from the costs for waste collection, the cost for the material disposed had to be calculated as well. EPS has a price of 250€ per m3, HD-EPS of 800€ per m3. These prices were required to calculate the costs of wasted material per dwelling. For semi-detached dwellings, the monthly material costs of waste are 18.490€. For terraced dwellings, the costs are 14.360€. Apartment blocks produce costs of 11.670€. This results in 44.520€ of material-waste costs per month. In conclusion, the **total waste costs per month per dwelling for material and waste collection are 37,03€**.

Machinery cost

The automated production process of INDU-ZERO requires a lot of machinery. At the time when this research was done, the majority of machinery was still in the developing phase. The numbers stated below are estimations made by experts from the University of Strathclyde and can be seen in appendix IXe.

The total acquisition costs for all machinery needed is estimated to be around 88.924.578€. Assuming an average service time of the machinery of 10 years, the total depreciation costs per year are around 8.892.457 €. This equals a price per dwelling of 8.892.457/15.000 = **592.83€.**

Table 3.9 - Aquisition costs

Overview acquisition costs machinery	
Total number of machines	*327*
Total investment costs	*88.924.578€*
Average service time	*10 years*
Annual depreciation	*8.892.457 €*
Number of dwellings annually	*15.000*
Price per dwelling	***592.83€***

Apart from the acquisition costs, system integration costs are a big cost element that should be taken into consideration. The systems integration costs are usually multiple times higher than the acquisition costs. According to multiple experts from the Saxion and Strathclyde University, the system integration costs are expected to be twice as much as the acquisition costs (Saxion & Strathclyde, personal communication, April 14, 2021). This would add a total amount of around 180.000.000€ of investment costs. These costs also need to be depreciated over a period of time. The estimation is that the integration costs are depreciated over the same period as the machines (10 years). This leads to additional costs per dwelling for system integration of 1.185,66€. This results in **total cost for machine acquisition and system integration of 1.778,49€.**

3.3 Sub-conclusion chapter 3

In summary, chapter 3 has answered sub-question 2.1 ‘What does the production cost structure of the INDU-ZERO production process look like?’.

The design engineers and product developers working for INDU-ZERO have the most experience with the ‘gluing’ production scenario. The machines and production lines that are currently in the developing phase are intended for the ‘gluing’ scenario. This is why INDU-ZERO asked for a production cost calculation of their future production process. Other stakeholders have mentioned the need of an evaluation of other production scenarios. Since there are other options, these need to be evaluated and compared. This is done in chapter 4 and 5. The archetypes chosen as the fundament for all calculations are semi-detached- and terraced dwellings as well as gallery-apartment blocks built between 1965-1974. The reason for this being that these dwellings are comparable regarding their floor size and overall look. The goal of the smart factory is to apply mass-production to a market where mass-customization is required. This should help to increase the volume of houses renovated per year in order to meet the 2050 climate targets. The labor costs cover various aspects such as number of employees, role of employees, working days, number of shifts and the average salary. The total labor costs per dwelling are around 489€. The costs for material are the highest. Based on the current BOM and market-share per dwelling type, the material costs are 22.543€. The costs for the material wasted and waste disposal are 37€ per dwelling. Within the first years after the building of the factory, energy costs are expected to be around 136€. The costs for machinery acquisition and system integration are around 1.778€ per dwelling. In total, the annual production costs for producing 15.000 retrofitting packages are 374.262.297,36€ which equals an average price of 24.984,76€ per dwelling. In figure 3.5, the production costs per dwelling are visualized by means of a bar chart.

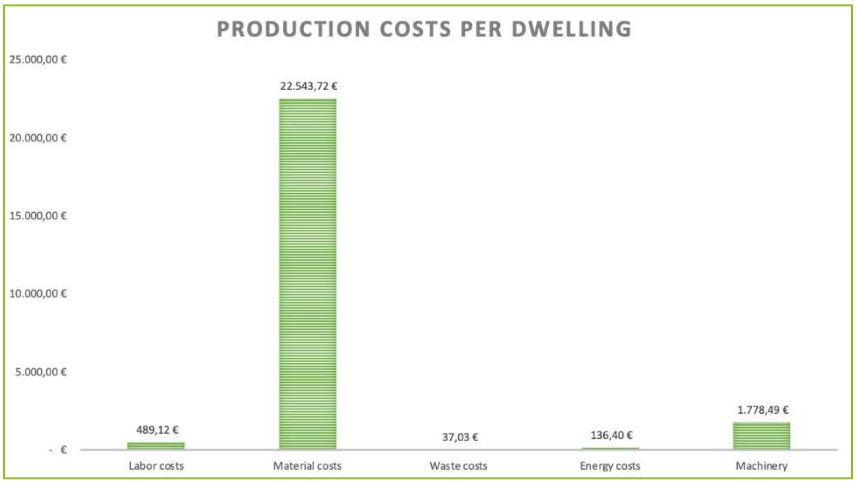


Figure 3.5 - Production costs per dwellings

4. Analyze-phase

Definition of terms

MCA	Short for Multi-criteria analysis. Also known as multi criteria decision analysis (MCDA). The MCA is a procedure used for the analysis of decisions made. It is mainly characterized by the fact that it is not using one criterion in order to make a decision but multiple.
DFM	Short for 'Design for Manufacturing'. DFM practices can help to improve design productivity, time-to-market and product performance and reliability. This can be achieved by "closely coupling semiconductor fabrication knowledge with product requirements during the initial phase of the product design" *(Wilcox, Forhan, Starkey, & Turner, 2002)*. DFM is the optimization of a product or component in order to make the production process more easily and cheaper.
DFA	Short for "Design for Assembly". "DFA is the key to very significant cost reductions in overall manufacturing costs. The technique involves two main steps: 1. minimization of the number of separate parts; 2. Improvement in the 'assemblability' of the remaining parts" *(Boothroyd, 2014)*. The DFA procedure has many implications for the DFM.
Circular / Circularity	Circularity is part of the idea of a circular economy. This is an economy designed to be an innovative and restorative system. Hereby the focus is on (re)designing business models with as main purpose to optimize the value of products, parts and materials in order to be able to reuse and recycle products to develop and manufacture equivalent products, not downcycling them. This value retention has to led to a more efficient use of (raw) materials and goods. The main goal of the circular economy is to close material loops in order to shape unified cycles. That's why it's called the 'circular' economy (Ellen Macarthur Foundation, 2013).

The fourth chapter answers following sub-questions:

2.1 What are the biggest cost elements in the calculation of the production costs?
2.2 Which factors other than production costs should be taken into consideration when choosing the optimal scenario?
2.3 How should the different factors of the MCA be weighed in order to be able to select the optimal scenario?

This chapter covers the third phase of the DMADV-model: Analyze. Sub-chapter 4.1 starts with the overview of the biggest cost elements and potential cost savings of the production process based on findings in chapter 3. In the following, the results from an MCA including conclusions of interviews (4.2.1), the chosen MCA assessment criteria (4.2.2) and a substantiation of the MCA (4.2.3) are mentioned in sub-chapter 4.2. Finally, a conclusion of chapter 4 is added to sub-chapter 4.3.

4.1 Biggest cost elements

The outcome of the calculations of expected production costs is stated below. It shows that the material costs have the biggest share in the production costs with an average amount of 22.543,72€. The second highest cost share belongs to the acquisition and integration costs of the machinery. They make up 1.778€ per dwelling. The lowest share belongs to the waste costs with a share of 37€. In total, **the average production costs for one retrofitting package are 24.984,76€**. Compared to the anticipated total average cost-price of a retrofitting package of 45.000€ (50% less than current average market prices), the **share of production costs is 55.5%.** Important to mention here is that the cost for the roof is seen as a maximum of 12.000€, since the roof panels with the required characteristics can be bought externally. If INDU-ZERO chooses to produce the roof themselves, these costs are expected to decrease significantly.

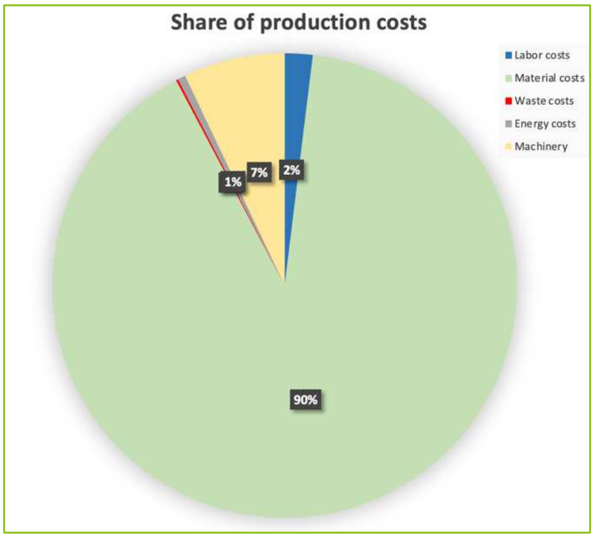


Figure 4.1 - Share of production cost

Another important aspect in this manner is that the production costs are one part of the total product costs. According to multiple research assistants, the project leader and partners from the industry, the biggest share of costs is expected to be caused by the installation and on-site mounting of the retrofitting packages (Saxion; Strathclyde; project leader; industry partners; personal communication, March-April, 2021). It will take approximately three working days to install the façade- and roof elements. Around five workers per dwelling are needed. This causes high costs that need to be taken into consideration when calculating the total cost-price of the product. As this study is limited to the production costs, these additional costs are not taken into consideration.

Potential cost savings

In all cost calculations, a bulk discount of 10% was taken into consideration. This value is based on the experiences from various industry partners and has been verified by the product developer of Bureau de Haan. For that reason, potential cost savings within the production costs are difficult to achieve. The prices of raw materials are increasing significantly at the moment. Reasons for that are the corona-crisis, increasing demand simultaneously to short supply or the immense glut of money caused by various central banks *(Deutsche Presse Agentur, 2021)*. The cost savings that are most likely to achieve are cost for waste and energy. The energy costs could be significantly lowered once the factory is able to go at least partly off-grid. The EPS and HD-EPS offcuts could be transferred to a company called 'PolyStyreneLoop' which has its grand opening on June 16th, 2021. They are recycling EPS and HD-EPS and extract the materials in order to make new products out of it *(PolyStyreneLoop, 2021)*.

It is important to mention that the goals of INDU-ZERO are not just achieved due to optimizing the production. The essential cost savings will not be made in the material costs. Actually, these could be even higher against the background of increasing prices. Relatively speaking, the position of INDU-ZERO in the market would not decrease by this, as the prices apply for all producers. Nevertheless, the size of the market would decrease. What is much more likely to happen are cost savings in labor costs, especially when compared to the current way of producing retrofitting packages. The total production cost of a traditional panel is expected to be at least double the amount of what has been calculated for the INDU-ZERO panel. This estimation is based on the total cost-price of a traditional panel of around 80.000€. As mentioned in the research design in chapter 1, the scope of this research is the production process only. Once all costs of other departments are added to the cost-price per element, the net labor cost savings can be determined.

Another important aspect to mention is the circularity. At the moment, being circular costs more money compared to common way of production (raw materials, more waste). If the prices are continuing to increase, this could change. It would have a big impact on the strategy and choices of INDU-ZERO. Becoming more circular would be financially more interesting than ever before.

4.2 Multi-criteria analysis

MCA - Multi criteria analysis

To be able to make the right decision regarding the four production scenarios, a multi-criteria analysis was chosen as the main analysis tool. The MCA is based on five main steps:

1. Formulating and categorizing the criteria
2. Define scores for the criteria
3. Assigning weights to the criteria
4. Determine ranking of the criteria
5. Assigning points to the alternative/scenario

For the MCA, different criteria are assigned to a weight which allows to make a well-founded decision. In the define phase, the following scenarios were presented: thermobonding EPS, gluing EPS, HD-EPS, current panel.

These four scenarios will be investigated with the help of various criteria that have been chosen based on interviews with relevant stakeholders. The outcome of those interviews including a conclusion of all relevant criteria is stated below. The extended version of the interviews can be found in appendix IX. The interviews were conducted with four different stakeholders from three different countries. They have been conducted in English, German and Dutch. Therefore, the interviews have not been written out word for word, but a detailed summary based on recordings was done. These are added to the appendix IX. According to the theory of *(Leen & Mertens, 2017)*, the interviews were semi-structured. This means that essential questions where an answer is inevitable have been prepared before the interview started. Throughout the interview, supplementary questions are added to get more detailed information from the interviewed.

The essential questions that were asked throughout the interview were:

1. How would you describe your role in the project?
2. Are you familiar with the four production scenarios?
3. Which factors other than production costs should be taken into consideration when choosing the optimal scenario?
4. How should the different factors of the MCA be weighed in order to be able to select the optimal scenario
5. Why should the different factors of the MCA be weighed in that exact order?

4.2.1 Results interviews MCA

The first questions regarding the roles of the respondents resulted in the following answers: project leader, digital engineer, product developer, manufacturing simulation engineer. All respondents were familiar with the four-scenarios mentioned. During the first interview with the project leader, another production scenario got mentioned: cast in a mould. This means pouring the heated HD-EPS directly into a form. This scenario is not further researched in this research because there is not enough information available yet. It is mentioned later on in chapter 4 as one possible option for manufacturing the 'HD-EPS' production scenario.

The main reasons why interviews were chosen as a research method was to find criteria that are relevant when comparing the four production scenarios. 100% of the respondents have mentioned the production costs, product cost, quantity, flexible building factory, easy to assemble, lifetime product, environmental impact and maintenance costs. 75% of the respondents have mentioned quality, tact time, robust components. Another 50% of the respondents said fire safety should be considered as criterion. Only one respondent (25% of respondents) has mentioned safety of employees and users and well as design for logistics as a relevant criterion. It became clear that a lot of criteria are part of the category 'Design for Manufacturing'. It shows how important a well-designed production process is for the INDU-ZERO project.

The second category 'costs', including the production costs as well as the final product costs, has also got high weights attached to it. This is because the main goal of the INDU-ZERO project is to reduce production costs by 50%, compared to the current panels. The 'after sales' criteria such as lifetime product, environmental impact and maintenance costs have been mentioned by each respondent, but do not have the highest weights attached to them.

The criteria and weights-factors collected based on these interview questions are summed up in the following list. A substantiation per criterion is added later on in chapter 4.2.3.

Table 4.1 - MCA-critera

Criteria mentioned		**Respondent 1** Project leader		**Respondent 2** Digital engineer		**Respondent 3** Product developer		**Respondent 4** Manufacturing simulation engineer		**Average %**
	Share %	Choice	Weight factor	Choice	Weight factor	Choice	Weight factor	Choice	Weight factor	
Costs										
Production costs	7,15%	X	8%	X	5%	X	12%	X	10%	9%
Product cost	7,15%	X	8%	X	13%	X	12%	X	7%	10%
Design for Manufacturing										
Quality	7,15%	X	12%	X	15%		0%	X	10%	9%
Tact time	7,15%	X	12%	X	0%	X	6%	X	10%	7%
Quantity	7,15%	X	12%	X	9%	X	6%	X	7%	9%
Robust components	7,15%	X	10%	X	8%		0%	X	8%	7%
Fire safety	7,15%	X	10%	X	16%		0%		0%	7%
Safety employees	7,15%					X	8%		0%	2%
Flexible factory building	7,15%	X	3%	X	10%	X	5%	X	9%	7%
Design for assembly										
Easy to assemble	7,15%	X	10%	X	11%	X	12%	X	13%	12%
After sales										
Lifetime product	7,15%	X	5%	X	6%	X	8%	X	9%	7%
Environmental impact	7,15%	X	6%	X	4%	X	15%	X	8%	8%
Maintenance costs	7,15%	X	4%	X	3%	X	9%	X	9%	6%
Design for logistics	7,15%					X	7%		0%	2%
Total	100%		100%		100%		100%		100%	

4.2.2 Assessment criteria MCA

The essential assessment criteria for the MCA according to interviews done with various stakeholders are stated below. The chart shows the average share of each criterion. The highest score (12%) is attached to criterion ‘easy to assemble’. The second highest score belongs to the product cost (10%). The third place with a share of 9% is shared by three criteria: production costs, quality and quantity. Those are the most important criteria according to the respondents. All criteria that performed worse than 5% were left out of the list of criteria for the MCA. This includes ‘safety for employees and users’ as well as ‘design to logistics’. The last criterion that was taken into account for the MCA was maintenance costs with a share of 6%. In total, twelve criteria were classified as relevant for the MCA. The criteria were ranked based on their average weight factor. The average weight factor was calculated for each criterion, based on the individual weight factors given by each respondent.

