Tampereen yliopisto

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DEVELOPMENT OF AUTOMOTIVE DISPLAY HOUSING STRUCTURES USING CPM/PDD FRAMEWORK

Master's thesis
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ABSTRACT

Eetu Huovinen: Development of automotive display housing structures using CPM/PDD framework
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Automotive product development is facing increasing performance requirements, cost pressure and shortening lead times, which leads to a need for systematic and effective product development approaches in early design phases. This thesis investigates the suitability of Christian Weber's Characteristics-Properties Modelling (CPM) and Property-Driven Development (PDD) frameworks for the use of the target company's product development process. Motivation for the study comes from the aim to improve early-phase decision making, to shorten design lead time and to study feasibility of a patent-based design. The patent-based design concept is integrated into a series-produced automotive display housing structure following the CPM/PDD approach. The initial housing design is used as a benchmarking device and results of the development process will be compared to its performance values.

The research was conducted as a constructive study. Following the CPM/PDD framework, five required properties were defined for the product which were weight, stiffness, manufacturability, assemblability and cost. Rating the mentioned properties, the initial design was scored at 34 points and the updated design at 35 points. Two development rounds were executed which focused on developing the products weight and stiffness on the first round, and manufacturability on the second round. Final design was 3,9 % lighter in weight than the initial design, which improved the scoring for weight property. Scoring for manufacturability was decreased as castability of the updated design was a bit worse than for the initial design. Scoring for stiffness, assemblability and cost stayed unchanged. The proposed patent-based design was not found feasible for manufacturing and therefore it was discarded.

The CPM/PDD framework was not found to be explicitly suitable for the company's product development process. Its systematic modelling of the product was found to be advantageous creating cross-department product knowledge. The systematically collected knowledge on product or system level can be useful in the development of updated revisions of earlier products or the recognized solution elements can be used to speed up creating new products. For further usage the framework was found to be a bit laborious.

Keywords: Characteristics-Properties Modelling, Property-Driven Development, Design for X, High-pressure die casting

The originality of this thesis has been verified using the Turnitin Originality Check service.

TIIVISTELMÄ

Eetu Huovinen: CPM/PDD-metodin käyttö autoteollisuuden näyttöjen runkorakenteiden tuotekehityksessä
Diplomityö
Tampereen yliopisto
Konetekniikan DI-ohjelma
Toukokuu 2026

Autoteollisuuden tuotekehitysprosessit kohtaavat jatkuvaa painetta kasvavien vaatimusten myötä suorituskyvyn, toimitusaikojen ja hinnan suhteen. Tämä johtaa tarpeeseen löytää ja hyödyntää systemaattisia ja tehokkaita tuotekehitysprosesseja heti suunnittelun alkuvaiheessa. Tässä työssä tutkitaan Christian Weberin CPM/PDD-metodin soveltuvuutta kohdeyrityksen tuotekehitysprosessin työkaluksi. Tutkimuksen motivaatio tulee yrityksen tavoitteesta kehittää ja tukea varhaisen vaiheen päätöksentekoa, parantaa suunnittelutyön läpimenoaikoja ja tutkia patenttiin perustuvan rakenneratkaisun käytännön soveltuvuutta hyödyntäen CPM/PDD-metodia. Sarjatuotannossa olevaa näytön runkorakennetta käytetään vertailukohtana ja kehitetyn rakenteen suorituskykyä verrataan siihen.

Tutkimus toteutettiin konstruktiivisena tutkimuksena. CPM/PDD-metodin mukaisesti tuotteelle asetettiin yhteensä viisi arvioitavaa vaadittua ominaisuutta, jotka olivat paino, lujuus, valmistettavuus, kasattavuus ja hinta. Alkuperäinen rakenne keräsi yhteensä 34 pistettä, ja päivitetty versio 35 pistettä. Rakennetta kehitettiin kahden iteratiivisen kehityssyklin ajan, joista ensimmäinen keskittyi tuotteen painoon ja lujuuteen ensimmäisen syklin aikana ja tuotteen valmistettavuuteen toisen syklin aikana. Lopullinen rakenne oli 3,9 % alkuperäistä kevyempi, joka paransi sen pisteytystä paino-ominaisuuden osalta. Tuotteen valmistettavuuden pisteytys laski hieman, sillä valusimuloinneissa sen suorituskyky oli hieman alkuperäistä heikompi. Lujuuden, kasattavuuden ja hinnan osalta pisteytykset pysyivät muuttumattomina. Patenttiin pohjautuva rakenneidea todettiin mahdottomaksi valmistaa, joten sen käyttö pidemmällä prosessissa hylättiin.

CPM/PDD-metodin ei todettu olevan yksiselitteisesti käyttökelpoinen kohdeyrityksen tarpeisiin. Sen systemaattinen tuotteiden mallinnus koettiin hyödylliseksi luoden osastorajat ylittävää tietoa tuotteesta. Tuote- tai systeemitason tieto tuotteesta voi olla hyödyksi uusien tuoterevisioiden kehityksessä, tai niistä löydetyt ratkaisuelementit voivat nopeuttaa uusien tuotteiden kehitysprosessia. Laajemmassa käytössä metodin hyödyntäminen koettiin melko työlääksi.

Avainsanat: CPM/PDD-metodi, Ominaisuusperusteinen suunnittelu, Design for X, Korkeapainevalu

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PREFACE

I would like to express my gratitude to Vesa Pelli, Jenni Nieminen, and Pyry Välimäki at AUO Mobility Solutions Finland Oy for providing me an opportunity to experiment, learn, and grow as a mechanical engineer during my studies, and to complete my studies with this thesis.

I would also like to thank Timo Lehtonen for his guidance during my thesis.

Time has flown since the first day I stepped into greyscale Hervanta. It has been my great pleasure to be a part of several communities and to get to know all the special people involved in them. Honorable mentions go to Spinni and KoRK. The memories remain, and hopefully the people with them—now and in the future.

I wouldn’t change an evening.

Tampere, 21.5.2026

Eetu Huovinen

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LIST OF SYMBOLS AND ABBREVIATIONS

AM	Additive Manufacturing
AMSC	AUO Mobility Solutions Corporation
CFD	Computational Fluid Dynamics
CID	Centre Information Display
CPM	Characteristics-Properties Modelling
DFMA	Design for Manufacturing and Assembly
DFQ	Design for Quality
DFX	Design for X
DTM	Design Theory and Methodology
FEA	Finite Element Analysis
FMEA	Failure Mode and Effects Analysis
HPDC	High Pressure Die Casting
ID	Industrial Design
OEM	Original Equipment Manufacturer
PDD	Property-Driven Development
PID	Passenger Information Display
RSE	Rear Seat Entertainment
TRIZ	Theory of Inventive Problem Solving
QFD	Quality Function Deployment

1. INTRODUCTION

Designing an automotive vehicle is a complex process including various concurrent processes that need to consider multiple non-predictable external and internal factors while trying to achieve all the set requirements for the final product. Intense competition between manufacturers drives the processes to reach cost-effective solutions with faster time to market times while technological advances are also rapid. (Bhise, 2017)

According to Sachseneder et al. (2024) benchmarking of product development processes has shown results where the best challenger OEMs (Original Equipment Manufacturers) reached 36 months' lead time for the development of an automotive platform. Time consumed for the same process by average volume OEMs and average premium OEMs were 46 and 56 months. Same benchmarking comparison established by Borden et al. (2025) display development times of 24, 45 and 53 months. This shows a trend where China's automotive industry crushes other OEMs in their lead times while having the world's fastest growing automotive market. Volume and premium OEM manufacturers on OEM and their subcontractor levels need to consider their product development processes to catch up with their competitors now and in the future.

This thesis follows Christian Weber's combination of Characteristics-Properties Modelling (CPM) and Property-Driven Development (PDD) frameworks to develop an automotive display housing structure. Given mass-produced design structure is used as a benchmarking device for the process and applicability of a proposed patent design is assessed during the process. The usability of the CPM/PDD framework for the target company's needs is also evaluated.

Following chapters define the research objectives, scope and its strategy and methods before a literature review on the design framework, design tools, and manufacturing methods. Chapter 6 covers the iterative CPM/PDD product development processes and chapter 7 collects its results including evaluation of the constructed design, answers to the research questions, and gathers a brief discussion on managerial impact and future development suggestions. Chapter 8 discusses the reliability, accuracy, validity, generalizability, and novelty of the research. Chapter 9 concludes the thesis.

2. RESEARCH OBJECTIVES AND SCOPE

In this section, research objectives and scope are defined, and research questions are formed based on them. Research objectives are based on the target company's needs which were collected and refined after interviewing experts in the company. Research scope is mostly based on the direction set by the patent idea and available resources for the research.

2.1 Research objectives

Motivation for this thesis comes from a patent idea that has not yet been studied for it to be applicable for the target company. This thesis' goal is to gather knowledge on the applicability of the proposed design solution for a mass-produced display housing. Various design methodologies or frameworks could be applicable for this evaluation process. Adaptation of Christian Weber's CPM/PDD framework for the company's needs has already made its first steps earlier and Välimäki (2021) suggests the following for the company related to the design framework: "Before this tool is used for the design of a mass produced product must the tool be validated and examined properly by testing it in development of various conceptual phase products." This suggestion leads to the first objective of the thesis **to examine the use of CPM/PDD approach for development of conceptual phase product to validate its usability for mass-produced devices.** Connecting this with the integration process of new design solution to an existing product suits well with the target company's needs.