Figure 4.2 - Order of criteria

Table 4.2 - List of classification

Points	Classification
1	Very insufficient
2	insufficient
3	sufficient
4	well
5	Very well

Each weight factor needed to be multiplied with a classification-value. This was done by the stakeholders as well by filling in a template MCA-list. The template got send to the stakeholder once all interviews were done and the criteria were ranked and filtered. The filled in templates are added to the appendix XI. The list of classification is stated on the left in table 4.2. Each scenario has been classified by the stakeholder according to this list. By multiplying the weighting factor with the points of classification, a final value per criterion emerged. By adding all values for each scenario, the total MCA score per scenario is the result. All results are summed up in the MCA-list below. All numbers mentioned in table 4.3 are averages based on interviews and estimations done by the respondents. One addition was made to the MCA based on the interviews and to be able to make the best, most realistic recommendation at the end of the research. The orange marked section in the table saying ‘technology tested and ready for practice’ is an important addition as not all of the production scenarios are ready to apply immediately.

Table 4.3 - Average MCA scores

Criteria	**Weighting factor**	**Scenario 1 - Thermobonding**	**Scenario 2 – Gluing**	**Scenario 3 – HD-EPS only**	**Scenario 4 – Current RC-Panel**
Technology tested and ready for practice?		Partly	Yes	No	Yes
Easy to assemble (DFA)	12	39	48	54	36
Product cost	10	37,5	32,5	17,5	32,5
Production costs	9	31,5	33,75	42,75	31,5
Quality	9	33,75	38,25	40,5	42,75
Quantities	9	33,75	38,25	36	29,25
Environmental impact	8	34	22	30	16

Tact time	7	29,75	26,25	33,25	15,75
Lifetime product	7	22,75	28	31,5	26,25
Robustness / strength	7	22,75	28	31,5	33,25
Flexible factory building	7	24,5	22,75	31,5	26,25
Fire safety	7	17,5	17,5	17,5	24,5
Maintenance costs	6	18	21	24	21
Total score MCA		344,75	356,25	390	335

4.2.3 Substantiation MCA

Based on the interviews with the stakeholders, the criteria for the MCA were determined. These criteria got weighted by each respondent afterwards and a total MCA-score has been calculated for each scenario. This resulted in the following order of scenario's:

Table 4.4 - Order of scenario's MCA

Order	*MCA Score*
HD-EPS	*390*
Gluing EPS	*356*
Thermobonding EPS	*345*
Current panel	*335*

Below, a substantiation for the outcome of each criterion and the order of scenarios is stated. This is based on statements done by the respondents throughout the interviews.

Easy to assemble (12%)

The criterion 'Easy to assemble' is part of the theory of 'Design for assembly'. It was rated the highest out of all criteria with an average weight factor of 12%. Which scenario is the optimal one depends on how simple it is to build the panel itself but also how easy it is to apply it to the houses. It is expected that the production scenario, whether it is thermobonding, gluing, HD-EPS only or the current version, has little to no effect on the on-site mounting. This is mainly due to the anchor systems that are placed on the panels which are always the same. This is why the focus remains on the assembly of the products.

Product cost (10%)

The final product costs are, inter alia, a result of the production costs. If the production costs are too high, the cost per product increase as well. This may vary within the different scenarios. It is expected that thermobonding has a positive effect on the production costs due to the amount of material saved. Furthermore, the process is faster than gluing, which makes it possible to produce more panels in less time. Using 'HD-EPS only' will cause significant extra costs. This has a positive effect on the final cost-price of the product and effectiveness of the smart factory.

Production costs (9%)

Production costs are considered as relevant due to the correlation with the overall goal of INDU-ZERO. The price of a retrofitting package should not be more than 50% of what a current package cost. The production costs are of high importance in this manner. If a production scenario produces significantly more production costs compared to the another, it most likely will not be available as an option.

Quality (9%)

Quality is a crucial factor in the production of the panels as well. It does not matter which production scenario is chosen: the quality has to remain top-notch. Otherwise, the whole project is likely to fail. The second interviewed research assistant, who has 20 years of experience in the automotive production, said that a new developed process needs to be geared for quality from the start. Once the process is set up, it would be nearly impossible to make drastic change in the design of the process. This is why design for manufacturing and assembly are of such importance in the choosing of the right scenario.

Quantity (9%)

Quantity has also been highly ranked by the stakeholders. Due to differences in production speed of each scenario, the quantity produced per day/year differs. The goal to reach the 15.000 retrofitting packages a day requires a tact time of around 2 minutes. If for example the gluing process requires significantly more curing time than the thermobonding process, the effect on the quantities produced is tremendously. This would lead to a lower score of the gluing process, as the quantity is attached to a higher score. Additionally, the quantities produced annually are of high importance for the INDU-ZERO project. The goal of 15.000 retrofitting packages per year must be fulfilled, otherwise the goals set by the Paris climate agreement will not be achievable.

Environmental impact (8%)

The environmental impact has been mentioned by all stakeholder as well. The reason for that is the difference in the amount of material used and energy consumed by different production scenarios. The thermobonding process is expected to require more energy due to the thermal heating process. This leads to more energy consumption. The gluing process requires more materials (especially glue) and therefore produces more waste. As the goal of the INDU-ZERO smart factory is to be energy neutral and as circular as possible, the environmental impact needs to be considered when comparing the different scenarios. Circularity should be the base of the factory and the environmental impact should be as low as possible.

Tact time (7%)

The tact time of the production process is a crucial criterion since it has effect on the number of pieces produced (quantity). The goal is to renovate 15.000 homes annually. This equals 1.250 dwellings per month. To achieve this ambitious goal, the tact time should be as fast as possible. The tact time differs when comparing the different scenarios. Thermobonding is expected to faster than for example the gluing process. This is mainly due to the curing that is required when the glue is applied in between the panels. Furthermore, the fourth respondent mentioned the set-up time of machines an important factor for the tact time. The faster a machine can be set up when for example an interruption in the production happens, the better.

Lifetime product (7%)

The product’s lifetime has been weighted lower compared to the before mentioned criteria. There are two main reasons for this. First of all, the production scenario is expected to not have as much of an impact on the lifetime of the product. The panels are produced to last for decades anyways. Secondly, the exact lifetime is hard to foresee at the moment. Based on the experience from other partners in the market, the facade- and roof elements should at least last

25 years without any maintenance required. Therefore, it has not highly ranked by the stakeholders. Yet it is important to keep in mind, as guarantees are linked to the lifetime of the product.

Robust components (7%)

The robustness of the panels is a relevant criterion as well. Due to the use of different materials, the strengths of the product may vary. Especially the thickness of the panel is of high importance as it defines the insulation values. The thicker the panel, the better the insulation value. The strengths of the product can also vary based on the density of the material. If it is chosen to use more HD-EPS, the insulation values increase without the panel getting significantly thicker.

Flexible building factory (7%)

The flexibility of the factory building concerns itself with the overall design of the production location. The production lines should be as flexible as possible, so that adjustments can be made more easily once the factory is set up. This again relates to the 'Design for Manufacturing'. The more focus is on the design of the factory building and production process, the better the overall efficiency of the process and quality of the products will be. This criterion will be of high importance if INDU-ZERO wants to transfer to another production technology or switch between the different production scenarios once the factory is built.

Fire safety (7%)

The criterion fire safety was considered as relevant by half of the respondents. In this case, fire safety is relating to the safety of the panel, the factory building and ultimately the house of the owners where the panel is attached to. Fire safety is one sub-aspect of quality, yet it was mentioned by the stakeholders as an individual criterion. It shows how important fire safety is. Each scenario should meet the standards for fire safety, otherwise it automatically will not be available as an option.

Maintenance cost (6%)

The maintenance costs for the retrofitting packages have been ranked low, even though it was mentioned by all stakeholders. This happened for various reasons. On the one side, the maintenance costs are difficult to foresee at the moment as there is no clarity about the cost for on-site mounting. One the other side, the maintenance costs are expected to not change drastically, no matter which production scenario is chosen.

4.3 Sub-conclusion chapter 4

Chapter 4 has answered three sub-questions. Sub-question 3.1 'What are the biggest cost elements in the calculation of the production costs' had the result that the material costs take the biggest share of all production costs with a share of 81%. The second highest costs are caused by the machinery. This covers acquisition as well as system integration costs and resulted in a share of 14%. The labor costs have a share of 4% while energy and waste costs both equal less than 1% of the total production costs.

Sub-question 3.2 'Which other factors than production costs should be taken into consideration when choosing the optimal scenario' and 3.3 'how should the different factors of the MCA be weighed in order to be able to select the optimal scenario' both were answered during interviews. Four relevant stakeholders were interviewed and the results were twelve main criteria (four different categories) with an average weight-factor attached to them (in brackets): Easy to assemble (12%), product cost (10%, production costs (9%), quality (9%) quantities (9%), environmental impact (8%), tact time (7%), lifetime product (7%), robustness (7%), flexible building factory (7%), fire safety (7%) and maintenance costs (6%). The highest score in the MCA was achieved by scenario 3 'HD-EPS only' with a total score of 390. The second scenario 'gluing' scored second best with a score of 356. Thermobonding scored 345 and the current panel performed the weakest in comparison to the other three scenarios with a total score of 335. The reasons for that and which scenario is the optimal one to choose are evaluated in chapter 5.

5. Design-phase

Definition of terms

Polystyrene beads	‘Polystyrene beads’ are the small pearls that EPS and HD-EPS are made of.
Cast in a mould	‘Cast in a mould’ describes another production scenario where the EPS or HD-EPS gets heated and poured directly into a form.

The fifth chapter answers following sub-questions:

4.1 What is the most suitable production scenario?

This chapter covers the fourth phase of the DMADV-model: Design. In sub-chapter 5.1, an evaluation of all scenarios is stated. The evaluation is based on the outcomes of the MCA done in the analyze-phase. Sub-chapter 5.2 is concerned with answering sub-question 4.1 regarding the optimal choice for the production process. A conclusion of chapter 4 is added to sub-chapter 5.3.

5.1 Evaluation optimal scenario choice

In this sub-chapter, an evaluation of each scenario based on the results from the MCA is stated.

HD-EPS only

According to the total MCA-scores, the optimal scenario to choose is ‘HD-EPS only’ with a total of 390. For three main reasons this scenario is not the best-fitting one for INDU-ZERO’s smart factory: 1. product costs are too high; 2. environmental impact (15x as much polystyrene beads); 3. not ready for implementation.

The problem with the HD-EPS scenario is that it costs significantly more money than any other scenario. Standard EPS costs around 250 euro per m3 while HD-EPS costs at least 800euro per m3. This is mainly due to the fact that HD-EPS needs fifteen times as much polystyrene beads per m3 than the standard EPS. Not only are the costs higher, but the environmental impact as well. This does not fit the mission of the INDU-ZERO project. Furthermore, the ‘HD-EPS only’ technology has not been tested for INDU-ZERO products yet. It is a very efficient option once the technology is further developed and the costs can be reduced drastically. Therefore, it is more of a theoretical option compared to all other scenarios that have been tested in practice already.

The biggest advantage of choosing for ‘HD-EPS only’ is the fact that it is easier to assemble. It does not require any outer skin or aperture lines. Furthermore, it could get ‘cast in a mould’ instead of being glued together and cut afterwards. This would lead to less waste produced by offcuts which will be good for the environment too.

It can be concluded that using HD-EPS only is a theoretical and according to the criteria chosen by the respondents the best choice but not feasible in the near future. It is not realistic to apply it as soon as the factory is built. The risk of applying an untested production technology is too high for a project that size. Once the technology is further developed and HD-EPS does not cost as much as it does now, it becomes a very serious option. For now, the risk is too high.

Gluing

The gluing scenario performed second best in the MCA with a total score of 356. One of the main reasons why scenario ‘gluing’ has scored that high is because most of the information available is available for the gluing process. The respondents knew more about this scenario than any other. Another reason for the high score is the consistent performance of the gluing scenario on all other criteria. It does not score the highest at any criterion but overall, it is performing well. Especially in the criteria with higher weights attached like easy to assemble, product cost or quality, it is always in first or second place.

The biggest disadvantages of the gluing scenario are the high environmental impact due to glue, higher production costs due to more material used and longer tact time due to curing time.

Even when considering the disadvantages, currently the gluing scenario seems to be the most realistic one. It performs better compared to the current version and is the furthest developed compared to ‘thermobonding’ or ‘HD-EPS only’ - scenario. It is the only scenario next to the current panel where the technology is tested and ready for implementation.

Thermobonding

Thermobonding performed third best out of all scenarios with a total score of 345. This is mainly because the technology is relatively new and also needs to be tested with INDU-ZERO products first. The main advantages of thermobonding compared to other scenarios are the environmental impact due to less material required (especially glue), overall cost savings, optimal insulation performance and faster processing time *(Bürkle, 2021)*.

The reason why thermobonding has not scored higher is the fact that the technology is new and has not proven itself in a mass-production. Additionally, other machines then the ones that have been developed the past few years are required. Because of this, thermobonding is not the first option to choose. On the medium- and long-term it is the second best and most feasible scenario. Especially regarding the environmental impact and further cost savings, it seems to be the logic choice to go for.

Current panel

Out of all scenarios, the current version of the panel performed worst with a total score of 335. This meets the expectations because otherwise, the project would not be necessary. The goal of the INDU-ZERO smart factory is to increase quantities of retrofitting packages produced per year, reduce prices simultaneously and lower the environmental impact of the products. This ultimately should lead to the achievement of the goals set by the Paris climate agreement. This can only happen if the new production scenarios perform better than the old ones.

The interviews have shown that the biggest advantage of the current panel is its lifetime, the robustness of the panels and when it comes to quality it performs equally to the other scenarios. The lifetime has proven itself already and the panels are thicker compared to the panels produced with other production methods. This is mainly due to the number of layers which is higher.

The disadvantages are predominating when it comes to the current panel. The environmental impact scores the lowest, the production costs and overall product cost are higher, less quantities can be produced and the tact time is slower compared to other scenarios.

Overall, the expectation was that the current panel will not score high and this has proven true. It is no option as the results are too bad and the build-up of the current panel is not fitting with the new automated production process of INDU-ZERO. It will not be feasible to achieve the climate goals mentioned in the Paris climate agreement if INDU-ZERO chooses for the current production method.

5.2 Optimal choice

The optimal choice of the production scenario therefore needs to be divided into two phases:

1. Short-term (0-5 years)
2. Medium-/Long-term (5-10 years)

Short-term

The only two realistic production scenarios on the short term are ‘gluing’ and ‘current panel’. The current panel is no production option for the smart factory, since the goal of the factory is to use less, more circular materials and replace the majority of tasks by machines instead of doing them by hand. Furthermore, the current panel has scored the lowest in the MCA with a score of 335. This is mainly due to bad performance when it comes to the criteria product costs, production cost, easy to assemble, environmental impact. This shows that the current way of producing a panel is no valid option for the production process of the INDU-ZERO smart factory.

The optimal choice on the short term is therefore to start with scenario 2: gluing EPS. The machines, production lines and materials were developed in order to glue the EPS-plates together. Apart from the current panel, this technology is the only one that has been approved already and is ready for mass-production.

Medium-/Long-term

In the long-term, there are two options for the production process of INDU-ZERO: Using HD-EPS only and thermobonding. Using HD-EPS only has actually scored the highest of all scenarios. One key reason for that is the criterion ‘easy to assemble’ which has the highest weight-factor attached to it. Even though it has the highest MCA-score, it is not an option on the short term. It may be an option on the long term (+10 years) when it is further developed and costs significantly less money. Furthermore, the risk of applying an untested production technology is too high.

The more realistic option for the medium and long term is the thermobonding scenario. Thermobonding has plenty of advantages compared to the other scenarios: optimal insulation values, greater manufacturing flexibility, shorter outsourcing times, less waste, unmixed end-product and no glue costs *(Bürkle, 2021)*. An example of a thermobonding production line is added to the appendix XII.

5.3 Sub-conclusion chapter 5

The fourth chapter ‘design-phase’ has answered sub-questions 4.1 ‘What is the most suitable production scenario?’. The evaluation of the results gathered in chapter 4 have shown that even if a production scenario is better in theory, it is not feasible to put it into practice immediately.

‘HD-EPS only’ is the scenario which scored the highest in the MCA. This is mainly because it performs well on the highest-weighted criteria ‘easy to assemble’. When looking into reality, it is not possible to apply this scenario to the production process because of significantly higher costs and environmental impact.

The two most realistic scenarios for the INDU-ZERO production process are ‘gluing’ and ’thermobonding’. Gluing is the scenario to go for on the short-term because it is the furthest developed and machinery were developed for this scenario. It has proven itself already and prototype-products have been developed. Thermobonding is the optimal choice on the medium- and long-term. It uses less material, saves costs and has a lower environmental impact. The problem is that it has not been tested for the products if INDU-ZERO and mass-production yet.

6. Verify-phase

Definition of terms

PFMEA	Short for 'Process failure mode effect analysis'. The Process-Failure-Mode-Effect analysis is an analytical tool used to evaluate the reliability of a process. Potential product defects and risks can be detected and evaluated according to their severity of impact of a failure event, their probability of occurrence and their probability of detection. Each of the criteria is attached to a score. By multiplying the scores for severity, occurrence and detection, a risk priority number (RPN) is calculated. The higher the RPN, the more urgency is demanded for immediate action. An event with a lower RPN is less risky *(Soni, 2020)*.

The sixth chapter should evaluate and answer the following sub-questions:

5.1 In reality, is it feasible to produce for half of the current average production costs?
5.2 Has the right scenario been chosen for the design of the production process?

This chapter covers the fifth phase of the DMADV-model: Verify. In sub-chapter 6.1 a step-by-step plan regarding the verification of the results of the research is stated.

6.1 Verifying results and completion project

The verify-phase exists to check the results developed in the earlier phases of the DMADV-model. In this case, the verify-phase is executed when the factory is built and first tests are running the production process.

The design can be implemented and checked by following the below mentioned steps:

1. Prove product and process suitability
2. Set up monitoring, carry out tests and piloting
3. Create process documentation
4. Submit and complete project

Prove product and process sustainability

To answer sub-question 5.1 'In reality, is it feasible to produce for half of the current average production costs?', the actual costs need to be added to the calculation sheet developed for this research. This can happen once the factory is built and the production is running. The results of this calculation need to be compared to the current average production costs. Therefore, partner companies need to share information about their current production costs. This used to be a problem in the past. Once this is achieved, both sides, INDU-ZERO as well as the collaborating companies, gain profit from sharing information with each other. INDU-ZERO can conclude if the automation of the producing retrofitting packages was a success and existing companies can learn what they can change to achieve significant cost reductions. Another thing that needs to be verified in this phase is whether or not the customer wants and needs can be met and guaranteed in the long term. All of this needs to happen keeping in mind the investment costs. If the customer wants and needs have been met can be checked by using the KANO-model. The Kano model is usually applied by product teams. Potential new features are vying for development resources and space on the roadmap. The features are weighted according to two criteria: 1. Potential to satisfy customer,2. Investment needed for implementation. A Kano-model template is added to the appendix XIII.

Set up monitoring, carry out tests and piloting

To guarantee success in the long term, a process-failure-mode-effect-analysis (PFMEA) can be applied. The PFMEA is an analytical tool used to evaluate the reliability of a process. Potential process defects and risks can be detected and evaluated according to their severity of impact of a failure event, their probability of occurrence and their probability of detection. A template for a PFMEA is added to the appendix XIV. The idea was to apply it already in the design-phase. This did not happen. The reason for that is that the lead design engineer at the University of Strathclyde remarked that “PFMEA’s a usually shared by a cross-functional team over a fairly intense block of regular meetings”. With the short period time remaining, it has been decided to not make a PFMEA at the expense of its quality. If the process is not suitable for mass production and meets the high-quality standards, the design fails. Carrying out tests is essential to make sure the process is running the way it should. Therefore, the University of Strathclyde is constantly busy with simulating the process with specific programmes for process simulation.

Create process documentation

Answering sub-question 5.2 ‘Has the right scenario been chosen for the design of the production process? can be done by starting with ‘process documentation’. Creating a reliable process documentation is essential to monitor progress. A detailed process documentation helps to keep track of a process during the execution of a project. The goal is to learn from the implementation so that the strategy can be adjusted and procedures can be improved. Creating process documentation can: eliminate flaws, reduce time spent on tasks, decrease costs, decrease resources, improve efficiency, improve overall quality, increase customer and employee satisfaction *(Lucid, 2021)*. The process documentation should be done by using a flowchart. The outcome will show if the right production scenario has been chosen and where room for improvement is.

Submit and complete project

These before mentioned steps can be followed once the INDU-ZERO smart factory is set up. The official deadline for the project is October 2021. The internal deadline for finishing the blueprint is 31st January 2022. The responsibility of the project leaders is to convince not just the EU, but most importantly the investors that the blueprint and business case have been a success. An investment needs to be profitable in the long term. Production costs and efficient production processes are an essential part of this. Once all these steps are done, it will show if the outcome of this research is feasible in practice.

7. Conclusion

By answering all sub-questions, the central question could be answered. The central question of the research was:
"In what way can the cost structure of the production process be designed in order to realize a 50% cost reduction of the production costs as compared to the current average price in the market, without compromising on quality and production speed, while avoiding high risk situations?"

The first chapter has shown that there are multiple options to choose from when thinking about the production scenarios. One key element is the second production step where a choice needs to be made in the assembly of the HD-EPS and EPS-plates. The other production steps remain the same for each scenario. Due to the project's deadline, it quickly became clear that the second production scenario 'gluing' is the only scenario where detailed information regarding the production costs is readily available. Most of the machines have been developed to fit the gluing process of HD-EPS and standard EPS. Furthermore, the first scenario 'thermobonding' as well as the second 'HD-EPS only' are either a too new technology or too expensive at the moment. Yet it was important to do research about other scenarios as well and compare them with each other, based on criteria chosen by relevant stakeholders.

The measure-phase has shown that the production costs are build up on five key cost elements: labor cost, material cost, machine acquisition and integration cost, waste and energy cost. The total cost for production is 374.262.297,36€ annually and 24.984,76€ per dwelling. The material costs are the highest cost factor of the future production costs with a share of 90%. Compared to the anticipated total average cost-price of a retrofitting package of 45.000€ the share of the total estimated production costs is 55.5%.

The analyze-phase has shown that four relevant stakeholders from the industry, knowledge institutions and the EU think twelve criteria are of high importance when comparing the production scenarios. The average weight factor is added in brackets: easy to assemble (12%), product cost (10%), quality (9%), production costs (9%), quantities (9%), the environmental impact (8%), tact time (7%), lifetime product (7%), robustness (7%), flexible building factory (7%), fire safety (7%), maintenance costs (6%). The outcome of the MCA was that scenario 3 'HD-EPS only' scored the highest with a total score MCA-score of 390. The second highest with a share of 356 was scenario 2 'gluing' and the third highest 'thermobonding' with a share of 345. The worst performing scenario was the current panel which reached a score of 335.

The design-phase has delivered a process that is ready to put into practice. The optimal scenario on the short term is gluing. On the medium- and long term, the optimal scenario is thermobonding. The main advantages are cost savings, material savings and lower environmental impact. Furthermore, the technology offers a greater manufacturing flexibility. The verify-phase delivered a step-by-step guide on how to verify the results from the define phase. It consists of four main steps: Prove product and process sustainability; set up monitoring, carry out tests and piloting; create process documentation; submit and complete project.

Coming back to the central question, it can be concluded that by answering all sub-questions, the answer on the central question was found. The cost-structure of the production process was created and is attached as an external Excel-sheet. It can be used by INDU-ZERO once the factory is built. One result of the research is that the production costs are not the only factor where cost-savings can lead to a 50% cost reduction. An important factor are the labor costs saved by automation of the factory. Further research on labor costs of other departments is required. The second part of the question was answered by evaluating different production scenarios to one another with the help of multiple criteria. The result of this is mentioned in chapter 5.

8. Recommendations

The recommendations listed below are based on the results gathered in this research. This includes all things that could not be researched and that should get more attention in the future.

Table 8.1 - Recommendations

Recommendation 1	When building the factory, use the gluing process as main production method. When thermobonding has been further developed and is ready for INDU-ZERO products and mass-production, switch to this technique in order to save material, costs and lower the environmental impact.
Recommendation 2	Always keep the two design practices 'design for manufacturing' and 'design for assembly' in mind. The interviews have shown that most of the relevant criteria belong to one of these two categories. It will be important to have a flexible factory and production process as well as products that are easy to assemble and attach to the dwellings. This should be the starting point for all designs regarding the production process. The faster the assembly of retrofitting packages is, the more money can be saved on the mounting site.
Recommendation 3	Do more precise research regarding the production costs of the roof. There is a maximum price mentioned in the production costs calculation based on the selling price of a partner. Information regarding what an archetype roof would cost if it was produced by INDU-ZERO is still missing. Significant cost savings could be made here.
Recommendation 4	Calculate the labor costs for other departments such as scanning, engineering, sales, marketing, in- and outbound logistics, warehousing or on-site mounting. All of these together have an impact on the total product cost as well. The labor costs per dwelling are expected to increase drastically when including all labor costs.
Recommendation 5	In a follow-up study, focus more on the costs caused by machinery. The acquisition- and integration costs are more precise once it is clear which machines are chosen for the production process. It then will be possible to do an in-depth research on the maintenance costs as well.
Recommendation 6	Make a follow-up study regarding the circularity of the factory and products. If prices for raw materials are further increasing, it may be more interesting to go fully circular immediately and organize the whole factory, including the products, according to the principle of circularity.

9. Implementation

The last chapter is dealing with the implementation plan. It is based on the conclusions and recommendations made earlier in chapter 7 and 8. In an implementation plan, the activities for the implementation of recommendations are worked out. The goal is to bring the solution to the problem that previously had been researched by putting it into practice. In this case, the implementation plan is placed in between the design- and verify phase.

9.1 Implementation plan

Implementation in a conceptual, multinational project like INDU-ZERO is different compared to an existing process or company. A lot of different stakeholders have influence on the project and the expertise of many parties is also influencing the project. The implementation takes place in a conceptual environment. The project leader has a central role in the implementation.

This research has focused on two main topics. On one hand, contributing to the calculation of the future production costs and developing a cost structure that can be changed and applied at any given time once the research is done. One the other hand, evaluating different production scenarios and being able to make recommendations on how to make the optimal choice.

The developing of a blueprint and business case for such a complex and innovative project takes a lot of time. This research is a contribution to the bigger picture. There is still a long way to go once this research is finished. A lot of questions need to be answered before - and after the smart factory is built. This implementation plan will sum up what needs to be done in the near future in order to ensure the outcomes of this research. The internal target date for finishing the blueprint is 31st of January 2022. This is the scope for this implementation plan as well. The implementation plan is split into three segments: 1. The conditions; 2. The approach; 3. The management plan

9.1.1 Conditions

In order to be able to take the required steps for the implementation, some conditions need to be met first:

1. Availability of expertise
   To realize such an ambitious production location and innovate the market, a lot of expertise is required. This counts especially for the production process. It is the key competitive advantage compared to the rest of the market. Keeping hiring expertise from external parties will be crucial in the future as well.
2. Availability of employees, internal and external specialists and managers
   The production of retrofitting packages is expected to require at least 181 workers in the production hall. Another additional 28 are required for other tasks regarding the production. These workers need to be hired. Considering the qualification and experience required, this will take some time and will be a big challenge before building the factory.
3. Availability of resources, materials and machines
   Once the factory is built, the availability of resources, materials and machines is crucial. If there are problems or delays within the supply chain, the whole production process falls behind. Reliable suppliers and partners need to be found before the project is finished.
4. Availability of testing locations
   The products as they are planned now, need to be produced and tested before the blueprint can be handed over to potential investors. It needs to be verified that the product functions and is ready for mass-production.

9.1.2 Approach

The activity planning below is based on the ‘vierballenmodel’ which can be translated as ‘four-ball model’ according to Marco de Witte and Jan Jonker *(Marco de Witte, 2019)*. The model includes four questions regarding the process of change. Please have a look at them below.

1) Why – Why do things need to change?
2) What – What do the current and future situations look like?
3) How – How do you structure the process of change in order to realize the desired situation?
4) Who – Who is involved in the process of change and what is their respective role?

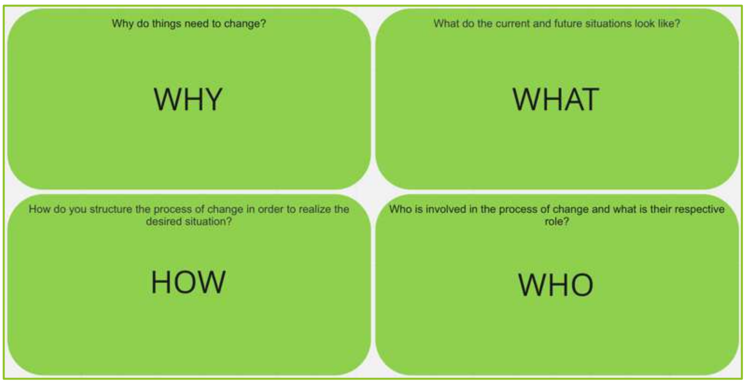


Figure 9.1 - Four-ball model

Why?

The main reasons why a change is required is because the goal of INDU-ZERO, to reduce the cost-price of a retrofitting package by 50%, can only be achieved when all processes (including the production process) are optimized to the fullest. Choosing the optimal production scenario is inevitable.

What?

The current situation covers detailed production cost calculations as well as an evaluation of the possible production scenarios. Still, there is some information missing in the calculations. This is what the implementation mainly is about: adjusting the existing data and do research to collect missing information. In the future, there should be a precise production cost calculation and the optimal production scenario should be chosen.

How?

The implementation is enclosed by the project’s deadline. This is important to mention, as the roles of stakeholders change once the factory is built. This means that the implementation needs to be done within eight months from the due date of this research. The production scenarios need to be further tested and costs need to be adjusted when more information is available. Especially information regarding the maintenance and energy cost of the machines, labor costs of other departments and production costs of the roof need to be determined.

Who?

The people mainly involved in the implementation process are the project leader, knowledge institutions such as Strathclyde University and Saxion University and different partners from the industry such as Bürkle, RC-Panels, Bureau de Haan. The project leader is the key player. She is responsible for organizing meetings, forwarding information to the different parties and keeping the project on the right track. The knowledge institutions (Strathclyde, Saxion) serve as advising and research institutions. They can set up new studies or develop process simulations. A potential follow-up study is described below. The partners from the industry are responsible for testing the process simulations in practice and share information regarding material costs or labor cost in order to make precise calculations.

A potential follow-up study could look like this:

Problem situation

The prices for raw materials were increasing drastically in 2021. Main reasons being the corona-crisis, increasing demand simultaneously to short supply or the immense glut of money causes by various central banks across the globe. At the same time, there is a trend towards circularity and creating net-zero emissions. INDU-ZERO is also trying to make its factory and products as circular and sustainable as possible.

If prices for raw materials keep increasing, it may be even more beneficial to become fully circular. Reasons are not just the potential cost savings or support by the government. There would be a positive effect on the image of INDU-ZERO's smart factory as well. It would be one more criterion for investors to invest into the INDU-ZERO smart factory.

INDU-ZERO would like to hand this task over to a student who is willing to be part of a multinational, innovative project and is interested in topics regarding circularity and sustainability. The research needs to be finished by 31st of January as is this the deadline for the blueprint of the smart factory.

Objective
Conducting a design-oriented study commissioned by the INDU-ZERO project group to show the advantages and disadvantages of becoming a fully circular smart factory. The findings should provide a detailed description of what circularity means for INDU-ZERO, what effect circularity has on the cost-price of the product and why becoming circular is beneficial on the short- and long term. At the moment, there is a desire within the project to become circular but no further research has been done regarding this topic.

9.1.3 Management plan

Below, the activities required for a successful implementation are stated including the responsible party, executor and deadline per activity. The overall deadline for all activities mentioned below is the project's deadline: 31st January 2022. The responsible person for coordinating the activities for implementation is the project leader.

Table 9.1 - Activity planning implementation

Activity	Responsible	Execution by	Deadline
Test thermobonding with INDU-ZERO products	Strathclyde University	Bürkle	31st August 2021
Calculation production costs roof	Project leader	Strathclyde University	7th October 2021
Calculate labor costs of other departments	Project leader	RC-panels	7th October 2021
Calculate remaining costs caused by machinery (focus: maintenance + energy)	Strathclyde University	Strathclyde University	7th October 2021
Do research on advantages/disadvantages of becoming fully circular	Project leader	Saxion University Student	31st January 2022
Improve production cost calculation for gluing process (verify/adjust estimations)	Project leader	Bureau De Haan RC-Panels	31st January 2022

Aftercare
After the implementation was put into practice successfully, there are further steps that need to be taken in order to keep the process up-to date. What is meant by that, is the evaluation of potential failures in the process as well as plans for improvement. The production costs should be tracked and traced at all times. Bottlenecks and other problems need to be found in order to further optimize the process and reach the goal of a 50% cost reduction of the final product. Optimization of the process also includes choosing the right production scenario. Technology and the way machines work change continuously. The factory should be designed as flexible as possible in order to be able to adapt to certain developments in the market. It will be important for the INDU-ZERO smart factory to follow certain trends in the market after the implementation is done.

Bibliography

Angermeier, D. G. (25. 05 2018). Business-case. Projektmagazin.