Recognized design restrictions due to manufacturability limitations sets the second objective for the thesis **to construct a lightweight and stiff display housing solution based on the original patent and compare its performance to the existing mass-produced solution.** Knowledge collected on the product and the applicability of the used design framework during the process are gathered and reported to the target company for their possibly advantageous usage in the future.

2.2 Research scope

Vehicle infotainment system can include many displays such as instrument cluster, centre information display (CID), passenger information display (PID) and rear seat entertainment (RSE) displays. This thesis' scope focuses on free-standing displays that are most familiarly used as CID and RSE displays. This sets the structural requirements for

the housing stiffness and displacement in extreme conditions such as collisions or misuse cases. The existing series product will be treated as a benchmark device for the development process and its material, outer dimensions and integration features will be inherited for the updated design. Methodological approach and research strategy for the set problem will be introduced in following chapter 3.

2.3 Research questions

Research objectives and scope being defined, four research questions were formed based on them:

RQ1: Which characteristics of the current design affect its performance properties?

RQ2: How can the found characteristics be developed?

RQ3: What is the impact of this development on the product's performance?

RQ4: How suitable is the CPM/PDD approach for the company's product development processes?

Formed research questions focus primarily on the applicability of the CPM/PDD framework where the first two lead the development process and the third and fourth one collects results of the process and analyses its suitability once answered. To find answers to the presented research questions research strategy is formed and introduced with suitable research methods in the following section.

3. RESEARCH STRATEGY AND METHODS

Researchers have adopted and successfully applied various research methods into engineering design that have their original usage in other fields. Review on used research methods in the field of engineering design collected by Escudero-Mancebo et al. (2023) shows that the field applies research methods widely instead of having a single standard method to use. Studies matching the aim of this thesis to develop and evaluate a specific product are categorized by their research method as case studies in most cases with either a qualitative or mixed approach. (Escudero-Mancebo et al., 2023)

Järvinen & Järvinen (2004) emphasize that the motivation for an innovation always comes from some kind of idea or concept. They also mention that constructive study will answer questions such as:

- Are we able to build a specific innovation and how useful it is?
- How should your innovation be and how it should be built?

Mentioned emphasis and presented questions match with the scope of this thesis so it can be defined as a constructive study. Lukka (2003) presents constructive research approach as an alternative definition to research that are typically introduced as less descriptive case studies. Case study may often be defined as a singular mode of research even though it covers multiple sub-methods under the term. The roots of case study methods always lead to ethnographic studies in the fields of anthropology and sociology. From there the constructive research approach was developed for the needs of business administration and later adapted to other fields such as engineering. (Lukka, 2003)

Table 1 introduces the key features of constructive study and connects them with elements of this thesis to create the base for this thesis' research strategy.

Table 1. *Core features of constructive research and how they are realized in this thesis*

Lukka, 2000	This thesis
Focuses on real-world problems that have a relevance to being solved in practice.	Initial task, motivation and objectives from target company.
Final product is an innovative construction that tries to solve the initially set problem.	Core idea for the construction is set by patent.
Tests construction's practical applicability by implementing the solution.	Practical applicability evaluated by FEA-study and casting simulations.
Experiential learning is expected to take place by researchers' and practitioners' intensive co-operation.	Usage of expert knowledge inside the target company.
Explicit linkage to prior theoretical knowledge.	Usage of DfX-methods and design theories.
Reflects empirical findings back to theory.	Discussion at the end of thesis based on literature review and results of the empirical section of the thesis.

Paniura et al. (2023) recognize multiple data collection methods for engineering sciences such as surveys, questionnaires, observations, measurements, interviews and analysis of documents. Some of these are also implemented in this thesis and are found in Table 1. The remaining can be considered as alternative methods. They also emphasize the evolution of computer aided technologies and their impact on data collection especially in engineering sciences. These are realized by the usage of finite element analysis (FEA) and casting simulations.

Due to the nature of the product being a structural construction part of a larger assembly and main developed aspects of the part are structural, the design methods studied are related to mechanical structures rather than industrial design (ID). In most cases in the industry, the required ID-surfaces are provided by the OEM's instead of being designed by the supplier themselves and therefore it falls out of the scope of this thesis.

Based on the scope and goals of this thesis, the following literature were found to be the main references:

- Weber, C. (2014). Modelling Products and Product Development Based on Characteristics and Properties. In An Anthology of Theories and Models of Design (pp. 327–352).
- Slocum, A. H. (2008). FUNdaMENTALS of Design.
- Eder, E. W. (2011). Engineering design science and theory of technical systems: Legacy of Vladimir Hubka. Journal of Engineering Design, 22(5), 361–385.
- Hubka, V., & Eder, W. E. (2012). Theory of Technical Systems: A Total Concept Theory for Engineering Design.
- Benabdellah, A. C., Bouhaddou, I., Benghabrit, A., & Benghabrit, O. (2019). A systematic review of design for X techniques from 1980 to 2018: Concepts, applications, and perspectives. The International Journal of Advanced Manufacturing Technology, 102(9–12), 3473–3502.

Research strategy and its steps with their main topics are illustrated in Figure 1 below.

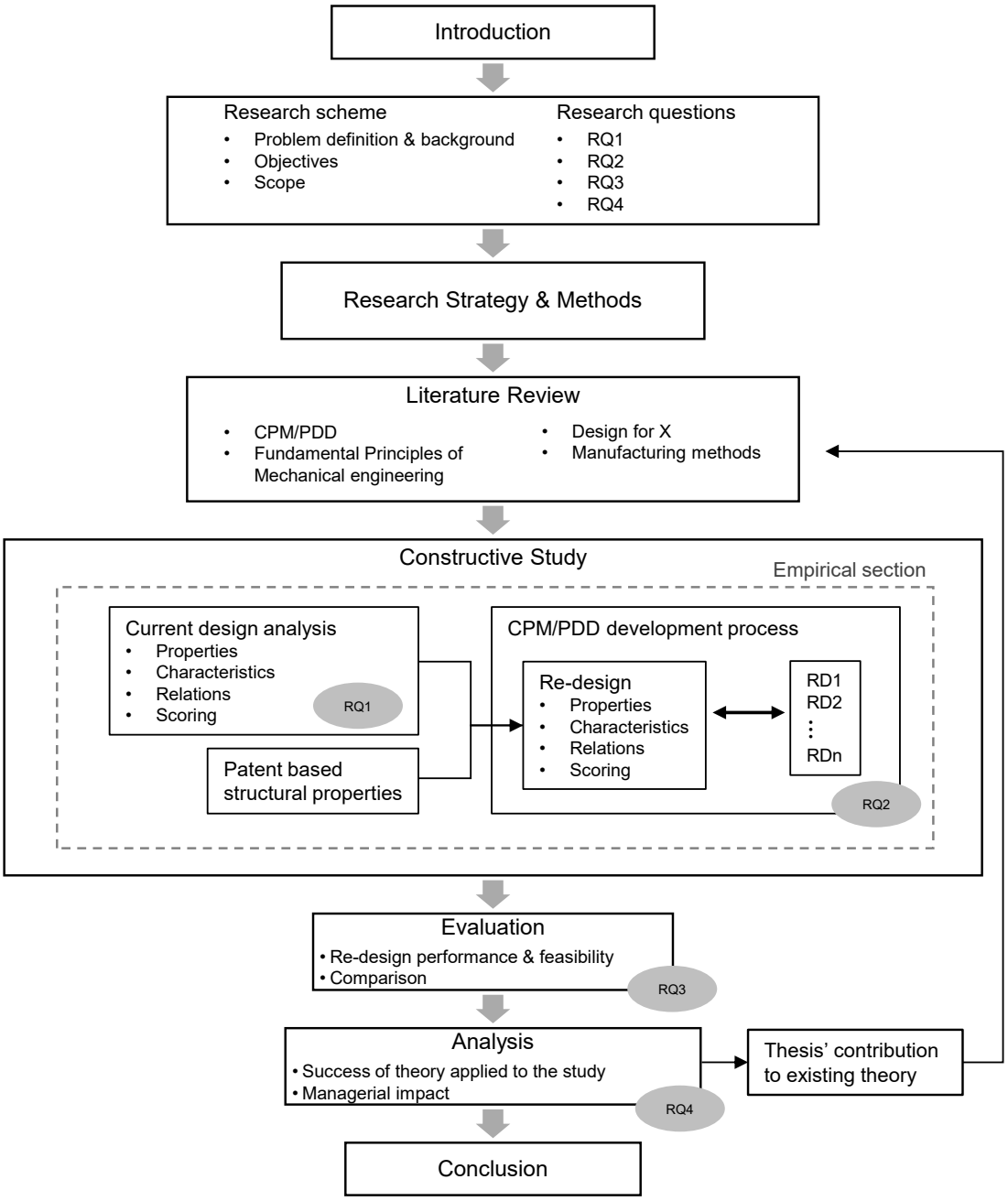

Figure 1. *Research strategy*

4. TARGET COMPANY AND BACKGROUND

The target company for this thesis is AUO Mobility Solutions Finland Oy, which is a part of AUO Mobility Solutions Corporation (AMSC). AMSC is a tier 1 supplier for automotive OEMs with infotainment displays being a significant part of their product portfolio. Series product example manufactured by the company is shown in Figure 2.

Figure 2. *Škoda Enyaq iV interior with CID (BHTC, 2021)*

Constantly evolving digital infotainment systems of automotive vehicles include multiple ever-growing displays in the use of CIDs, PIDs, RSE and instrument clusters. This strengthens the importance of robust, lightweight and cost-effective display assembly solutions to achieve an immersive user experience and competence in the field.

The target company provides the practical context with benchmarking device design and technological motivation for this thesis. The results are intended to improve the display housing under the study and to support methodological learning and its suitability in the context of cross-department product development and early-phase decision making.

5. LITERATURE REVIEW

The literature review was executed to gather relevant information and knowledge related to the set research objectives and scope. The review is divided into sub-sections which each cover a single topic needed to achieve the thesis' objectives and information to proceed a step closer to answering the set research questions.

Search engines used for the review were Andor and Google Scholar. Main used publication databases were IEEE Xplore, ScienceDirect and ResearchGate. Various guides provided by foundries or foundry associations and Altair's Inspire Cast guide were also used to gather knowledge about casting simulation and analysis. Keywords used for research included e.g. property-driven development, characteristics-properties modelling, design for X and high pressure die casting.

Mechanical design engineering best practices related to this thesis' topic were picked and are presented in Table 2. They are sorted by their chapters as in Ullman (2016) and the most relevant ones are highlighted by underlining. These practices can be taken as guideline on some level for the constructive design process performed later in the empirical section of this thesis. They also lead to relevant design topics, in addition to the CPM/PDD approach, which are handled in the literature review and considered during the design process.

Table 2. *Design engineering best practices, adapted from Ullman (2016)*

Introduction
Develop mechanical, electronic, and other systems concurrently.
Understanding mechanical design
Benchmark existing products to understand how they are made, assembled, and function.
Designers and Design Teams
Assemble product design teams with diverse, specific expertise.
Make positive use of team members' problem-solving behaviours.
The Design Process
Recognize that the design process is a series of decisions.
Document all concepts and decisions for reuse, patent application and defence, and regulatory requirements.
Project Definition
Ensure you have good reasons for beginning a project.
Use models and prototypes as learning opportunities.
Product Definition
Identify product customers.
Capture customers' requirements.
Generate clear and measurable engineering specifications.
Determine how the engineering specifications relate to customers' requirements.
Establish targets, thresholds, and inter-dependence of engineering specifications.
Concept Generation
Generate multiple concepts.
Reverse engineer to understand function.
Build functional models as a basis for form generation.
Generate concepts using brainstorming.
Generate concepts using analogies with nature and devices in other fields.
Generate concepts using prior patents.
Generate concepts using TRIZ (Theory of Inventive Problem Solving).
Generate concepts using morphologies.
Develop product architectures using design structure matrices.
Concept Evaluation and Selection
Know each system's technology readiness.
Use decision matrices to evaluate concepts and support decision making.
Understand the product, project, and decision risks.
Make robust decisions—decisions insensitive to noise.
Product Evaluation
Design for X
Wrapping up the Design Process and Supporting the Product
Manage post-release engineering changes.
Apply for design and utility patents as good design and business practice.

5.1 Fundamentals of CPM/PDD approach

The CPM/PDD approach is formed by Christian Weber with his team and introduced in their papers which are one of the main references for this thesis. Weber states clearly that the approach is mainly built on top of former knowledge in design theory and methodology (DTM) created by e.g. Pahl et al. (2003), Suh (2001) and Hubka & Eder (1992). It is not supposed to be a completely new or an alternative methodology for an existing one, but rather its goal is to be able to integrate and bring existing theories together by creating a suitable framework and furthermore to provide explanations to some design phenomena that have not been thoroughly understood or explained by existing methodologies. In addition to this main goal, the CPM/PDD approach also defines providing design process for existing products and implementing computer-based tools and methods for the design process as one of its sub-goals. (Weber, 2014)

According to Conrad et al. (2018) the CPM/PDD approach has proven its usability across various fields. It has been successfully applied in cost-driven development (Deubel, 2007), engineering change management (Köhler, 2009) and for capturing design knowledge (Conrad, 2010). Used terminology in various design methodologies varies across several sources and in this paper characteristics and properties are defined and used as in Table 3.

Table 3. *Typical examples of product characteristics and properties (Weber, 2014)*

Characteristics	Properties
Structure	Weight
Shape	Safety
Dimensions	Reliability
Materials	Aesthetics
Surfaces	Manufacturability
	Assemblability
	Environmental impact
	Cost

From the point of view of a designer, product properties cannot be directly influenced whereas characteristics are directly modifiable. Structuring product characteristics and properties properly is vital for them to be efficiently and successfully handled during the

design process as the total amount of them reaches thousands in more complex products. Figure 3 introduces a structuring model for characteristics and properties and their main two relations of synthesis and analysis. (Weber, 2014)

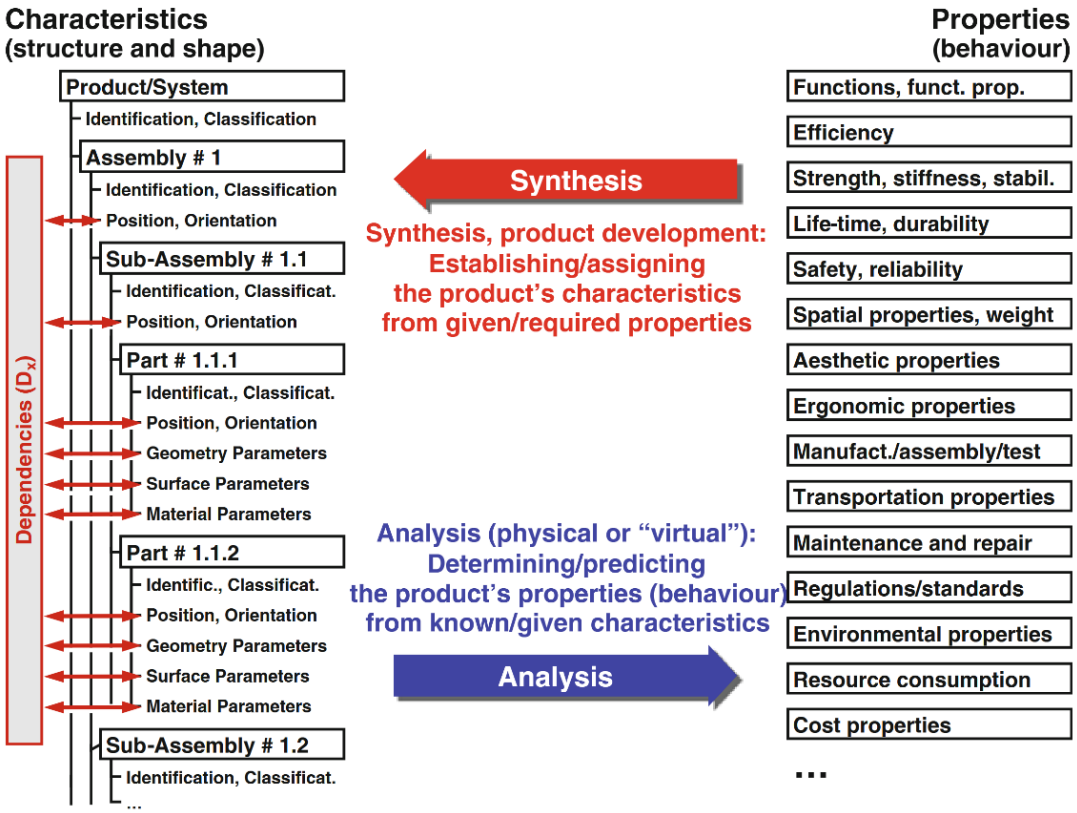

Figure 3. *Relations between characteristics and properties (Weber, 2014)*

The left side of Figure 3 presents the characteristics in a hierarchical form from product/system level down to part level characteristics. This characteristics tree follows similar structure for different types of products whereas structuring properties need case specific more accurate sub-properties with measurable parameters to suit their use case. This decomposition of properties is mentioned to be the first step to an application specific design methodology. Far left of the figure presents dependencies $\boldsymbol{D_x}$ of the product characteristics. This and other symbols used for expressions in this paper are introduced in Table 4 below. Understanding the dependencies of product characteristics makes the designers work of designing a product plausible as existing dependencies limit the amount of design freedoms and therefore decreases the number of independent characteristics that the designer needs to take care of one by one. Structuring-wise significant difference between characteristics and properties is that for characteristics you can, in most cases, easily state their completeness where for properties it is impossible per se.

Design process cannot ever control all product's behavioural parameters but the most relevant ones and the rest will follow. (Weber, 2014)

Table 4. *Symbols used in the context of CPM/PDD (Weber, 2014)*

C_i	Characteristics
P_j	Properties
PR_j	Required properties
D_x	Dependencies
R_j	Relations between characteristics and properties (for analysis)
R_j^{-1}	Relations between characteristics and properties (for synthesis)
EC_j	External conditions

The middle section of Figure 3 introduces the main two relations between characteristics and properties: Analysis, where properties are determined or predicted, and synthesis, where characteristics are assigned and their parameters updated based on given properties (Weber, 2014). These processes will be introduced more in detail in sections 5.1.1 and 5.1.2. As stated earlier, the approach can be divided into two separate sections, Characteristics-Properties Modelling and Property-Driven development, which will be introduced in the following sub-sections.