Ausbau + Fassade. (2021). energetische sarnierung. *Retrieved from ausbauundfassade.de: https://www.ausbauundfassade.de/energetische-sanierung*

Büdeker & Richert GbR. (2021). Arbeitsbeispiele. *Retrieved from br-dortmund.de: https://www.br-dortmund.de/wir-ueber-uns/arbeitsbeispiele*

Bürkle. (2021). Modernste Technologie: Thermobondinganlagen von BÜRKLE . *Retrieved from burkle.tech: https://www.burkle.tech/de-de/anwendungen/xps-und-eps-bearbeitung/thermobonding*

Bürkle, R. (2013, september 6). Thermobonding auf Wachstumskurs. *Retrieved april 2021, from k-online.de: https://www.k-online.de/de/News/Robert_Bürkle_Geschäftsfeld_Thermobonding_auf_Wachstumskurs*

Bachl. (2020). Thermobonding - technologie die überzeugt. *Retrieved from bachl.de: https://bachl.de/index.php/aktuelles/38-aktuelles/689-thermobonding-neue-technologie-die-ueberzeugt*

Bachl. (2021). Thermobonding - Eine Technologie die überzeugt. *Abgerufen am april 2021 von bachl.de: https://bachl.de/index.php/aktuelles/38-aktuelles/689-thermobonding-neue-technologie-die-ueberzeugt*

Barnes, D. (2001). Understanding Businesses: Processes. *London: Routledge.*

Baukom Trockenbauprofil Alu. *(5. May 2021). Von globus-baumarkt.de: https://www.globus-baumarkt.de/baukom-trockenbauprofil-alu?sPartner=Zanox&utm_source=Awin&utm_medium=Produkt&utm_campaign=Affiliate&gclid=CjwKCAjwtdeFBhBAEiwAKOIy57VFMlYMjYWMVhmSGpAaYVlb0dL7xt4sOcz1dvkV2_EuF4PHOctzNxoCS6cQAvD_BwE abgerufen*

Berenschot. (2017, 04 22). Gemiddeld salaris per beroep. *Retrieved from gemiddeld-inkomen.nl: https://www.gemiddeld-inkomen.nl/gemiddeld-salaris-per-beroep/*

Boothroyd, G. (2014). Design for assembly - The key to design for manufacturing. *Retrieved April 2021, from springer.com: https://link.springer.com/content/pdf/10.1007/BF02601481.pdf*

Bundesinstitut für Bau,- Stadt- und Raumforschung (BBSR). (september 2012). Was ist Interreg? *Von interreg.de: https://www.interreg.de/INTERREG2014/DE/Interreg/WasistINTERREG/wasistinterreg-node.html abgerufen*

Bundesministerium für Bildung und Forschung. (2017). Industrie 4.0 - Innovation für die Produktion von morgen. *Berlin: Bundesministerium für Bildung und Forschung (BMBF).*

Cambridge University Press. (2021). Cost-price. *Retrieved from dictionary.cambridge.org: https://dictionary.cambridge.org/de/worterbuch/englisch/cost-price*

Cengiz Ay. (2020). CNC-Grundlagen: Computerized Numerical Control. *Retrieved from cnc-lehrgang.de: https://www.cnc-lehrgang.de/cnc-grundlagen/*

Chen, P. J. (2016). Strategic marketing and its environment. Spokane, Washington, USA.

Connect Sealant Systems. (5. May 2021). PU 110 PU Klebstoffschaum für eps. *Von connect-systems.eu: http://www.connect-systems.eu/izdelek/pu-110-pu-klebstoffschaum-fur-eps/ abgerufen*

DAP. (2021, May 5). spray-foam-insulation. *Retrieved from dap.com: https://www.dap.com/products-projects/product-categories/spray-foam-insulation/straw-foams/barrier/*

Department for Communities and Local Government. (2009). Multi-criteria analysis: a manual. *London, Great-Britain: Crown.*

Deutsche Presse Agentur. (2021, 02 22). Experten sprechen von "Superzyklus " Darum explodieren gerade die Rohstoffpreise. *Retrieved May 2021, from rtl.de: https://www.rtl.de/cms/superzyklus-darum-explodieren-gerade-die-rohstoffpreise-4709200.html*

dk-westment. (2021, May 5). XPS-Platten / Hartschaumplatten. *Retrieved from dk-westment.de: https://www.dk-westment.de/produkte/sockel-und-perimeterdaemmung/xps-platten*

Ellen Macarthur Foundation. (2013). Towards the circular economy. *Retrieved from ellenmacarthurfoundation.org: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf*

Eriksen-Coats, F. (2021). What is Mendelow Matrix. *Retrieved from oxfordcollegeofmarketing: https://blog.oxfordcollegeofmarketing.com/2018/04/23/what-is-mendelows-matrix-and-how-is-it-useful/*

Etzkowitz, H., & Leydesdorff, L. (1995, January). The Triple Helix - -University-Industry-Government Relations: A Laboratory for Knowledge Based Economic Development. *Retrieved from researchgate.net: https://www.researchgate.net/publication/241858820_The_Triple_Helix_-_-University-Industry-Government_Relations_A_Laboratory_for_Knowledge_Based_Economic_Development*

European Regional Development Fund. (2018, June 1). Project Applications - Industrialization of house renovations towards energy-neutral (INDU-ZERO).

F.Linnemans. (2020). Verduurzamen op grote Schaal. *Retrieved from future-factory : https://future-factory.nl*

Flamme, P. D.-I. (2020). Was ist EPS? *Retrieved from mit-sicherheit-eps.de: https://mit-sicherheit-eps.de/was-ist-eps*

Gartner. (2021). Information Technology. *Retrieved from gartner.com: https://www.gartner.com/en/information-technology/glossary/system-integration*

geofoamintl. (2021, april). ASTM. *Retrieved from geofoamintl.com: https://geofoamintl.com/pdfs/ASTM-D-6817.x39190.pdf*

Guo-Ping Sheng, H.-Q. Y.-Y. (2010, November). Extracellular polymeric substances (EPS) of microbial aggregates in biological wastewater treatment systems: A review. Biotechnology Advances, 6*(28), pp. 892-894.*

Heimbaustoffe. (5. May 2021). Fassadenplatte EPS WDV Grau 032 30 mm. *Von heim.baustoffe.de: https://www.heim-baustoffe.de/Wand/Fassadendaemmung/Styropor-EPS/Fassadenplatten-EPS-Grau/WLG-032/Fassadenplatte-EPS-WDV-Grau-032-30-mm.html abgerufen*

Helge Toutenburg, P. K. (2009). Six Sigma - Methoden und Statistikfür doe Praxis *(Vol. 2). Munich, Bavaria, Germany: Springer.*

Integrierte Produktion Hannover. (2021). Fehlermöglichkeits- und -Einflussanalyse (FMEA). *Von iph-hannover.de: https://www.iph-hannover.de/de/dienstleistungen/fertigungsverfahren/fmea/ abgerufen*

Interreg North Sea Region. (2020). About the Blueprint. *Retrieved from northsearegion.eu: https://northsearegion.eu/indu-zero/about-the-blueprint/*

Jesse, H. (2021, 01 04). The Kano model: how to wow your customers. *Retrieved from dmexco.com: https://dmexco.com/stories/kano-model/*

Jos Marcus, N. v. (2015). Organisatie en Management *(Vol. 8). Groningen, Houten: Noordhoff Uitgevers.*

Klieverik. (2021). Thermobonding Verfahren. *Von klieverik.com: https://www.klieverik.com/de/thermobonding-kalander-fur-vliesstoffe/thermobonding-verfahren/ abgerufen*

Krämer, U.-B. (2018, 03 05). Project Applications. Zwolle, Overijssel, Netherlands. Retrieved from https://overijssel.sharepoint.com/sites/InduZero/Shared%20Documents/Full%20application,%20agreements%20and%20contracts/Full%20application%20and%20project%20changes/Full%20application/INDU-ZERO%20Full%20application%20after%20Major%20change%202.pdf

Leen, J., & Mertens, J. (2017). Praktijkgericht onderzoek in bedrijf. *Bussum: Coutinho.*

Lucid. (2021). what is process documentation. *Retrieved May 2021, from lucidchart.com: https://www.lucidchart.com/pages/tutorial/process-documentation*

Marco de Witte, J. J. (2019). De kunst van veranderen. *Kluwer.*

Milieu Service Nederland. (2021, April 29). Perscontainer. *Retrieved from milieuservicenederland.nl: https://www.milieuservicenederland.nl/app/uploads/2018/02/Perscontainers.pdf*

Ministerie voor Binnenlandse Zaken en Koninkrijkrelaties. (2011). Voorbeeldwoningen 2011. *Sittard: Agentschap NL.*

Miro. (2021, 25 3). dashboard. *Retrieved from miro.com: https://miro.com/app/dashboard/*

National Institute of Standards and Technology . (2021, February 8). weights and measures. *Retrieved from nist.gov: https://www.nist.gov/pml/weights-and-measures/metric-si/si-units*

Niezink, L. (2017). Kritisch zoeken, denken en evalueren: Informatievaardigheden als 21st centruy skill. *Groningen: Noordhoff.*

Perscontainerhuren. (2021, April 29). Perscontainer huren. *Retrieved from perscontainerhuren.l: http://www.perscontainerhuren.nl*

PolyStyreneLoop. (2021, may). Polystyreneloop. *Retrieved from polystyreneloop.eu: https://polystyreneloop.eu/#cir*

Polyureatec. (2008). Polyurea Beschichtung. *Retrieved from polyureatec.de: https://polyureatec.de/wiki/polyurea-beschichtung/*

Rana Majumdar, K. S. (2014, april). Six Sigma- Overview of DMAIC and DMADV. International Journal of Innovative Science and Modern Engineering (IJISME)*(2), 16-19.*

Robin Jansen, J. D. (2021). Final Project Report. *Saxion University of Applied Sciences, Enschede.*

Saxion University. (2018). blackboard. *Retrieved from OND1: https://leren.saxion.nl/webapps/portal/execute/tabs/tabAction?tab_tab_group_id=_1818_1*

Soni, A. (2020). FMEA. *Retrieved from isixsigma.com: https://www.isixsigma.com/tools-templates/fmea/fmea-quick-guide/*

s-polytec. (2021, May 5). Facadescrew unpainted. *Retrieved from s-polytec.com: https://www.s-polytec.com/facadescrew-unpainted.html*

Stamatis, D. (2003). Failure mode and effect analysis *(Vol. 2). (Q. Press, Ed.) Milwaukee: American Society for Quality.*

Sullivan, A. (2021, May 21). How To Install Hinge Pin Door Stop The Right Way. *Retrieved from tchardwaretools.com: https://tchardwaretools.com/how-to-install-hinge-pin-door-stop/*

SWR Fernsehen RP. (24. April 2020). Nisthilfen für Gebäudebrüter. *Von swrfernsehen.de: https://www.swrfernsehen.de/landesschau-rp/gutzuwissen/hilfe-fuer-gebaeudebrueter-100.html abgerufen*

Tegnis. (2019, October 16). Brochure SmartRoof 2019. *Retrieved from tegnis.nl: https://www.tegnis.nl/wp-content/uploads/2019/10/Brochure-SmartRoof-2019-okt_1.0.pdf*

Torsten Klanitz, p. m. (2021). smart factory. *Von refa.de: https://refa.de/service/refa-lexikon/smart-factory abgerufen*

Ulla-B. Krämer; Arjan de Haan. (2020, March 3). Presentation Energiesprong Berlin. *Retrieved from energiesprong.de: https://www.energiesprong.de/test/user_upload/INDU-ZERO_Presentation_Energiesprong_Berlin_05.03.2020_2.pdf*

Weber, P. D. (2020). Anschaffungskosten. *Retrieved from wirtschaftslexikon.gabler.de: https://wirtschaftslexikon.gabler.de/definition/anschaffungskosten-29431*

Wilcox, R., Forhan, T., Starkey, G., & Turner, D. (2002). Design for manufacturability: a key to semiconductor manufacturing excellence. *Retrieved from IEEE xplore: https://ieeexplore.ieee.org/document/731579*

Appendix

Appendix I: Reflection

This reflection is an important part of this research as it shows the difficulties, challenges, positive experiences and lessons learned throughout the journey. It will put some results into the right context and help to understand why certain decisions were made.

Challenges

For me personally, the semester was an even bigger challenge than expected. Never before have I worked in such an innovative, multinational and complex project. Finding my role in such an ambitious project differed a lot from what I was used to in previous internships. One essential aspect in this was the corona-crisis. After all, I had to work from home throughout the whole semester. I did not get the chance to meet any of the project's research assistants and partners in person. This made it even harder to build a relationship with them. If you add to this, the fact that the flow of information was hindered by international barriers such different time zones, communication problems and different work ethics, the weight of the challenge becomes clear. For one, I was highly dependent on information from partners such as the Strathclyde University in Scotland. It sometimes took two weeks before I received a reply, even with multiple reminders sent. Furthermore, it was hard to get the right information because lots of things that should have been done already, were not finished. One example are the costs for machinery such as acquisition costs, maintenance costs and energy cost. I had to find solutions concerning this. One solution was to make estimations in cooperation with various partners. This taught me to accept the fact that in the economy, you barely have access to all the information you need. You have to search for ways to find the best solution possible.

In addition to this, I heavily relied on information from a partner from the industry who produces the current version of the panel. The situation was that I needed detailed information regarding the cost structure of the production process. Especially labor costs, some material costs and information regarding the current panel would have been helpful. After requesting it multiple times, the information still was not shared. As I have found out towards the end of my research, this concerned others as well. The assumption is that the respective company did not want to share information due to trade secrets. This made it harder to find reliable data which caused conflicts with my time management towards the end of the semester. Yet I understand that partners from the industry are working in a full-time job by themselves and that they also do not always have access to the information I needed.

One solution for getting the right information and be able to deliver a good thesis was to show clearly to the partners that I have a deadline and need the information as soon as possible. Sending multiple reminders definitely helped in most cases.

As addressed earlier, making estimations and assumptions was a big part of this research. In a conceptual and innovative project like INDU-ZERO, it is a common method to make estimations whenever there are no reliable facts available. The lack of data and cooperation made it hard to find reliable information. The expertise from various partners who were willing to cooperate helped with solving this issue. Throughout the project I got to know who could help with the respective topics and used this experience to collect the data I needed. The assumptions were only made when the source it came from was reliable. If there was no information regarding for example a cost-element, I mentioned this clearly in the report. One example are the maintenance costs for machinery.

Another challenge during the research was to find a reliable way to collect information. As there was no working place or location where I could talk to people in person, the process of asking for information only happened online. A lot of information within the INDU-ZERO project was forwarded in individual- and group meetings. In the report, this was marked as personal communication.

Lessons learned

The number of challenges I faced were simultaneously many opportunities to learn new things. The semester has taught me a lot about working in (multinational) projects and how solutions to problems can be found where there is a lack of data. I personally think the experiences from the last couple of months were a good indication and preparation on how working in the business world works. Not everyone is willing to forward information and there are often situations where you have to find a solution by yourself.

In addition to this, I have expended my professional skillset and was able to apply the knowledge and skills I have learned throughout my study in real life. My first internship (which was part of the study) mainly covered topics regarding logistics and warehousing. The reason why I have applied for the INDU-ZERO project was because I wanted to expand my personal portfolio and work within a modern production environment. I did not have a lot of experience with making calculations and was interested in the ‘engineering’ side of my ‘Industrial engineering and management’ study. Throughout my journey in the INDU-ZERO project, I got in touch with people from various fields such as engineering, marketing, product development, management and science. They gave me the chance to improve my own professional skillset by digging deeper into various different topics. Now I have a better impression of how multinational projects and organization’s function.

Besides that, I had the chance to improve my English writing and speaking skills during this semester. In half of all meetings and interviews, people from either Scotland, Sweden, Norway, Germany, Italy or The Netherlands attended. The language used was English. Furthermore, all results and this report had to be written in English. All of this helped to improve my professional English skills.

Conclusion

In conclusion, the last semester of my study has helped me improve my professional skillset, especially regarding the production process and how it can be developed. This covers production cost calculations as well as an evaluation of different technologies and production scenarios. Furthermore, I learned how multinational projects and organizations work. I was able to participate in a European project and help to make progress on the field of blueprint- and business case development. The biggest challenge I faced during the semester was the continuous lack of information. It barely happened that data I requested was forwarded immediately or even existed at all. A lot of time went into the measure- and analyze-phase of the research. This caused conflicts in my time management and bundled a lot of work towards the end of the semester.

Overall, I am happy to have participated in the project INDU-ZERO. I had the chance to apply my skills, improve them and be a part of a project that effects a significant amount of people living in the NSR.

The reason why the INDU-ZERO project exists is affecting myself and everyone around me. Houses in the NSR region (and all over the world) need to be renovated to be energy neutral. If this does not happen, the goals set by the Paris climate agreement will not be achieved. The planet and our future are, amongst other things, dependent on an environmentally friendly renovation of the houses we live in. This is why the Paris climate agreement has been created and why INDU-ZERO is such an important project.

Appendix II: Work Packages Definition

The objective of the first work package ‘Project management’ (WP1) is to coordinate the administration and overall cooperation among partners. All partners have chosen a management structure should be as simple and efficient as possible. Therefore, the Lead Beneficiary (LB) Province Overijssel has chosen an overall project manager whose responsibility it is to manage the daily project activities and communication.

The second work package ‘Communication’ (WP2) is aiming to create a large visibility of the INDU-ZERO project. INDU-ZERO is of interest to many parties like end-users, the general public and everybody interest in the achievement of EU targets set for climate and energy. WP2 is aimed at the stakeholder’s government and the private and commercial house owners.

Work package 3 ‘Co-creative development of a smart factory blueprint’ aims to design a blueprint for a smart factory including a business case. This blueprint should be able to manufacture retrofitting packages for renovation towards energy-neutral to achieve the goals set by the EU.

The objective of the fourth work package ‘testing and piloting components of the manufacturing innovation’ (WP4) is to test the essential technology’s and elements before building the smart factory into reality. This is inevitable as it is not feasible to build the factory during the project. By doing this, the potential and strengths of key aspects are demonstrated.

The fifth work package ‘showcasing and encouraging adoption’ (WP5) focuses, compared to the second work package, on dealmakers like housing associations, investors or construction companies that are interested in building the actual smart factory. The long-term impact of INDU-ZERO depends on the market adoption. This means that investors must be willing to use the developed blueprint in order to produce high-volume automated retrofitting packages.

(Krämer, 2018)

Appendix III: Clients and competitors

At the moment, there are no direct/operating competitors to INDU-ZERO. Their approach to enter the market with an automated production factory for custom retrofitting packages is innovative. If the project succeeds, it’s likely to be implemented by others as well. Therefore, INDU-ZERO must focus on their continuous innovation in order to keep their first-mover advantage.

Nonetheless, there are competitors in the market who produce retrofitting packages currently. According to *(Chen, 2016)*, professor at the Gonzaga University in Washington, there are four main categories of competitors: budget competitors, generic competitors, product-category competitors and competitors through the shape of production.

Budget competitors are the ones who offer a product in the same price range as yours that could satisfy similar needs of your customers. A private house owner could spend his money on a new car or choose to spend it on a retrofitting package from INDU-ZERO. The challenge for INDU-ZERO is to convince the client to spend the money on their retrofitting package. There needs to be a good communication of potential advantages like saving energy costs due to an energy-neutral retrofitting package or the cheaper price tag compared to other competitors in the market.

Generic competition can fulfill the needs of customers with a slightly different product. Again, the private house owners and housing association are the main target group. They could choose to buy solar panels to save energy costs and become more CO2-friendly. The challenge for INDU-ZERO remains the same as for budget competitors: convince through pointing out advantages.

Product-category competitors offer a similar product as INDU-ZERO. One example of a competitive project is the 'Future Factory'. The ambition of this project is to create a company that produces, delivers and sells elements for large scale housings so that they can become energy neutral. The final objective is to have a production facility able to make 25.000 houses energy neutral annually. INDU-ZERO needs to compare their goals to the ones from Future Factory. These goals are stated below.

The last type competitor are the competitors through the shape of production. These are the main competitors for INDU-ZERO as they offer similar products in the same market segment such as façade and roof elements for energy neutrality. These companies are listed below as well.

1. Future Factory goals
    1) The creation of at least two production facilities within 5 years. Each factory should be able to create about 5.000 renovations per year. One of the goals aligned with this goal is to continually improve in quality and to improve the cost price.
    2) The development of a production facility that can produce about 25.000 roof and façade elements per year. In these elements there should be integrated energy systems. The goals below are aligned with this:
       -20% cost reduction of components in the fabric through smarter design, smarter engineering and to get rid of factors and margins in the supply chain.
       -20% cost reduction by upscaling by at least 5.000 per year.
       -20% cost reduction by using different methods and processes like onsite mounting for example-20% cost reduction by optimizing logistics for the building process and other streams.
    3) Improve a few market conditions in a way that customers can have an interesting product. This has to be done in a way that the product can still be financed via a understandable manner *(F.Linnemans, 2020)*.

2. Building companies who offer a similar product
    - Novition Habringsbroek
    - Plegt Vos
    - RC-panels Vroomshop
    - Webo Rijssen gevelelementen
    - Dijkstra Drijsma
    - De Groot Vroomshop
    - Prefab fabriek Culemborg
    - Emergo
    - Van Wijnen

    (Robin Jansen, 2021)

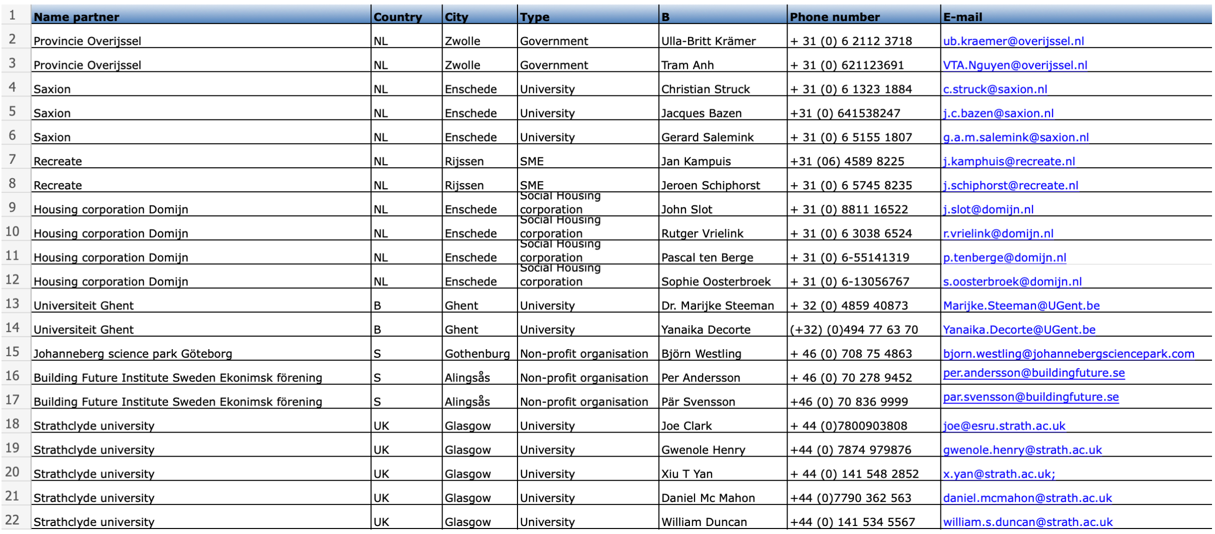
Appendix IV: Production process

Figure IV.1 - Production process

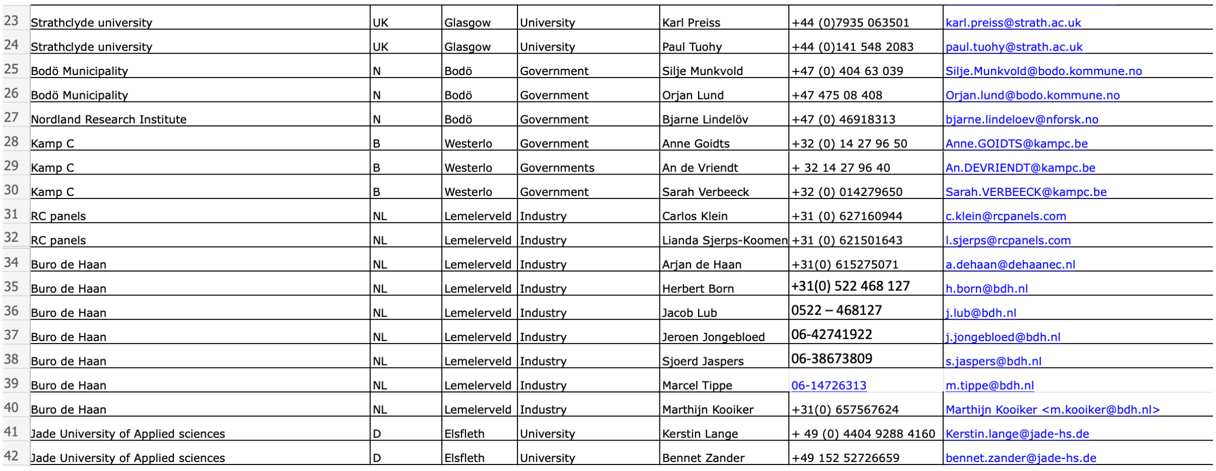
The production process starts on the left side and ends on the right. The two production lines at the top are dedicated to the production of façade elements, the bottom line is for all roof elements. The goal is to produce 525 elements per day. This equals 58 retrofitting packages each day. One average retrofitting package includes five façade and two roof elements.

Appendix V: Contact information project partners

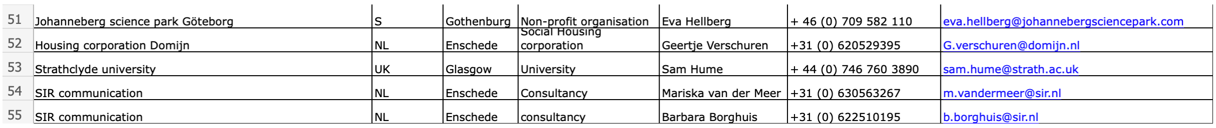
Table V.1 - Contact information project partners



1	Name partner	Country	City	Type	B	Phone number	E-mail
2	Provincie Overijssel	NL	Zwolle	Government	Ulla-Britt Krämer	+ 31 (0) 6 2112 3718	ub.kraemer@overijssel.nl
3	Provincie Overijssel	NL	Zwolle	Government	Tram Anh	+ 31 (0) 621123691	VTA.Nguyen@overijssel.nl
4	Saxion	NL	Enschede	University	Christian Struck	+ 31 (0) 6 1323 1884	c.struck@saxion.nl
5	Saxion	NL	Enschede	University	Jacques Bazen	+31 (0) 641538247	j.c.bazen@saxion.nl
6	Saxion	NL	Enschede	University	Gerard Salemink	+ 31 (0) 6 5155 1807	g.a.m.salemink@saxion.nl
7	Recreate	NL	Rijssen	SME	Jan Kampuis	+31 (06) 4589 8225	j.kamphuis@recreate.nl
8	Recreate	NL	Rijssen	SME	Jeroen Schiphorst	+ 31 (0) 6 5745 8235	j.schiphorst@recreate.nl
9	Housing corporation Domijn	NL	Enschede	Social Housing corporation	John Slot	+ 31 (0) 8811 16522	j.slot@domijn.nl
10	Housing corporation Domijn	NL	Enschede	Social Housing corporation	Rutger Vrielink	+ 31 (0) 6 3038 6524	r.vrielink@domijn.nl
11	Housing corporation Domijn	NL	Enschede	Social Housing corporation	Pascal ten Berge	+ 31 (0) 6-55141319	p.tenberge@domijn.nl
12	Housing corporation Domijn	NL	Enschede	Social Housing corporation	Sophie Oosterbroek	+ 31 (0) 6-13056767	s.oosterbroek@domijn.nl
13	Universiteit Ghent	B	Ghent	University	Dr. Marijke Steeman	+ 32 (0) 4859 40873	Marijke.Steeman@UGent.be
14	Universiteit Ghent	B	Ghent	University	Yanaika Decorte	(+32) (0)494 77 63 70	Yanaika.Decorte@UGent.be
15	Johanneberg science park Göteborg	S	Gothenburg	Non-profit organisation	Björn Westling	+ 46 (0) 708 75 4863	bjorn.westling@johannebergsciencepark.com
16	Building Future Institute Sweden Ekonimsk förening	S	Alingsås	Non-profit organisation	Per Andersson	+ 46 (0) 70 278 9452	per.andersson@buildingfuture.se
17	Building Future Institute Sweden Ekonimsk förening	S	Alingsås	Non-profit organisation	Pär Svensson	+46 (0) 70 836 9999	par.svensson@buildingfuture.se
18	Strathclyde university	UK	Glasgow	University	Joe Clark	+ 44 (0)7800903808	joe@esru.strath.ac.uk
19	Strathclyde university	UK	Glasgow	University	Gwenole Henry	+44 (0) 7874 979876	gwenole.henry@strath.ac.uk
20	Strathclyde university	UK	Glasgow	University	Xiu T Yan	+ 44 (0) 141 548 2852	x.yan@strath.ac.uk;
21	Strathclyde university	UK	Glasgow	University	Daniel Mc Mahon	+44 (0)7790 362 563	daniel.mcmahon@strath.ac.uk
22	Strathclyde university	UK	Glasgow	University	William Duncan	+44 (0) 141 534 5567	william.s.duncan@strath.ac.uk



23	Strathclyde university	UK	Glasgow	University	Karl Preiss	+44 (0)7935 063501	karl.preiss@strath.ac.uk
24	Strathclyde university	UK	Glasgow	University	Paul Tuohy	+44 (0)141 548 2083	paul.tuohy@strath.ac.uk
25	Bodö Municipality	N	Bodö	Government	Silje Munkvold	+47 (0) 404 63 039	Silje.Munkvold@bodo.kommune.no
26	Bodö Municipality	N	Bodö	Government	Orjan Lund	+47 475 08 408	Orjan.lund@bodo.kommune.no
27	Nordland Research Institute	N	Bodö	Government	Bjarne Lindelöv	+47 (0) 46918313	bjarne.lindeloev@nforsk.no
28	Kamp C	B	Westerlo	Government	Anne Goidts	+32 (0) 14 27 96 50	Anne.GOIDTS@kampc.be
29	Kamp C	B	Westerlo	Governments	An de Vriendt	+ 32 14 27 96 40	An.DEVRIENDT@kampc.be
30	Kamp C	B	Westerlo	Government	Sarah Verbeeck	+32 (0) 014279650	Sarah.VERBEECK@kampc.be
31	RC panels	NL	Lemelerveld	Industry	Carlos Klein	+31 (0) 627160944	c.klein@rcpanels.com
32	RC panels	NL	Lemelerveld	Industry	Lianda Sjerps-Koomen	+31 (0) 621501643	l.sjerps@rcpanels.com
34	Buro de Haan	NL	Lemelerveld	Industry	Arjan de Haan	+31(0) 615275071	a.dehaan@dehaanec.nl
35	Buro de Haan	NL	Lemelerveld	Industry	Herbert Born	+31(0) 522 468 127	h.born@bdh.nl
36	Buro de Haan	NL	Lemelerveld	Industry	Jacob Lub	0522 – 468127	j.lub@bdh.nl
37	Buro de Haan	NL	Lemelerveld	Industry	Jeroen Jongebloed	06-42741922	j.jongebloed@bdh.nl
38	Buro de Haan	NL	Lemelerveld	Industry	Sjoerd Jaspers	06-38673809	s.jaspers@bdh.nl
39	Buro de Haan	NL	Lemelerveld	Industry	Marcel Tippe	06-14726313	m.tippe@bdh.nl
40	Buro de Haan	NL	Lemelerveld	Industry	Marthijn Kooiker	+31(0) 657567624	Marthijn Kooiker <m.kooiker@bdh.nl>
41	Jade University of Applied sciences	D	Elsfleth	University	Kerstin Lange	+ 49 (0) 4404 9288 4160	Kerstin.lange@jade-hs.de
42	Jade University of Applied sciences	D	Elsfleth	University	Bennet Zander	+49 152 52726659	bennet.zander@jade-hs.de



51	Johanneberg science park Göteborg	S	Gothenburg	Non-profit organisation	Eva Hellberg	+ 46 (0) 709 582 110	eva.hellberg@johannebergsciencepark.com
52	Housing corporation Domijn	NL	Enschede	Social Housing corporation	Geertje Verschuren	+31 (0) 620529395	G.verschuren@domijn.nl
53	Strathclyde university	UK	Glasgow	University	Sam Hume	+ 44 (0) 746 760 3890	sam.hume@strath.ac.uk
54	SIR communication	NL	Enschede	Consultancy	Mariska van der Meer	+31 (0) 630563267	m.vandermeer@sir.nl
55	SIR communication	NL	Enschede	consultancy	Barbara Borghuis	+31 (0) 622510195	b.borghuis@sir.nl

Appendix VI: 6W-formula

Problem analysis (6W-formula)

INDU-ZERO wants to reduce the manufacturing costs of retrofitting packages by 50%. The problem is that this goal hasn't been specified yet. It is not clear for which aspects of the process the cost-reduction of 50% needs to be achieved. One important aspect in this manner is the cost-price of the products. Without the right numbers and a well-fitting cost-price calculation tool, it cannot be proven to potential dealmakers that the new manufacturing process will reduce costs enough to make a good return on investment. The goal of this research is to develop a calculation tool and calculate the cost-price of the product(s) that fits with the wants and needs of INDU-ZERO based on information collected by different partners of the project.

The cause of the research is that there is no proper calculation tool for the cost price yet. This implies that there is no current or desired cost-price calculation as well. The right numbers for this need to be collected from different project partners and based on these, a calculation tool can be developed.

The problems owner is the project group INDU-ZERO commissioned by the European Union. They are the ones who need to deliver a detailed and reliable cost-price calculation to motivate an investment for potential dealmakers.

Since the project started in 2018 and the overall objective was to reduce costs for energy-neutral retrofitting packages by 50%, the problem occurred ever since the project started. It became more urgent throughout the process and needs to be solved within the next 4 months.

It is a problem because without a detailed calculation of current average and designated costs, the business case will not be complete. The dealmakers need to be convinced that an investment in the factory is profit-making and an evolution to the current housing market. If the cost-price of the façade and roof-elements cannot be reduced drastically, there is no extra value compared to the current retrofitting packages. Furthermore, the deadline given for the INDU-ZERO project is 7th October 2021. The blueprint for the factory, including the business case and precise cost-calculations, need to be finished by then.