5.1.1 Characteristic-Properties Modelling

Shown in Figure 4, the basic analysis model can be read such that product's relevant properties P_j get determined by different combinations of its given characteristics C_i. With an existing physical product, the product acts as a representation of relations R_j of the model as analysis of the properties can be done by testing and measuring. For analysing properties during the product development phase without a physical product, appropriate models, methods, and tools introduced in Figure 6 need to be used to populate the relation boxes selected accordingly depending on the development stage.

Finally, the analysis model presents the affection of external conditions EC_j to each relation box respectfully. The external conditions create an environment where the quality of property is valid. Given example introduces manufacturing system to be the external condition for products manufacturability property. (Weber, 2014)

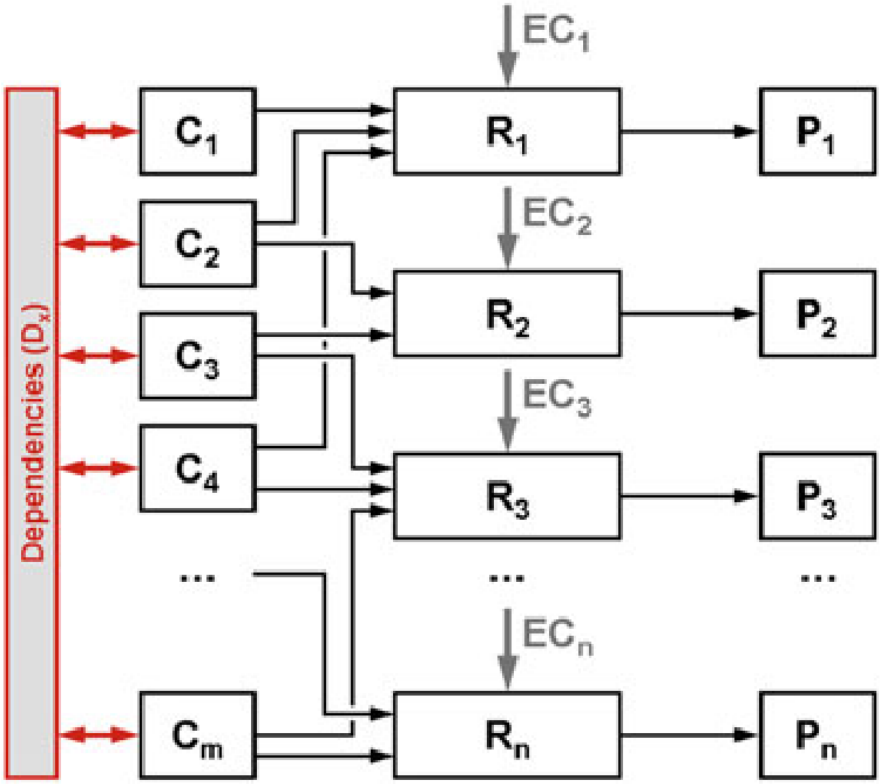

Figure 4. *Analysis model (Weber, 2014)*

Following the analysis model, comes synthesis model. Essentially being reversed analysis model, the synthesis model represents connections between required properties and characteristics through their inverted relations R_j^{-1} and external conditions. Again, utilizing the tools and methods presented in Figure 6, we can re-determine and assign values to product characteristics. Looking at Figure 5, it can be quickly noticed that two or more required properties have relations to the same characteristics, and to meet with the requirements, the characteristic needs to be adjusted in opposite directions. This leads to a paradoxical situation where, for example weight cannot be minimized simultaneously with stiffness being maximized as they both affect to e.g. beams cross-section dimensions in opposite directions. (Weber, 2014)

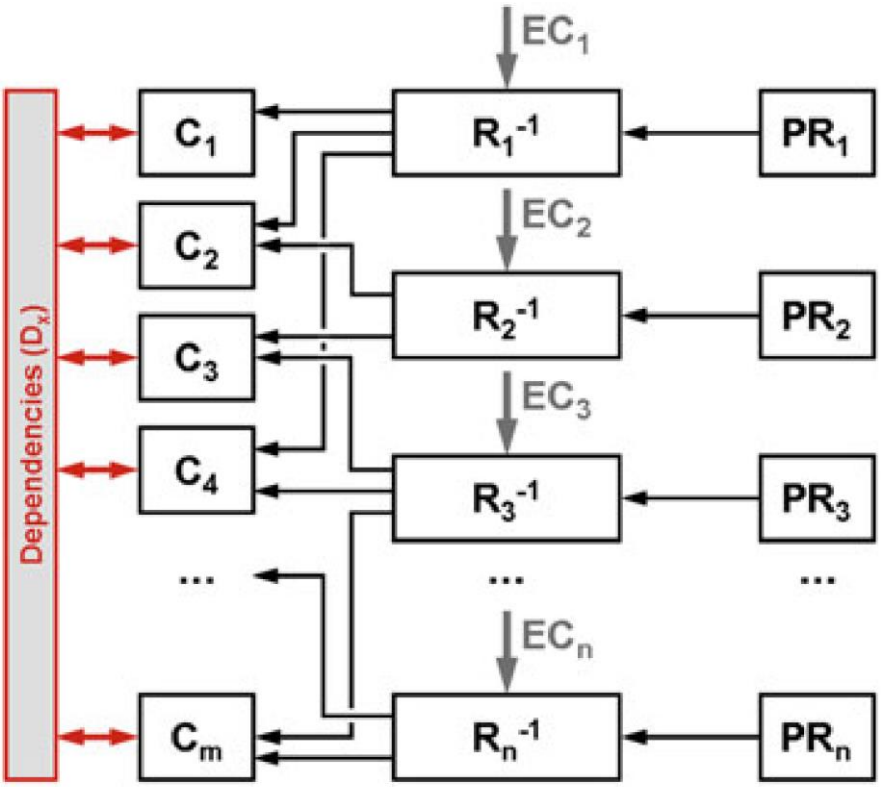

Figure 5. *Synthesis model (Weber, 2014)*

Figure 6 presents the models, methods and tools to populate relation and inverted relation boxes for both analysis and synthesis models sorted starting from informal to more strongly formalised ones.

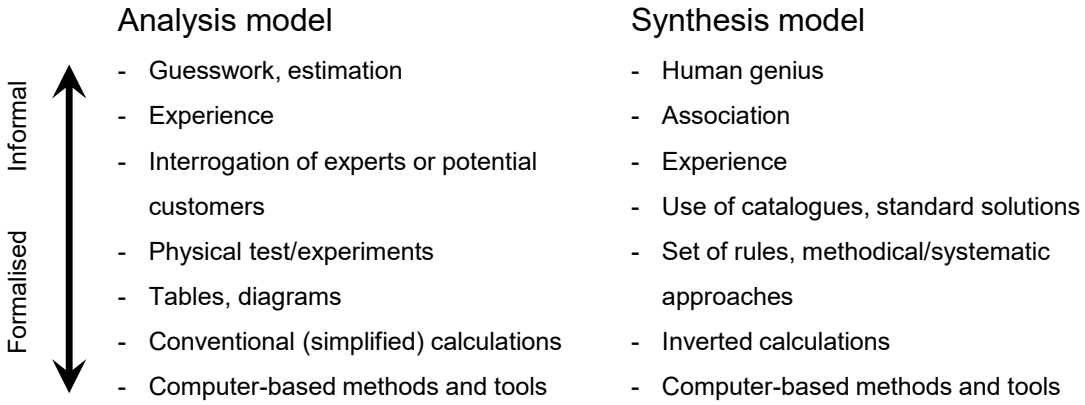

Figure 6. *Models, methods & tools to realize relations* R_j & R_j^{-1} *(Weber, 2014)*

The relations between characteristics and properties can be such as formulas, tables, simulations, physical mock-ups and expert knowledge. These relations transform product information into product knowledge as described in data information knowledge continuum by Probst et al. (2010). Conrad et al. (2008) state this more open presentation with fluent transitions causes less confusion compared to more classic discrete distinction and hierarchical structure between data, information and knowledge.

Utilizing solution elements and patterns are vital for the reuse of product knowledge and they also lead to opportunities for product modularization and standardization. Solution element is essentially a group of product characteristics and properties with known relations. Example schematic view of a solution element is presented in Figure 7. (Weber, 2014)