The problem arises in the future production process of the smart factory. The right machines and technology have just been developed and are currently in the testing phase. There is still no proper cost-price calculation for the future production process and the structure of the current average price of a retrofitting package is not known either.

Appendix VII: SMART-method

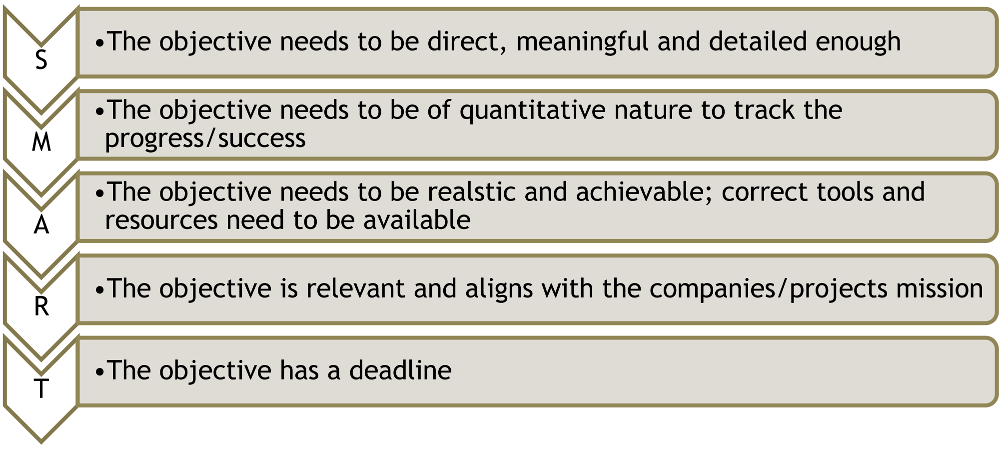


Figure VII.2 - SMART method

The SMART-method is used to formulate a research-objective as precise as possible. The five initials stand for: **S**pecific, **M**easurable, **A**chievable, **R**easonable and **T**ime-bound. The first phase 'Specific' aims for the objective to be specific which means direct, meaningful and detailed. Without a detailed objective, the research can get too complex and has too many ways to interpret it. The following phase 'Measurable' describes that the objective needs to be quantitative. Somehow it must be able to be tracked down to see any potential progress or success made. The 'Achievable' phase speaks for itself. The objective needs to be realistic enough to achieve it within a given period of time. In this case, it's the period from February 2021 to June 2021. The fourth phase 'reasonable' wants the objective to align with the, in the context of this research, projects rationale. If the objective is not relevant and for example not complex enough, it is not reasonable enough to do a research. The last phase 'Time-Bound' simply means that the project needs to have a deadline and should be achievable within a given timespan.

Appendix VIII: Table of data collection

Table VIII.2 - Table of data collection

Model-phase	*Sub-questions*	*Method data collection*	*Method data analysis*	*Result*
Define				
1.1	What do the scenarios of the INDU-ZERO production process look like?	- Literature research - Interviews, personal communication	- Flowchart(s) - Overview production scenarios	- Flowchart desired process - List of different scenarios
1.2	What are the most important aspects in the calculation of the production costs?	- Literature research - personal communication	Comparing different calculation methods/tools	Overview relevant categories & key figures
1.3	Who are the stakeholders?	- Interviews, personal communication - Literature research	Mendelow Matrix	Stakeholder matrix

Measure				
2.1	What does the production cost structure of the INDU-ZERO production process look like?	- Interviews with stakeholders and project partners - Literature research, specifically: existing data	- analyzing data based on other calculation tools and advise from experts from the business field	- Overview costs in Excel calculation tool - Overview different scenarios
Analyze				
3.1	What are the biggest cost elements in the calculation of the production costs?	Analyzing results from the measure phase		- List of biggest cost-elements - Overview of potential cost savings
3.2	Which factors other than production costs should be taken into consideration when choosing the optimal scenario?	Interviews MCA	Multi-criteria analysis	- List of most important criteria when comparing the four production scenarios - Filled in MCA
3.3	How should the different factors of the MCA be weighed in order to be able to select the optimal scenario?	Interviews	MCA	- Filled in MCA
Design				
4.1	What is the most suitable production scenario?	Results from Analyze and Measure phase are the base for choosing the right scenario	- Implementation plan - evaluation right scenario based on MCA	- Overview desired production costs calculation - choosing right scenario
Verify				
5.1	In reality, is it feasible to produce for half of the current average costs?	When factory is running, compare the calculations with what the reality looks like Customer wants and needs	- Calculation tool - KANO-model	- Improved calculation tool - Overview risks/failures in the process - Ratio of: Potential to satisfy customer,2. Investment needed for implementation

5.2	Has the right scenario been chosen for the design of the production process?	Based on the results of the MCA a scenario has been chosen but was this the right decision based on practical experience?	- PFMEA - Process documentation	- Overview risks/failures of the production process

Appendix IX: Detailed calculations

Appendix IXa: labor cost

Table IX.3 - Calculation labor cost

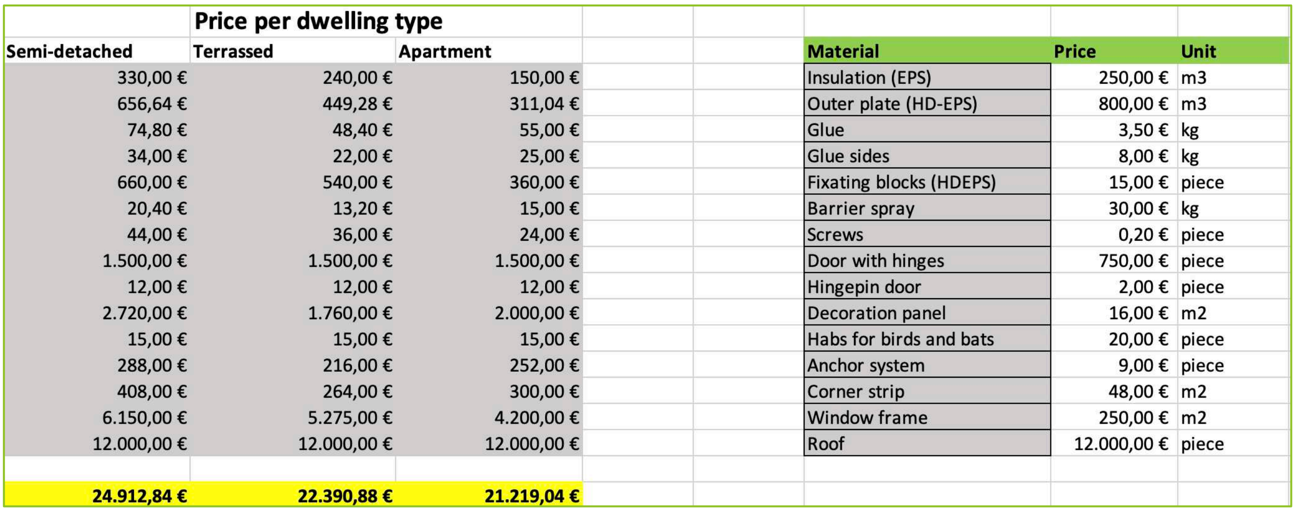
Production	Role	Number/shift	Nb of shifts	Number days worked	Sub total employee
	Machinery control operator	4	3	220	12
Roof element	Panel sizing	2	3	220	6
	Place EPS panel and HDEPS	2	3	220	6
	CNC Machining Center	2	3	220	6
	Spray polyurea	2	3	220	6
	Place lifters	1	3	220	3
	Place solar panels	1	3	220	3
	Place window	1	3	220	3
	Place conduit and cables	2	3	220	6
	Place hinges	1	3	220	3
	Assemble panel	2	3	220	6
	Quality assurance / rework	3	3	220	9
	Roof total				69
Façade element 1	Machinery control operator	4	3	220	12
	Panel sizing	2	3	220	6
	Place EPS panel and HDEPS	2	3	220	6
	CNC Machining Center	2	3	220	6
	Spray polyurea	2	3	220	6
	Place lifters	1	3	220	3
	Place corner tile, spraying plaster	1	3	220	3
	Place conduit and cables	2	3	220	6
	Place window	1	3	220	3
	Place door	1	3	220	3
Façade element 2	Machinery control operator	4	3	220	12
	Panel sizing	2	2	220	4
	Place EPS panel and HDEPS	2	2	220	4
	CNC Machining Center	2	2	220	4
	Spray polyurea	2	2	220	4
	Place lifters	1	2	220	2
	Place corner tile, spraying plaster	1	2	220	2
	Place conduit and cables	2	2	220	4
	Place window	1	2	220	2
	Place door	1	2	220	2
	Quality assurance / rework	6	3	220	18
	Facade 1 and 2 total				112

Production Management	Production Manager	1	1	220	1
	Line leader	1	1	220	1
	Manufacturing engineer	10	1	220	10
	Maintenance technician	15	1	220	15
	Process and lean manager	1	1	220	1
	Production management total				28
	Total number production workers				209
	Total production staff	181			
	Total production management	28			
	Total facade	130			
	Total roof	78			
	Average salary production staff NL	2.050,00 €			
	Average salary HQ staff NL	3.545,00 €			
	total salary costs (+30%)	2.665,00 €			
	total salary costs (+30%)	4.608,50 €			
	Salary production staff annually	5.788.380,00 €			
	Salary HQ staff annually	1.548.456,00 €			
	Total production labor costs annuall	**7.336.836,00 €**			
	Total production costs per dwelling	**489,12 €**			

Appendix IXb: material cost

Table IX.4 - Calculation material cost

		Amount per dwelling type				
	Semi-detached	**Terrassed**	**Apartment**	**Yearly demand**	**Single cost-price**	**Unit**
Insulation (EPS)	11	8	5	120000	30,00 €	piece
Outer plate (HD-EPS)	19	13	9	205000	34,56 €	piece
Glue plates	170	110	125	2025000	0,44 €	sqm
Glue sides (25% of other glue needed)	42,5	27,5	31,25	506250	0,80 €	sqm
Fixating blocks (HD-EPS)	44	36	24	520000	15,00 €	piece
Barrier spray (5% of glue)	8,5	5,5	6,25	101250	2,40 €	sqm
Screws	220	180	120	2600000	0,20 €	Piece
Door with hinges	2	2	2	30000	750,00 €	Piece
Hingepin door	6	6	6	90000	2,00 €	Piece
Decoration panel	170	110	125	2025000	16,00 €	sqm
Habs for birds and bats	1	1	1	15000	15,00 €	Piece
Anchor system	32	24	28	420000	9,00 €	Piece
Corner strip (5% of decoration)	8,5	5,5	6,25	101250	48,00 €	sqm
Window + glass standard	24,6	21,1	16,8	312500	250,00 €	sqm
Roof total (PV connectors, PV panel, G	1	1	1	15000	12.000,00 €	Piece
Total costs						
Semi detached	3000	packages				
Terraced	7500	packages				
Apartment	4500	packages				
Average material costs annually	338.155.800,00 €					
Average price per dwelling	22.543,72 €					



	Price per dwelling type				
Semi-detached	**Terrassed**	**Apartment**	**Material**	**Price**	**Unit**
330,00 €	240,00 €	150,00 €	Insulation (EPS)	250,00 €	m3
656,64 €	449,28 €	311,04 €	Outer plate (HD-EPS)	800,00 €	m3
74,80 €	48,40 €	55,00 €	Glue	3,50 €	kg
34,00 €	22,00 €	25,00 €	Glue sides	8,00 €	kg
660,00 €	540,00 €	360,00 €	Fixating blocks (HDEPS)	15,00 €	piece
20,40 €	13,20 €	15,00 €	Barrier spray	30,00 €	kg
44,00 €	36,00 €	24,00 €	Screws	0,20 €	piece
1.500,00 €	1.500,00 €	1.500,00 €	Door with hinges	750,00 €	piece
12,00 €	12,00 €	12,00 €	Hingepin door	2,00 €	piece
2.720,00 €	1.760,00 €	2.000,00 €	Decoration panel	16,00 €	m2
15,00 €	15,00 €	15,00 €	Habs for birds and bats	20,00 €	piece
288,00 €	216,00 €	252,00 €	Anchor system	9,00 €	piece
408,00 €	264,00 €	300,00 €	Corner strip	48,00 €	m2
6.150,00 €	5.275,00 €	4.200,00 €	Window frame	250,00 €	m2
12.000,00 €	12.000,00 €	12.000,00 €	Roof	12.000,00 €	piece
24.912,84 €	**22.390,88 €**	**21.219,04 €**			

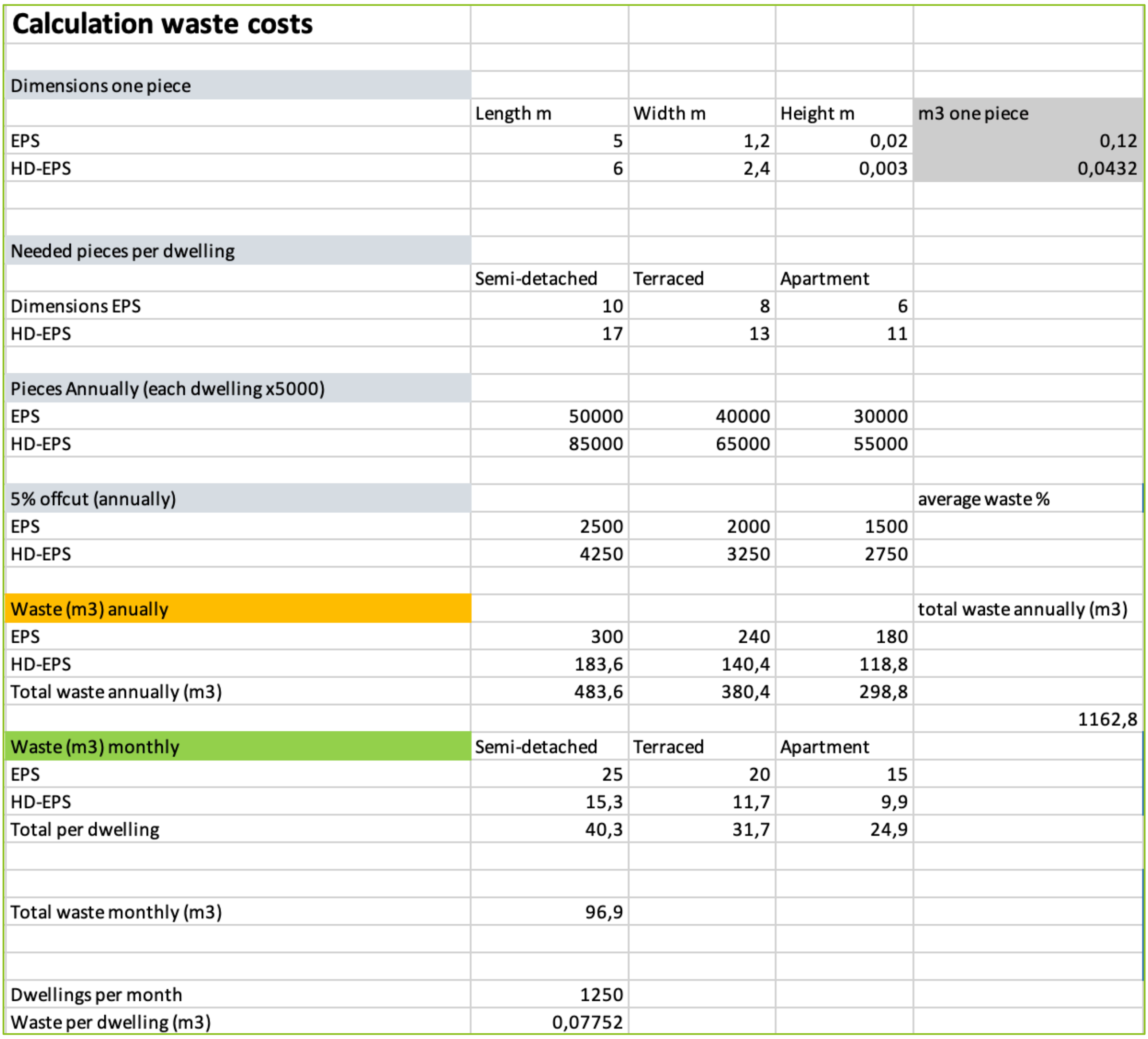
Appendix IXc: energy cost

Table IX.5 - Calculation energy cost

Electricity	133.000,00 €	Monthly
Water	20.200,00 €	Monthly
Gas	17.300,00 €	Monthly
Total monthly	170.500,00 €	
Total annually	2.046.000,00 €	
Per dwelling	136,40 €	

Appendix IXd: waste cost

Table IX.6 - Calculation waste cost



Calculation waste costs				
Dimensions one piece				
	Length m	Width m	Height m	m3 one piece
EPS	5	1,2	0,02	0,12
HD-EPS	6	2,4	0,003	0,0432
Needed pieces per dwelling				
	Semi-detached	Terraced	Apartment	
Dimensions EPS	10	8	6	
HD-EPS	17	13	11	
Pieces Annually (each dwelling x5000)				
EPS	50000	40000	30000	
HD-EPS	85000	65000	55000	
5% offcut (annually)				average waste %
EPS	2500	2000	1500	
HD-EPS	4250	3250	2750	
Waste (m3) anually				total waste annually (m3)
EPS	300	240	180	
HD-EPS	183,6	140,4	118,8	
Total waste annually (m3)	483,6	380,4	298,8	
				1162,8
Waste (m3) monthly	Semi-detached	Terraced	Apartment	
EPS	25	20	15	
HD-EPS	15,3	11,7	9,9	
Total per dwelling	40,3	31,7	24,9	
Total waste monthly (m3)	96,9			
Dwellings per month	1250			
Waste per dwelling (m3)	0,07752			

Price per m3 EPS	250,00 €			
Price per m3 HD-EPS	800,00 €			
	Semi-detached	Terraced	Apartment	
Material costs of waste monthly (Euro)	18.490,00 €	14.360,00 €	11.670,00 €	
Total waste costs (material + collection) monthly	46.287,96 €			
Total waste costs (material + collection) per dwelling	37,03 €			

25	Capaciteit m3 per perscontainer	
150	Transportkosten € 150 per lediging.	
175	Bedrijfsafval € 175,- per ton (1000 kg)	
375	Huur per maand € 375,-	
Total waste monthly	4,5312	Tons
Number of full container loads	4	
Variable costs waste collection	1.392,96 €	
Fixed costs waste collection	375,00 €	
Total costs waste collection	1.767,96 €	
Total waste collection costs per dwelling	1,41 €	

Appendix IXe: machinery cost

Table IX.7 - Calculation machinery cost

	Unit	Cost	Model	Company	Integration costs
Small AGV	24	£50.000			
AGV Control and integration					£2.000.000
Electric line conveyor	9	£ 2.000,00			
Large overhead storage management robot/EPS panel feeding robot	6				£ 1.500.000,00
Vertical wire cutting machine	6	£118.620,00	VPW 36-55	Edge sweet	
Automated press system	3	£500.000,00			£ 1.000.000,00
Electric line conveyor	9	£ 2.000,00			
CNC milling	6	£350.000,00	4008 Infinite	AXYZ	
Electric line conveyor	9	£ 2.000,00			
Electric line conveyor	3	£ 2.000,00			
Small overhead storage management robot/EPS panel feeding robot	3				£ 500.000,00
Overhead robot pick & place system for cut EPS panels	3				£ 2.000.000,00
Material transfer platens	90	£ 1.000,00			
Panel Assembly robot	3	£ 38.000,00	IRB 4600-40	ABB	
Barrier Spray robot	6	£ 40.000,00	IRB 5500	ABB	
Fiberglass Spray robot	6	£ 40.000,00	IRB 5500	ABB	
Paternoster buffer 8.5m 20 part capacity	2				£1.000.000
Paternoster buffer 12m 20 part capacity	1				£1.500.000
Barrier Spraying station	6				£ 500.000,00
Fiberglass spraying station	6				£ 1.000.000,00
Paternoster buffer 8.5m 20 part capacity	2				£1.000.000
Paternoster buffer 12m 20 part capacity	1				£1.500.000
Three return loops for plattens	3				£ 1.000.000,00
Cross-tracking roller beds	2	£ 40.000,00			
Overhead transfer to roof assy line	1				£2.500.000,00
Barrier Spray robot	6	£ 40.000,00	IRB 5500	ABB	
Barrier Spraying station	2				£ 500.000,00
Cross-tracking roller beds	1	£ 40.000,00			
Solar panel assembly robot	2	£ 38.000,00	IRB 4600-40	ABB	
Solar panel assembly station	2				£ 500.000,00
Window assembly robot	2	£ 38.000,00	IRB 4600-40	ABB	

Window assembly station	2				£ 500.000,00
Hinge assembly robot	2	£ 38.000,00	IRB 4600-40	ABB	
Hinge assembly station	2				£ 500.000,00
Roof elements connecting station	1				£ 500.000,00
Cross-tracking roller beds	1	£ 40.000,00			
Stone strip placement robot	27	£ 25.000,00	IRB 360	ABB	
Stone strip placement station	7				£ 500.000,00
Cross-tracking roller beds	6	£ 40.000,00			
Butterfly table small	2	£ 17.500,00	BS20 table 6m	Randek	
Butterfly table medium	4	£ 23.000,00	BS20 table 9m	Randek	
Butterfly table long	2	£ 29.000,00	BS20 table 12m	Randek	
Corner tile pacement robot	3	£ 38.000,00	IRB 4600-40	ABB	
Corner tile pacement station	3				£ 500.000,00
Heating and conduit placement robot	2	£ 38.000,00	IRB 4600-40	ABB	
Heating and conduit placement station	2				£ 500.000,00
Window assembly robot	3	£ 38.000,00	IRB 4600-40	ABB	
Window assembly station	3				£ 500.000,00
Door assembly robot	1	£ 38.000,00	IRB 4600-40	ABB	
Door assembly station	1				£ 500.000,00
Quality check station	4				£ 500.000,00
Storage for curing	6				£ 2.000.000,00
Long AGV	18	150000			
Storage outside the factory					
			sub total		£ 77.325.720,00
			Sub-total in euro (acquisition cost)		88.924.578,00 €
			Factor 1.15		
			Depreciation per year		8.892.457,80 €
			Cost's per dwelling		592,83 €
			Integration costs		177.849.156,00 €
			Depreciation per year		17.784.915,60 €
			Costs per dwelling		1.185,66 €
			Total costs acquisition + integration		
			Per dwelling		1.778,49 €

Appendix X: Extended version interviews

Summary interview 1

Date of interview	5th May 2021
Place	***Microsoft Teams; Gronau (DE), Zwolle (NL)***
Duration	00:51:05 min
Language	German

The interview started with a short introduction including the cause of the interview and general questions regarding the privacy and anonymity of the respondent. The interviewer assured himself that the respondent verified the recording of the interview.

The interview then continued with an explanation of the context of the interview. The data used in the interview is going to be used to fill in an MCA and to be able to compare the different scenarios to each other.

The first question asked was ‘How would you describe your own role in the project?’. The answer was project leader.

The second question of the interview was ‘are you familiar with the different production scenarios?’. The respondent said she was familiar with all scenarios and added one more option for the scenarios. This option includes a ‘cast in the mould’ method where the EPS is not glued or thermobonded but poured directly into a form. Due to communication problems between a partner and the project leader, there is no further information available at the moment where the interview is done. The project leader and interviewer agreed that this scenario should be addressed in the report shortly. Regarding the thermobonding scenario the respondent added that based on information from a partner company, thermobonding is less expensive compared to the gluing process.

The interview continued with the question ‘which other factors than production costs should be taken into consideration when choosing the optimal scenario?’. The respondent considered the following criteria as relevant: production costs, maintenance cost, tact time, quantity, strengths of the products, product costs, environmental impact, lifetime product, quality, flexible building factory, easy to assemble, fire safety. In total, there were 12 criteria mentioned.

The supplementary question then was ‘could you explain why you think these criteria are relevant?’. Tact time was considered relevant because this is expected to differ when for example thermobonding is used instead of gluing. Glue needs curing time which the thermobonded EPS-Panel does not require. With strengths of the product, the respondent wanted to point out the overall robustness of the panel. This may vary within the different scenarios as the layer thickness differs per scenario. This also counts for the criterion quantity. The number of panels produced per day/year may vary when choosing thermobonding as it leads to less time required for curing of the panel.

The product- and production costs are considered relevant because they are part of the project rationale. The goal of INDU-ZERO is to produce retrofitting packages for half of the current market price. The costs produced by each production scenario are relevant for the final cost calculation.

When thinking about the environmental impact, the responded meant the circularity of the product. The future INDU-ZERO panel should score better compared to current panels in the market.

After all criteria have been determined, the question regarding the weight-factor per criteria was asked: ‘How should the different factors of the MCA be weighed in order to be able to select the optimal scenario?’. Out of the twelve criteria, tact time, quality and quantity were rated the highest (12%). The strengths of the product, fire safety and easy to assemble were weighted with 10% each. The overall product cost and the production costs were weighted 8% each. The environmental impact received a weight-factor of 6%, lifetime product 5%, maintenance cost 4% and the lowest score was given to flexible building factory.

In the end, the interviewer summed up all criteria including attached weight-factors and let it verify by the respondent. The respondent then got asked if there are any criteria left but this was not the case.

Ultimately, the respondent got informed that he will receive the final MCA including all criteria and weight factors mentioned by all participating stakeholders. He got informed that his responsibility then is to classify each criterion for each scenario so that in the end, a total MCA-score per scenario can be calculated.

Summary interview 2

Date of interview	7th May 2021
Place	*Microsoft Teams; Gronau (DE), Zwolle (NL)*
Duration	01:02:56 min
Language	English

The interview started with a short introduction including the cause of the interview and general questions regarding the privacy and anonymity of the respondent. The interviewer assured himself that the respondent verified the recording of the interview.

The interview then continued with an explanation of the context of the interview. The data used in the interview is going to be used to fill in an MCA and to be able to compare the different scenarios to each other.

The first question asked was ‘How would you describe your own role in the project?’. The answer was research assistant that is also busy on the field of digital manufacturing.

The second question of the interview was ‘are you familiar with the different production scenarios?’. The stakeholder mentioned that he is just partly familiar with the four production scenarios thermobonding, gluing, HD-EPS only and current RC-Panel. Therefore, the interviewer explained them to him shortly. The interviewed then stated to have understood the essentials of each scenarios and that he now feels confident to answer the questions.

The interview continued with the question ‘which other factors than production costs should be taken into consideration when choosing the optimal scenario?’. To not miss any criteria mentioned by other stakeholders, the results from the first interview were shown to the interviewed. He then verified the ones that already had been mentioned but added new ones as well. The new criteria were quality, fire safety (production area + panel + homes), robust components (easily to assembly and repair), Design for manufacturing, Design for assembly, simple to build (panel), simple production processes, flexible factory building.

The stakeholder then got asked to give more insights in the meaning of each criteria. By fire safety he means the safety of the product as well as the production area and the fire safety of the homes where the final products are attached to. With robust components he meant that the panel should be easy to assemble and repair for each scenario. For design for manufacturing and assembly he chose because the entire quality of the product is depending on a well-designed production process. The design of the product should be made for manufacturing and easy assembly. He also pointed out that design for manufacturing and assembly are probably the main criteria in all those he mentioned.

With simple to build he meant that the panel itself should be easy to build, no matter which scenario is chosen. This also relates to a simple production process as well as a flexible factory building in case of adjustments that need to be done once the factory is running.

After mentioning all criteria, the idea of the stakeholder was to categorize all criteria mentioned. This resulted in the following categories for the criteria:

1. Design for manufacturing: tact time, quantity, robust components, quality, fire safety, flexible factory building
2. Design for assembly: simple to build, simple production processes
3. Costs: production costs, product costs
4. After sales: maintenance, lifetime product, environmental impact

After categorizing all the different criteria, the question regarding the weighting of each criteria was asked. The interviewed pointed out that some criteria will share the same weight-factor.

Fire safety got the weight-factor 16%. The respondent said it was the most important criterion as it counts for the product, factory building and houses where the products are attached to. The second most important criterion was quality (15%), followed by the overall product cost (13%). The 'easy to assemble' criterion also got a high weight-factor of 11%. This is followed by the criterion 'flexible building factory' (10%) and quantity (9%). The lower scores were given to the criteria robust components (8%), lifetime product (6%), production cost (5%), environmental impact (4%) and maintenance costs (3%). The only criterion considered not relevant by the respondent was the tact time (0%).

In the end, the interviewer summed up all criteria including attached weight-factors and let it verify by the respondent. The respondent then got asked if there are any criteria left but this was not the case.

Ultimately, the respondent got informed that he will receive the final MCA including all criteria and weight factors mentioned by all participating stakeholders. He got informed that his responsibility then is to classify each criterion for each scenario so that in the end, a total MCA-score per scenario can be calculated.

Summary interview 3

Date of interview	12th May 2021
Place	*Microsoft Teams; Gronau (DE), Staphorst (NL)*
Duration	00:43:35 min
Language	Dutch

The interview started with a short introduction including the cause of the interview and general questions regarding the privacy and anonymity of the respondent. The interviewer assured himself that the respondent verified the recording of the interview.

The interview then continued with an explanation of the context of the interview. The data used in the interview is going to be used to fill in an MCA and to be able to compare the different scenarios to each other.
The respondent described his own role in the project as product developer from an external company who

helps the INDU-ZERO project group to work on product designs and the finishing of the blueprint. He joined the project around one year ago.

Questions two regarding the familiarity with the four scenarios has been answered with yes. The only comment made was that he is familiar with all scenarios, just not too much into detail. From the current RC-Panel for example he only knows the composition of materials, not the exact production process behind it.
The respondent then continued with answering the third question ‘which other factors than production costs should be taken into consideration when choosing the optimal scenario?’. He started listing the following criteria:

1. Safety for employees and users
2. Fire safety
3. Robustness of components
4. Safe production process
5. Circularity
6. Acceptable for environment
7. Design to logistics

After mentioning these criteria, the interviewed asked if the respondent wanted to see which criteria were mentioned by other respondents. He confirmed this proposal. After verifying the majority of criteria mentioned by other stakeholders, he started differentiated some of the criteria such as fire safety, quality, tact time and quantity and interpreted them differently. For the respondent, the fire safety is a requirement and not a criterion that may or may not me left out of the MCA. When fire-safety class B is not achieved by the products, the products cannot be sold. He therefore rated the fire safety with 0%. The same happened with the criterion ‘quality’. The quality of the product is a requirement, not a wish.

Tact time and quantity were, according to the respondent, the same. If the tact time of around 2 minutes per element is not achieved, the quantities per day/year are not achieved either. He rated both of them together with 12% (each criterion 6%). The interviewer then explained to the respondent that in an earlier interview, four categories were determined to categorize the criteria: costs, design for manufacturing, design for assembly, after sales. The respondent said that the new added ‘safety for employees and users’ can be added to design for manufacturing. Design to logistics is a category by its own.

The interview then continued with giving weight factors for the criteria left. He rated the environmental impact as most important with a share of 15%. The reason for that is that according to the respondent, the factory cannot be built if the environmental impact (Co2-emission) of the factory is much higher than the problem it is solving. If the environmental impact of not building the factory at all is lower than building it, the factory shouldn’t be built. Production costs and product costs were rated with 12% each because this is part of the goal of INDU-ZERO: producing 15.000 retrofitting packages a year for half of the current price. Easy to assemble (DFA) got weighted with 12% as well.

Maintenance costs once the product is finished got weighted with 9%. The lifetime of the product got weighted 8%. The robustness of components got also weighted 0% because there are different requirements regarding the strengths of the product that need to be fulfilled. It again is a requirement, not a wish. The flexibility of the building factory got weighted 5%, safety of employee and user 8% and design to logistics 7%.

The interview ended with showing the responded an example of the MCA-template so that he knows what to expect once all interviews are done. He got informed that his responsibility then is to classify each criterion for each scenario so that in the end, a total MCA-score per scenario can be calculated.

Summary interview 4

Date of interview	13th May 2021
Place	*Microsoft Teams; Gronau (DE), Glasgow (SCO)*
Duration	00:23:20 min
Language	English

The interview started with a short introduction including the cause of the interview and general questions regarding the privacy and anonymity of the respondent. The interviewer assured himself that the respondent verified the recording of the interview.

The interview then continued with an explanation of the context of the interview. The data used in the interview is going to be used to fill in an MCA and to be able to compare the different scenarios to each other.

The respondent described his own role as research assistant and that he is mainly working within the project as a manufacturing simulation engineer. He is responsible for production process modelling and the factory layout. The second question 'are you familiar with the four production scenarios' was answered with yes. For answering the third question regarding the criteria needed for a MCA, the respondent thought it was a good idea to look at what already has been mentioned by other stakeholders and maybe add some more criteria.

The respondent did not add any new criteria. The next question 'how should the different factors of the MCA be weighted in order to be able to elect the right scenario' got answered with the following weight factors:
Production costs got weighted 10%, tact time including machine set up time got also weighted 10% and the overall quality of the product also got weighted 10%. The responded also mentioned that the maintenance costs are quite important to him which is why they were weighted 9%. The same counts for the lifetime of the products (9%) because it is closely related to the lifetime of the product. The quantity got weighted 7% because of the space and storage needs to be designed based on the quantities produced each day. The environmental impact got weighted with 8% because it is an important aspect in the production (waste), but it is more of a long-term criterion. The robustness and strengths got weighted 8% as well.