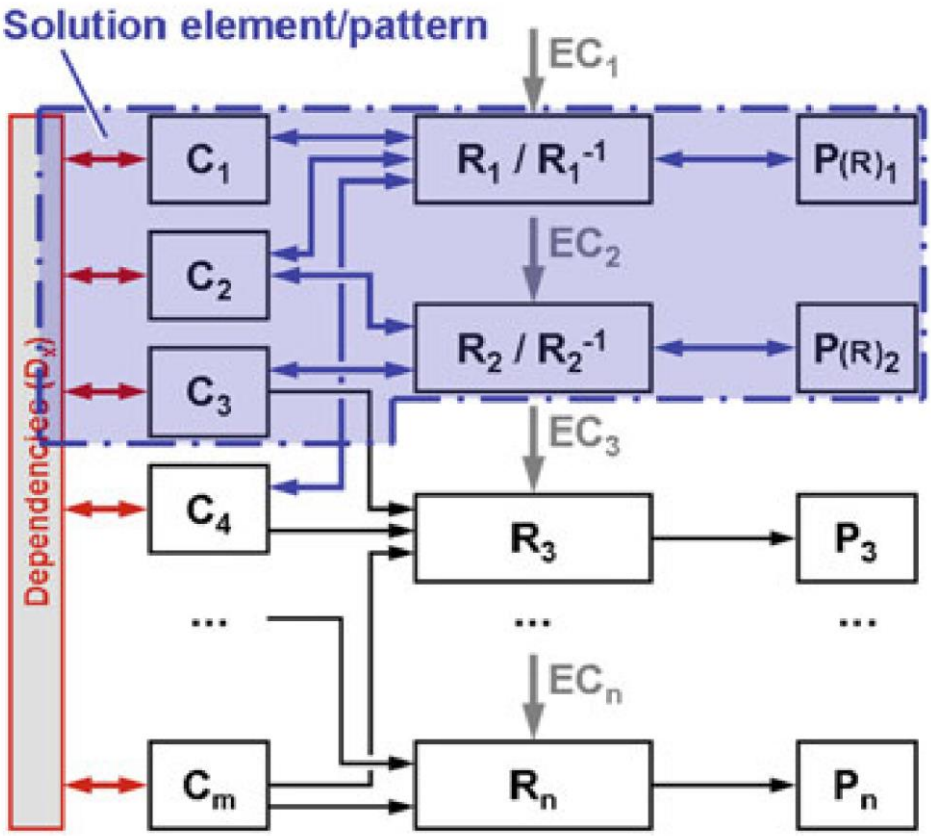

Figure 7. *Solution element in analysis/synthesis model (Weber, 2014)*

Solution elements where all characteristics, properties and relations are known leads to an advantageous situation where this product knowledge is useful in both directions. It can be used for synthesis of suitable characteristics based on required properties and analysis of properties based on given characteristics. (Weber, 2014)

5.1.2 Property-Driven Development

PDD presents the product development process as repetitive cycle of synthesis and analysis processes, and these two processes are linked with an evaluation step. During the development cycles the synthesis section updates the list of characteristics and their values and the analysis section provides more information on the product's properties. Following Figure 8 and Figure 9 present an overview of the PDD-cycles. (Weber, 2014)

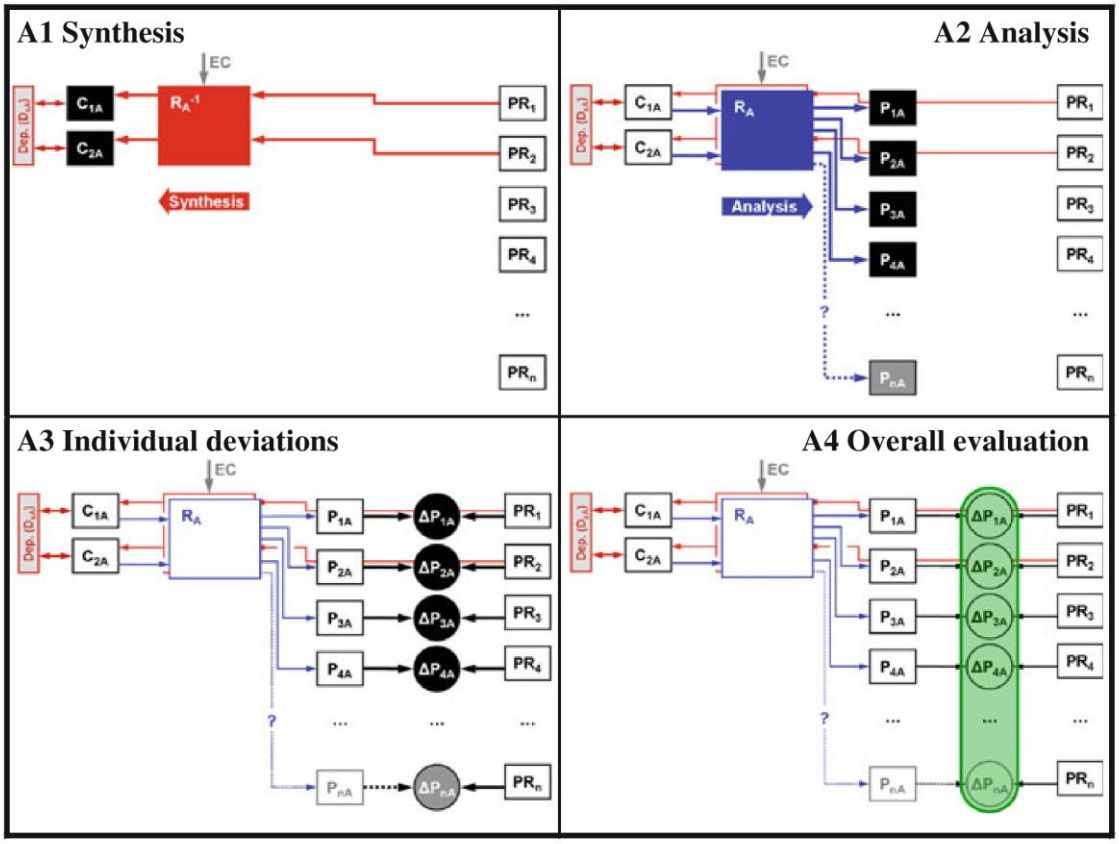

Figure 8. *First development cycle of PDD (Weber, 2014)*

A1: First synthesis step using selected properties generated from list of required properties. Solution patterns, as presented in Figure 7, often lead to the establishment of first characteristics based on the selected properties.

A2: Based on the established properties all relevant properties, which can include also other properties than which were selected for the first synthesis step, are analysed.

A3: Now the analysed properties can be compared to the values of required properties. This generates deviation values for individual properties and the stage of satisfactory for the current design solution can easily be recognized.

A4: As the last step of the first development round, the designer needs to recognize the relevant properties for the next development round and appropriate tools and methods

to reach the required values. If the overall evaluation shows satisfactory values with the deviations of analysed and required properties, the designer can also decide to terminate the development process and final solution is reached. (Weber, 2014)

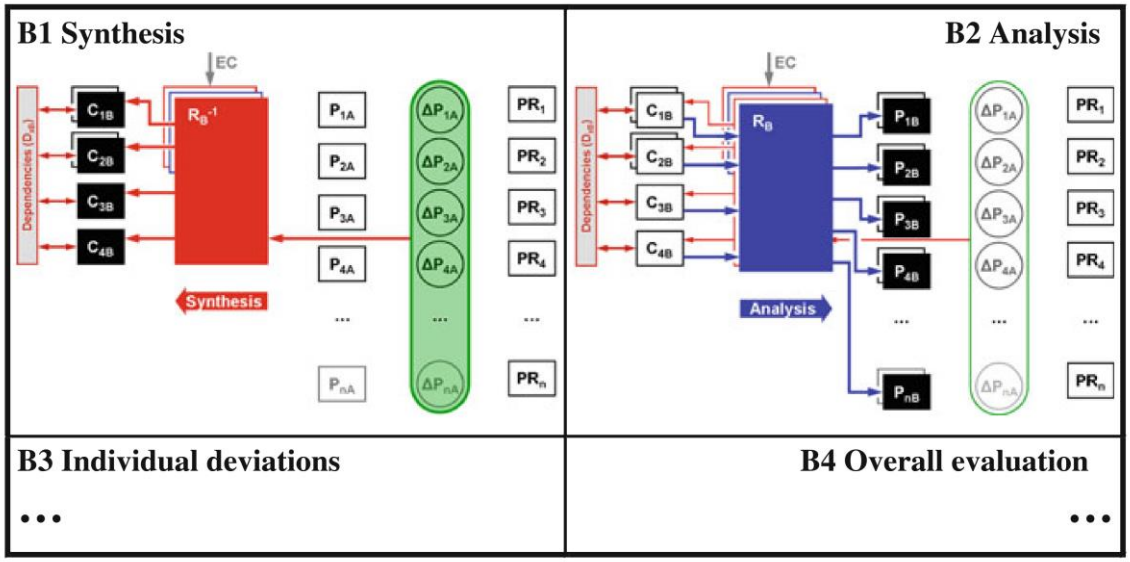

Figure 9. *Second and further development cycles of PDD (Weber, 2014)*

B1: Second and further synthesis steps get their starting point from previous rounds' overall evaluation step where the properties to continue with are selected. As a result of the synthesis the existing characteristics can either be updated or new ones be established.

B2: In successful development processes, now the analysis process gets to exploit the more detailed characteristics and therefore use more detailed analysis tools and methods to create new, supposedly better, results for the analysis.

Steps **B3** and **B4** are essentially the same as already introduced steps **A3** and **A4**.

The amount of development rounds may vary from single round to infinity but the decision of satisfactory and termination of the process is always done in the overall evaluation step. The product development process can be terminated and stated successful as following requirements set by Weber (2014) are achieved:

1. All characteristics needed for manufacturing and assembly of the product are established and assigned
2. All relevant properties can be determined or predicted
3. with sufficient certainty and accuracy, and
4. all determined or predicted properties are close enough to the required properties.

Weber (2014) points out that other approaches are often limited to only requirements 1 and 4 listed above, where CPM/PDD approach adds two more requirements in between which focus on the usage of appropriate analysis tools and methods.

5.2 Design for X

Design for X refers to design methodologies that focus on guiding design decisions towards specific objectives such as manufacturability, quality, reliability, cost-effectiveness, safety or sustainability. Since its roots from the 1980s, DfX has evolved into a systematic framework that serves designers with principles, guidelines and assessment methods leading products to a state where they meet technical, organizational and customer requirements. (Benabdellah et al., 2019; Kuo et al., 2001)

Benabdellah et al. (2019) have gathered a systematic review of design for X methods with a total of over 75 different techniques found. Utilizing DfX methods can be beneficial for companies in a sense of competitiveness, reaching improved and rationalized decisions in designing products, process and resources, quality improvement and reductions in lead time, product risks and product material costs. Depending on the chosen method they can be sorted into phase- and virtue-specific ones. E.g. design for manufacturing, design for assembly, and design for supply chain for different stages of product life cycle and design for environment, design for cost, and design for quality for different virtues. Categorization chart of various X's is presented in Figure 10. Utilizing DfX methods is said to be the key factor to have production with the wanted quality in a set schedule to make your company competitive in today's markets and to keep customers satisfied. (Benabdellah et al., 2019)

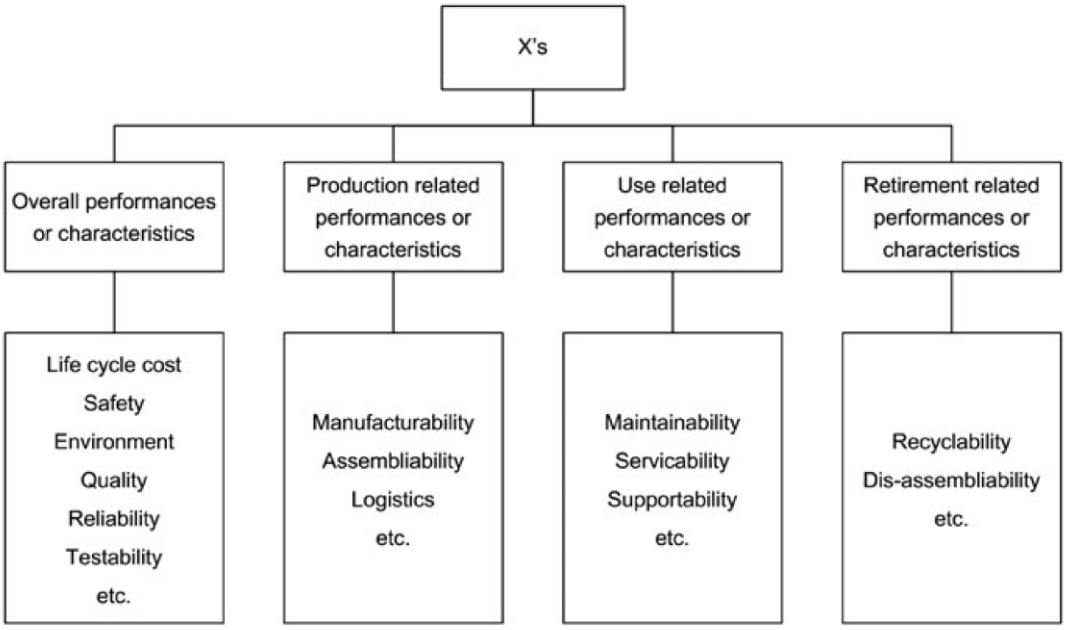

Figure 10. *DfX method categorization (Jiang, 2015)*

Huang & Mak (1997) present ten functions which are characteristics of a DfX-tool, and each tool should fulfil at least some of them. The 10 functions are as presented below:

1. Gather and presents facts.
2. Measure performance.
3. Evaluate whether a product/process design is good enough.
4. Compare design alternatives.
5. Highlight strengths and weaknesses.
6. Diagnose why an area is strong or weak.
7. Provide redesign advice by pointing out directions for improving design.
8. Predict “what-if” -effects.
9. Carry out improvements.
10. Allow iteration to take place.

DfX-techniques should not be utilized as stand-alone tools but rather as a concurrent approach in a broader product development process. Even though a large pool of DfX techniques is introduced and recognized, most of them face challenges of being too complex, time-consuming or otherwise don’t meet with the users’ needs are therefore cannot be adapted for usage in practice. The applicability of each method is also dependent on the design stage of the product. (Benabdellah et al., 2019, 2020)

5.2.1 Design for manufacturing and assembly

Design for manufacturing and assembly's (DfMA) focus is on minimizing production and assembly related costs by simplifying product structure while being aware of available manufacturing processes and their capabilities. (Boothroyd et al., 2010)

Designers should be familiar with manufacturing processes to avoid situations where designers design products that are difficult and costly or even impossible to manufacture. According to Suh (1990) this can be avoided by the designer by properly defining, analysing and understanding product functional requirements and design parameters dependencies. To reach this state, the designer must have the required level of knowledge on manufacturing processes, laws of nature and scientific principles. Desai & Mital (2020) introduce three types of assembly methods and their characteristics: manual, robotic and automatic assembly. Due to large yearly production volumes in the automotive industry, automatic assembly would be the suitable option for this thesis' application. Relative costs of different assembly types by production volume are presented in Figure 11.

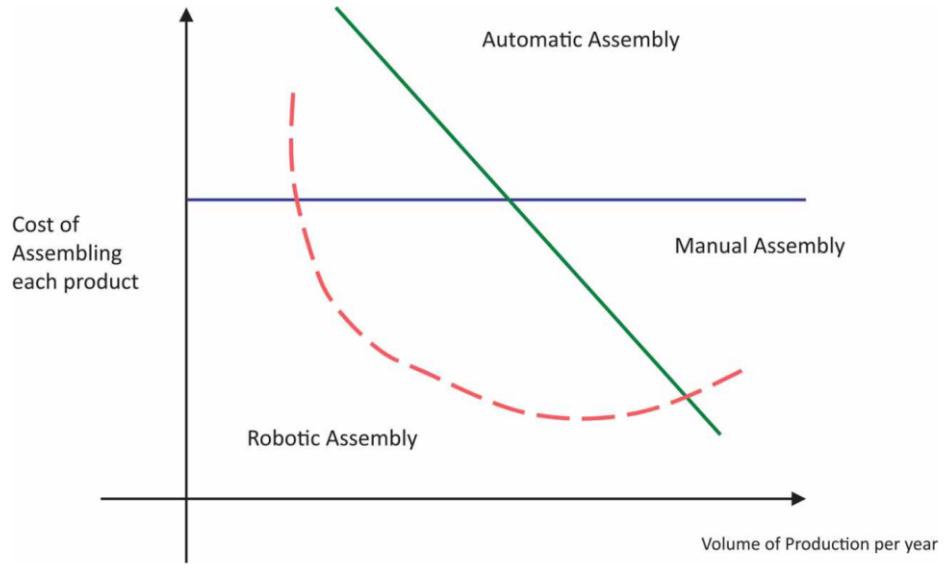

Figure 11. *Relative assembly cost comparison (Desai & Mital, 2020)*

As design guidelines for automatic assembly lines Desai & Mital (2020) suggest the following:

- Parts should have self-aligning and self-locating features such as chamfers, guide pins, dimple and cone and oval screws.
- Assembly should be done layer by layer using gravity for your advantage and using the most rigid part of the assembly as a base. Assembly can optionally be divided into smaller sub-assemblies to be joined together at a later stage.
- Standard parts should be preferred such as fasteners and other standard modules.
- The need to reorient the assemblies should be avoided.
- Parts should be fed into assembly machines in correct orientation, and they should be easy to orient by being symmetrical or clearly asymmetrical. Low centre of gravity also makes parts easy to feed.
- Parts should withstand the forces they face during feeding and assembly. Flexible, fragile and abrasive parts should be avoided.

Slocum (2008) notes that as production quantities get higher such as in automotive applications, in most cases minimizing weight and number of components outweigh any complexity caused in manufacturing as the tooling and machines used in the process are quickly amortized.

5.2.2 Design for quality

Both Jiang (2015) and Kuo et al. (2001) emphasize the importance of design quality aspect to be noted as early as possible in the product development process. Design for quality (DfQ) promotes the systematic translation of customer needs and functional requirements into engineering characteristics that can be controlled, optimized and made robust. Garvin (1988) has gathered eight dimensions for quality: performance, features, aesthetics, reliability, durability, serviceability, conformance and perceived quality. Objectives for DfQ can be divided into three main points: to design a product that meets customer requirements, to design a product that is robust against variation in manufacturing processes and product's environment, and to be able to continuously improve the product's reliability, performance and technology to reach performance beyond customer requirements. (Kuo et al., 2001)

Structured risk assessment methods are a key mechanism supporting DfQ. Failure Mode and Effects analysis (FMEA) being the most common one to identify failure mechanisms

early in design. Ouyang et al. (2022) note that traditional FMEA approach faces limitations such as equal weighting of factors and discontinuities in risk scoring, which can conceal major risks. Their proposed improvements include pairwise risk-factor combinations, grey relational analysis and fuzzy classification to provide designers better guidance on where quality improvements matter the most.