The product cost got weighted 7% because the majority of costs, according to the respondent, is produced by the installation of the products and not in the production. The factor building should be flexible according to the respondent which is why it got weighted 9%. Easy to assemble is the most important criteria for the respondent because he thinks that a product that is easy to assemble will lead to advantages on the on-site mounting and transportation as well. Fire safety, safety for employees and design to logistics got weighted 0% due to the same reasons as mentioned by the respondent in interview 3. There are standards that need to be reached and without these standards, the products cannot be sold to anyone.

The interview ended with showing the responded an example of the MCA-template so that he knows what to expect once all interviews are done. He got informed that his responsibility then is to classify each criterion for each scenario so that in the end, a total MCA-score per scenario can be calculated.

Appendix XI: Filled in MCA-templates

Respondent 1

Table XI.8 - MCA scores 1

Criteria	**Weighting factor**	**Scenario 1 - Thermobonding**	**Scenario 2 – Gluing**	**Scenario 3 – HD-EPS only**	**Scenario 4 – Current RC-Panel**
Easy to assemble (DFA)	12	60	60	60	36
Product cost	10	40	30	40	20
Production costs	9	45	36	45	18
Quality	9	45	45	45	45
Quantities	9	45	45	45	27
Environmental impact	8	32	24	32	16
Tact time	7	35	28	35	14
Lifetime product	7	35	35	35	35
Robustness / strength	7	35	35	35	35
Flexible factory building	7	28	28	35	21
Fire safety	7	21	21	21	14
Maintenance costs	6	24	18	30	12
Total score MCA		445	405	458	293

Respondent 2

Table XI.9 - MCA-scores 2

Criteria	**Weighting factor**	**Scenario 1 - Thermobonding**	**Scenario 2 – Gluing**	**Scenario 3 – HD-EPS only**	**Scenario 4 – Current RC-Panel**
Easy to assemble (DFA)	12	24	36	60	24
Product cost	10	40	30	10	30
Production costs	9	36	36	45	27
Quality	9	27	36	45	45
Quantities	9	18	36	27	18
Environmental impact	8	32	24	16	24
Tact time	7	28	28	35	14

Lifetime product	7	21	21	35	21
Robustness / strength	7	21	28	35	28
Flexible factory building	7	21	21	35	21
Fire safety	7	21	21	21	28
Maintenance costs	6	18	18	18	24
Total score MCA		307	335	382	304

Comment:

HD EPS Has the advantage of being very easy to assemble as it does not need any outer skin or aperture liners. Just scores low for product cost and environmental impact due to the fifteen times as much raw polystyrene beads that it is produced from. We would probably be able to build the facades to a “close to net shape” and be able to assemble them with the aperture holes already present. This is because the sandwich panels need to be fully skinned and cured as whole panels. All that would be needed would be a CNC machining skim all round to get the final sizes and some milling of holes and other features. It would be a balance and judgement call between material cost vs process cost savings vs environmental impact.

Respondent 3

Table XI.10 - MCA-scores 3

Criteria	**Weighting factor**	**Scenario 1 - Thermobonding**	**Scenario 2 – Gluing**	**Scenario 3 – HD-EPS only**	**Scenario 4 – Current RC-Panel**
Easy to assemble (DFA)	12	48	48	48	36
Product cost	10	30	30	10	40
Production costs	9	27	27	45	36
Quality	9	36	36	36	36
Quantities	9	36	36	36	36
Environmental impact	8	32	16	32	8
Tact time	7	28	21	35	7
Lifetime product	7	21	28	28	14
Robustness / strength	7	21	21	28	35
Flexible factory building	7	35	21	21	35
Fire safety	7	14	14	14	21
Maintenance costs	6	24	24	24	18
Total score MCA		352	322	357	322

Comment: Current panel scores 5 for flexible factory because a lot of work is done by hand

Respondent 4

Table XI.11 - MCA-scores 4

Criteria	**Weighting factor**	**Scenario 1 - Thermobonding**	**Scenario 2 – Gluing**	**Scenario 3 – HD-EPS only**	**Scenario 4 – Current RC-Panel**
Easy to assemble (DFA)	12	24	48	48	48
Product cost	10	40	40	10	2
Production costs	9	18	36	36	45
Quality	9	27	36	36	45
Quantities	9	36	36	36	36
Environmental impact	8	40	24	40	16
Tact time	7	28	28	28	28
Lifetime product	7	14	28	28	35
Robustness / strength	7	14	28	28	35
Flexible factory building	7	14	21	35	28
Fire safety	7	14	14	14	35
Maintenance costs	6	6	24	24	30
Total score MCA		275	363	363	383

Appendix XII: Thermobonding production line (example)

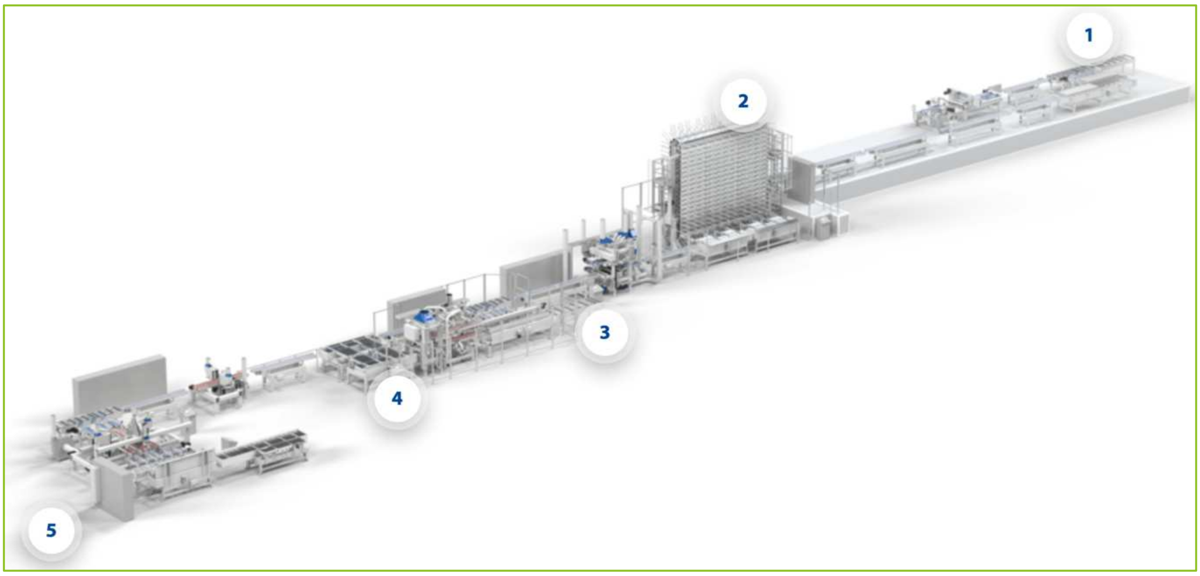


Figure XII.3 - Full thermobonding production line

1) Pre-trimming and flying knife: The endless XPS is pre-trimmed in width by up to 200mm. It gets cut exactly to size by the flying knife on up to 14m length plates per minute.

2) Cooling and handling by paternoster: A paternoster is used not only for cooling but also intelligently compensating for height differences. At full production capacity, 64 long plates can be cooled and traded at the same time in 32 compartments.

3) Surface treatment with thermobonding in the bypass: After overcoming the differences in hall height, the plates can be milled either on both sides or only the top for two-layer welding at this station.

4) Surface treatment with subsequent thermal bonding: In the event that welding is to be carried out, the plates are guided laterally through the thermobonding according to the planner. The two-layer panels are fed back into the extrusion line via the self-assured angle transfer. As an additional option, the plates can also be welded offline, while the extrusion of monolayer plates can continue undisturbed.

5) Finishing of the longitudinal and transverse edges: The panels, which are up to 400mm thick, are finished at the last station. On request, the saw systems can be halved to short panels. After the bundle stacking station, the bundles are transferred to the downstream packaging system *(Bürkle, 2021)*.

Appendix XIII: KANO-model template

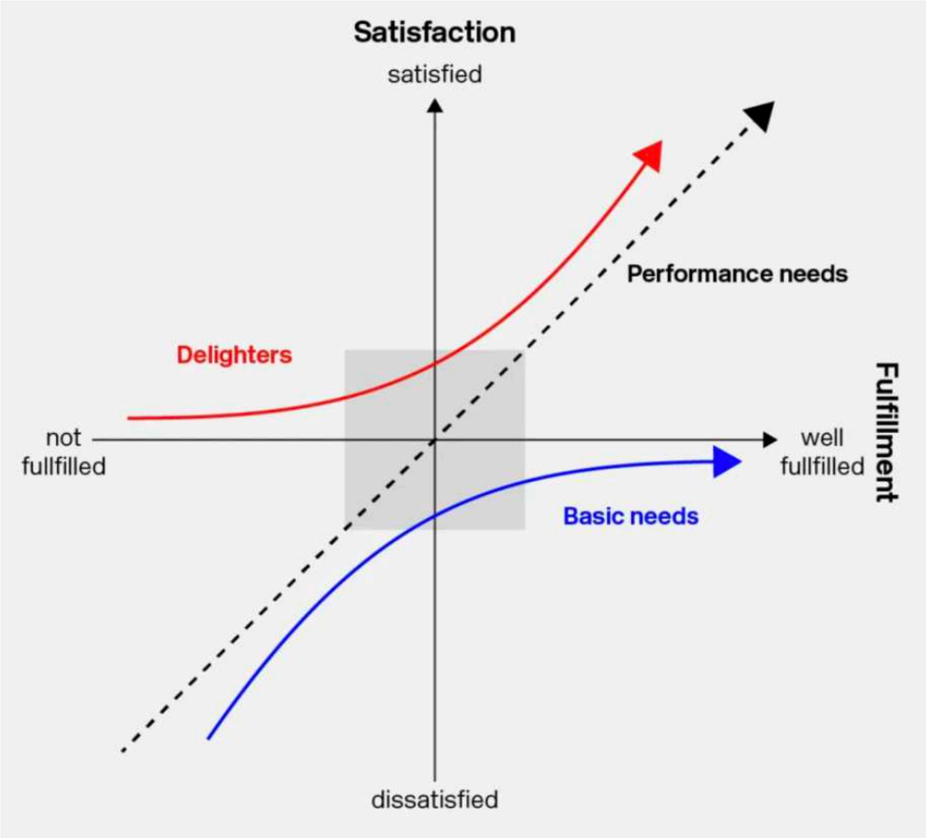


Figure XIII.4 - Kano-model template (Jesse, 2021)

Appendix XIV: PFMEA

The Process-Failure-Mode-Effect analysis is an analytical tool used to evaluate the reliability of a process. Potential product defects and risks can be detected and evaluated according to their severity of impact of a failure event, their probability of occurrence and their probability of detection. Each of the criteria is attached to a score. By multiplying the scores for severity, occurrence and detection, a risk priority number

(RPN) is calculated. The higher the RPN, the more urgency is demanded for immediate action. An event with a lower RPN is less risky.

The PFMEA should be structured according to the steps of the future production process of INDU-ZERO.

Table XIV.12 - Template PFMEA

Process step	*Potential failure mode*	*Potential failure effect*	*SEV(*)*	*Potential causes*	*OCC (**)*	*Current processes controls*	*DET (***)*	*RPN (****)*	*Action recommended*
Cutting panels and sheets									
CNC cutting chapes and holes									
Assemble EPS panels									
Place reinforcement									
Barrier spray									
Tiles laying									
Corner tiles and plaster									
Fixing mounting rails and hooks									
Window and door mounting									

* **Severity**: severity of impact of failure event. It is scored on a scale of 1 to 10. A high score is assigned to high-score events while a low score is assigned to low-score events.

** **Occurrence**: Frequency of occurrence of failure event. It is scored on a scale of 1 to 10. A high score is assigned to high-score events while a low score is assigned to low-score events.

*** **Detection**: Ability of process control to detect the occurrence of failure events. It is scored on a scale of 1 to 10. A high score is assigned to high-score events while a low score is assigned to low-score events.

**** **Risk priority number**: the overall risk score of an event. It is calculated by multiplying the scores for severity, occurrence and detection. An event with a high RPN demands immediate attention while events with lower RPN's are less risky. *(Soni, 2020)*

Appendix XV: Example of materials

EPS

Figure XV.5 - EPS example (Heimbaustoffe, 2021)

HD-EPS

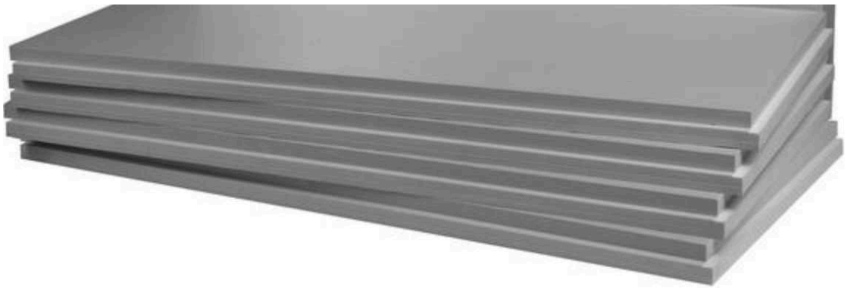


Figure XV.6- HD-EPS example (dk-westment, 2021)

Glue

Figure XV.7 - PU glue example (Connect Sealant Systems, 2021)

Fixating blocks

The fixating blocks are blocks made of HD-EPS and are applied around the anchor system.

Barrier spray

Figure XV.8 - Barrier spray example (DAP, 2021)

Screws

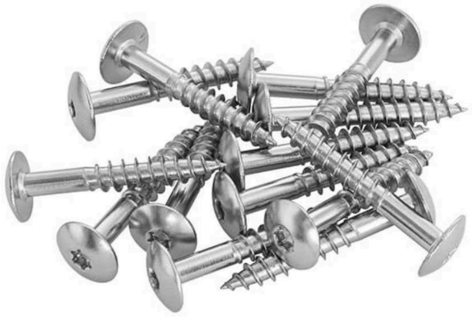


Figure XV.9 - Screws example (s-polytec, 2021)

Door with hinges

Figure XV.10 - Door example (Büdeker & Richert GbR, 2021)

Hingepin door

Figure XV.11 - Hingepin door example (Sullivan, 2021)

Decoration panel

Figure XV.12 - Stonestrips example (Ulla-B. Krämer; Arjan de Haan, 2020)

Habs for birds and bats

Figure XV.13 - Habs for birds and bats example (SWR Fernsehen RP, 2020)

Anchor system

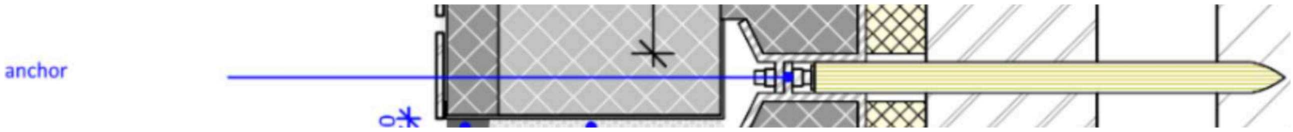


Figure XV.14 - Anchor system example (internal document)

Corner strip

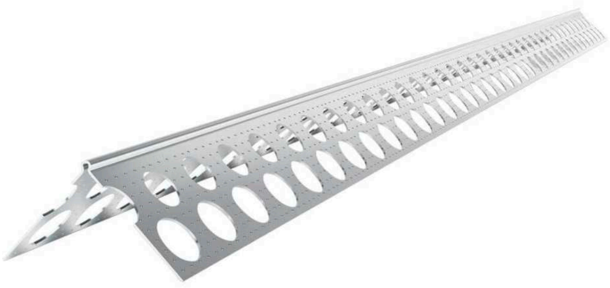


Figure XV.15 - Corner strip example (Baukom Trockenbauprofil Alu, 2021)

Window frame

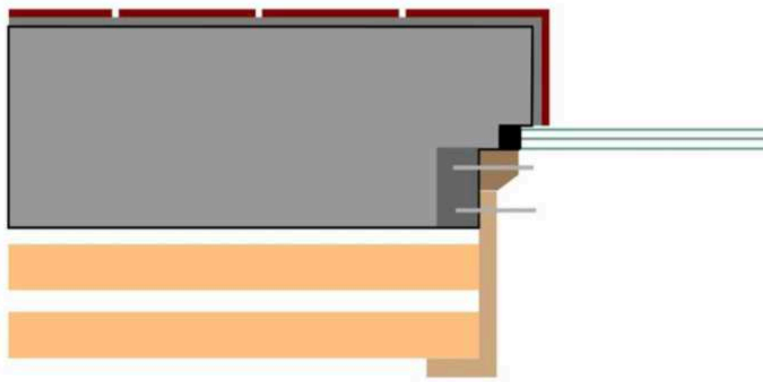


Figure XV.16 - Triple glass standard window example (Ulla-B. Krämer; Arjan de Haan, 2020)

Roof

Figure XV.17 - Roof example (Tegnis, 2019)

Interreg
North Sea Region
INDU-ZERO
European Regional Development Fund

EUROPEAN UNION