DfQ also adapts tools for embedding customer expectations into design decisions. Quality function deployment (QFD) converts customer attributes into measurable engineering parameters, enabling designers to align technical choices with user-defined quality targets. It is also recognized as a predecessor of DfQ. With consistent design decisions, products are made robust against variation in manufacturing processes and external conditions. (Jiang, 2015)

Other significant tool for DfQ is benchmarking. It is a process where you gather information and learn from the best in the industry on various business areas. It can be divided into internal, external and generic benchmarking. These include inspecting best performance inside an organization, among best competitors and best business practices in the world. Successful adaptation of benchmarking is a tool for competitive analysis and continuous improvement. (Kuo et al., 2001)

5.3 High pressure die casting

High pressure die casting (HPDC) is a casting method used generally for large series of a product, and it is capable to reach smaller wall thicknesses and more complex shapes than most other casting methods. Used alloys for the process consist of mainly non-ferrous metals such as aluminium and magnesium. The process is optimized for high dimensional accuracy, near net-shape complex parts with high production volumes. HPDC process includes melting desired cast alloy, injecting molten metal to a die cavity at high-speed using high pressure, solidifying the part under pressure, mold opening and finally part ejection from the die. (Lordan et al., 2022)

HPDC mold design development must consider and balance between three major factors of durability, productivity and dimensional accuracy. The mold faces ultimate thermal cycling and corrosive effects of the used cast alloys risking its longevity while to reach wanted production volumes and cost effectiveness the cycle times are being minimized. This on the other hand risks the quality of the formed part. Lastly to maintain dimensional stability the designer needs expertise to handle the complex solidification and shrinkage patterns of used alloys. To optimize these factors the research focus has shifted towards understanding fluid dynamics, thermodynamics and metallurgy. Tools used by engineers

to reach these goals include computational fluid dynamics (CFD) tools to design effective gate and runner systems and additive manufacturing (AM) methods to create more complex mold cooling systems compared to traditional ones. CFD-tools can help create optimized gating systems to reach laminar flow inside the mold cavity to minimize air entrapment. AM-methods can help produce mold cooling systems that follow the mold cavity precisely to ensure uniform cooling of the casting system. This can shorten the cooling cycle-times, decrease defects of the cast part caused by rapid uneven cooling and lengthen the lifetime of the mold. (Li, 2026)

Bonollo et al. (2015) state that an average of 5-10 % scrap rate is common using HPDC process. They list nine defects which are from the most common to least common: filling related defects, shrinkage defects, gas-related defects, undesired phases, thermal contraction defects, metal-die interaction defects, out of tolerance defects, lack of material and excess of material. The most effective way to prevent defects is using cast simulation tools but they still cannot predict all of them. They also state that to minimize the defect rate the process requires integrated tools that can combine real time sensor data with process parameters in addition to expert knowledge on relationships between process variables and defect types.

Designing tablet-like devices with minimal wall thicknesses, the main design challenge casting-wise is to reach sufficient flowability. With thinner cavities the contact area to the mold will increase significantly compared to the volume of the casting. This will cause the molten metal to lose heat rapidly to the mold during the filling stage. Higher injection speeds, mold temperature and usage of vacuum in the filling process can be applied to ensure complete filling of the mold cavity. (Li, 2026)

6. DEVELOPING PRODUCT PROPERTIES USING CPM/PDD

In this section, the CPM/PDD-method is applied to the design process of refined display housing to guide the process to be executed in a structured and traceable manner. The initial housing held as a benchmark product for the development process is used as a part of a centre information display assembly in a series production automotive vehicle. This usage environment sets some standardized legal and/or customer requirements, e.g. for stiffness, that are fulfilled by the initial design and the updated design should follow these requirements too. Section 6.1 creates the foundation for the development process by defining required product properties, characteristics and their relations. Initial design is evaluated, and its required properties are scored in section 6.2. This sets the benchmark scoring that will be compared to the scoring of the refined design at a later stage. Section 6.3 covers the needed amount of development cycles until satisfactory results are reached and termination of the development process is therefore justified.

6.1 Defining product properties, characteristics and relations

The required properties of a product form a guideline for assessing the feasibility and effectiveness of the proposed design. For this thesis' case the required properties include the following:

- Weight
- Stiffness
- Manufacturability
- Assemblability (Integration features, geometrical tolerances, dimensional tolerances, flatness)
- Cost

Out of these requirements, stiffness is the only one which goal is to be kept the same as in the previous design, while the other properties are minimized, maximized or optimized during the re-design.

The weight refers to the overall weight of the part or assembly, affecting handling of the product during production and power consumption during its use. Stiffness requirement is inherited directly from the performance values of the previous design which fulfils the

previously mentioned legal and/or customer requirements that have been followed in this product. Manufacturability comes mostly from the determined manufacturing processes and their capabilities for the proposed design. Assemblability considers its design of integration features and the specifications of geometrical and dimensional tolerances. Proper integration features have an impact on the final assembly complexity and time whereas appropriate tolerances ensure that the mounting interfaces fit together as planned. Cost covers all expenses related to the part or assembly including e.g. materials, tooling, processing, quality control and potential scrap and rework costs. All these factors make cost a major factor in evaluating the overall product feasibility for series production.

CPM/PDD-method suggests handling product characteristics in a structured form to enable systematic design decisions that align with performance, manufacturing and customer requirements. Table 5 recognizes and categorizes the main product characteristics based on the existing solution and the proposed patent design. Some characteristics are already defined as they should stay unmodified for the new design, so the previous and new design stay comparable in the most suitable manner for the research. Underlined items indicate the modifiable characteristics for the new design.

Table 5. *Product characteristics*

Geometry	**Material**	**Manufacturing processes**	**Quality**
Outer dimensions - Height - Width - Depth	Base material(s) & alloy(s)	<u>Casting method</u>	Surface quality
	<u>Surface treatment</u>	<u>Sheet metal forming method</u>	<u>Material porosity</u>
		<u>Machining</u>	
Mounting brackets		<u>Welding</u>	
Integration features		<u>Post-processing</u> - Heat treatment - Surface finish	
<u>Rib features</u> - Amount - Placement - Height - Width - Depth			
<u>Sheet metal features</u> - Thickness - Shape			
Machining allowances			

Characteristics were sorted into four main groups and their sub-groups for them to be more structured and more suitable to be visualized later in Figure 12. With required properties being defined and product characteristics recognized, we can proceed to defining

their relations. Figure 12 illustrates direct relations between product characteristics and required properties.

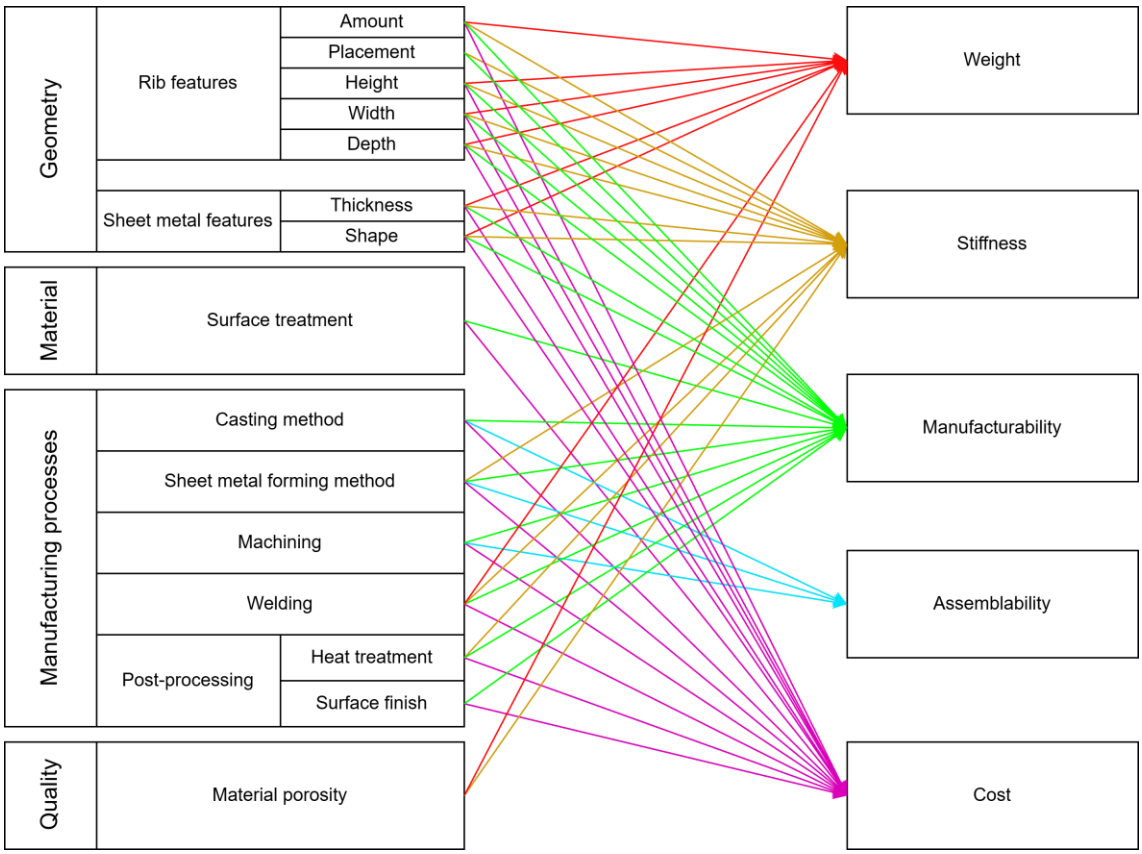

Figure 12. *Relations between product characteristics and properties* ***(RQ1)***

With product properties and characteristics being defined, we can proceed to the actual PDD-development cycles in the following section.

6.2 Initial design evaluation

To be able to properly compare the updated design to the initial solution, we need to evaluate its previously defined five required properties. Each required property will be scored on a scale of 0–10, where 0 is the worst and 10 is the best score. Scores will then be summed together to create overall score for the evaluated design. Table 6 summarizes the scoring of the initial design.

Table 6. *Initial design scoring*

Property	Score
Weight	5
Stiffness	7
Manufacturability	7
Assemblability	8
Cost	7
Sum	34

Total mass of the initial design is its greatest weakness currently, and it is also one of the main motivations for this development project. Excess usage of material for the back cover due to manufacturing process limitations also increases the cost of the device. In its current state the back cover thickness needs to be balanced between manufacturability capabilities and material usage which affects both weight and cost of the part in a negative manner.

The design fulfils the set stiffness requirements so in a sense it is on a good level. The amount of used material might still not be so optimized to reach the requirements. Therefore, the scoring for stiffness is lowered a bit as it sacrifices the quality of other properties by using material where it is not necessary stiffness-wise.

High pressure die casting using aluminium is a common manufacturing method for this type of structure with high production volumes. It is a stable process, but it has its limitations related to e.g. minimum wall thickness. The initial design is feasible for relatively simple two-piece mold with single pulling direction and ejection pins without the need to use e.g. slides. In addition to casting and its limitations, the part needs to have some features machined to meet with surface quality and dimensional tolerance requirements.

Assemblability is ensured by locating features being machined instead of being raw cast features. Fixturing features for machining are generated in the casting process for easier handling and accurate mounting.

HPDC as a process is the most cost-effective manufacturing method for high volume cast parts. Though its previously mentioned weaknesses indirectly affect the total cost

of the manufactured part. The need for machining is also a negative feature for the product's cost.

6.3 CPM/PDD development cycles

In this section and its sub-sections, introduced PDD-method development rounds will be executed based on defined product properties and characteristics to meet with defined requirements and to terminate the development process. Each development round is handled in their own sub-section and each round will focus on properties that are found to be the most relevant for the product's performance at the time. Each development round with their solutions will provide answers to the second research question of how the selected properties can be developed. **(RQ2)**

6.3.1 Round 1

The first PDD-development round focuses on optimizing the products' weight and stiffness as they are heavily dependent on each other as presented in Figure 12. This also leads to the first paradoxical situation as generally decreasing mass also decreases stiffness while in ideal situation mass would get minimized and stiffness would get maximized. The initial design uses a honeycomb shaped rib structure, so its simulation results will be used as a benchmark and alternative solutions are compared to the performance of the benchmark design. Figure 13 illustrates the first synthesis step.

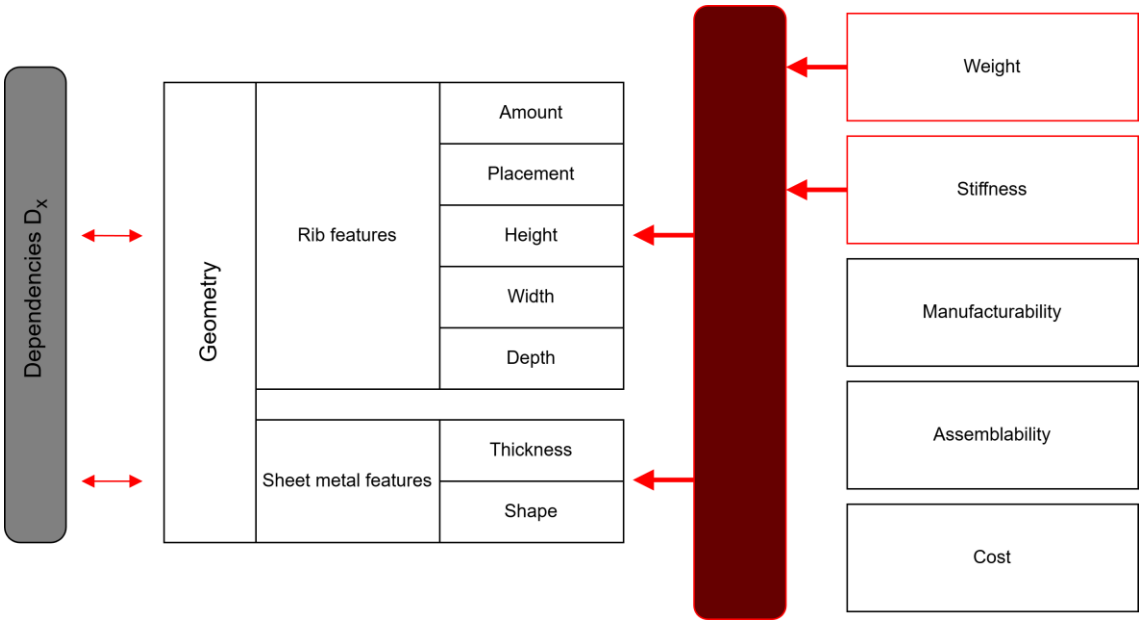

Figure 13. *Round 1 synthesis*

Four additional rib structure shapes were defined to be evaluated: triangle, rectangle, freeform and combined which adds diagonal support ribs to the rectangle shapes. Each

rib structure variation was dimensioned to match the mass of the initial design for their stiffnesses to be directly comparable. Mass of the initial housing with honeycomb shaped rib structure was 683,7 g and suitable accuracy for the mass matching was defined to be ± 5 g between different variants.

FEA-study was performed on the variants using Catia V5's Generative Structural Analysis workbench. The housing's performance was evaluated by comparing found maximum von Mises stress and displacement values from the simulation results while a force of 100 N was applied to a circular area with a radius of 10 mm to the part via cover glass and adhesive as the part would be assembled in its final use case environment. The simulation was repeated while the force was directed to the centre of the cover glass and secondly to the corner of the cover glass. Areas where force was applied are illustrated in Figure 14.

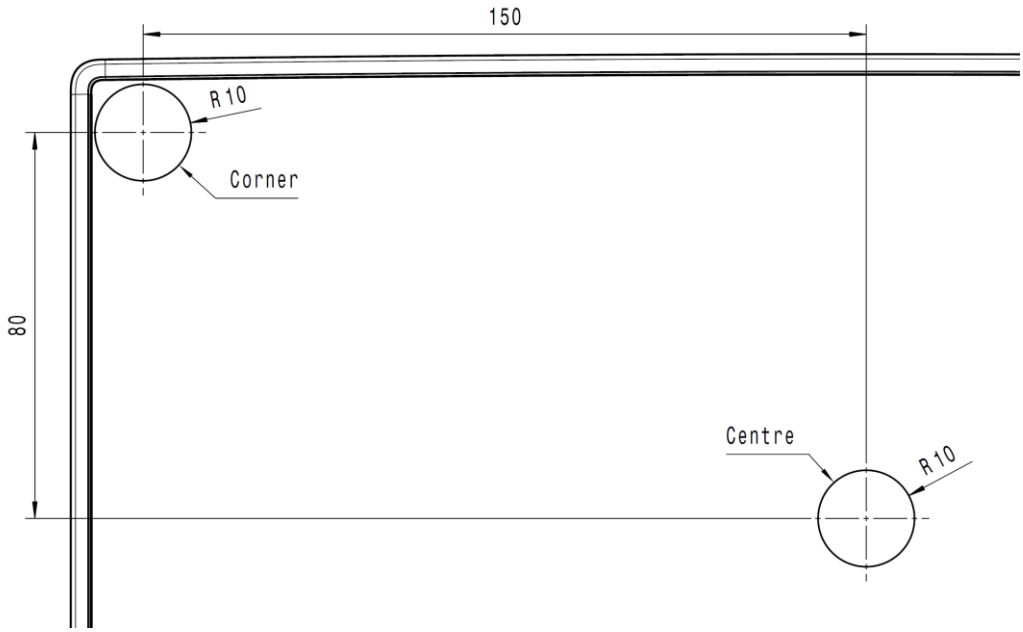

Figure 14. *Applied force areas*

Simulation results are reported in Table 7 with red and green cells highlighting the best and worst designs for each simulation result. Screenshots of the simulation results can be found in appendix A.

Table 7. *FEA-study results for varying rib shapes*

	Mass (g)	Von Mises stress (MPa)		Displacement (mm)	
		Centre	Corner	Centre	Corner
Honeycomb	683,7	11,4	28,8	0,0869	0,156
Triangle	678,7	10,6	28,6	0,0672	0,147
Rectangle	685	12,4	31	0,0643	0,159
Freeform	684,8	9,92	28,2	0,0617	0,144
Combined	683,9	12,9	30,8	0,0689	0,144

The simulation results clearly indicate that the freeform shaped rib structure performs in the most effective way under the given conditions. The effect of the back wall thickness of the housing will therefore be studied while using the freeform rib shape for the part. The back wall thickness is varied on a range from 2,5 mm down to 0,25 mm using 0,25 mm steps and simulated while the force is applied to the corner of the assembly as earlier. The simulation results for maximum von Mises stresses and displacement values are presented in Table 8.

Table 8. *Simulation results for variable back wall thicknesses*

Thickness (mm)	Mass (g)	Von Mises stress (MPa)	Displacement (mm)
0,25	352,9	69,4	0,285
0,50	390,6	49,2	0,246
0,75	428,0	43,6	0,224
1,00	465,2	41,0	0,208
1,25	502,2	39,0	0,198
1,50	538,9	37,5	0,182
1,75	575,4	40,4	0,179
2,00	611,5	37,5	0,169
2,25	647,4	36,0	0,158
2,50	683,4	33,2	0,149

Total mass of the housing was logged for each back wall thickness and its trend is visualized in Figure 15. As expected, the change is quite linear compared to the back wall thickness. The draft angle of the ribs affects the linearity of the mass development as the bottom of the ribs get wider while the back wall thickness is decreased. It can also be read from the trendline that the mass of the freeform shaped ribs total at around 315 g when the back wall thickness is reduced to zero. This is worth noting as while keeping the outer dimensions of the housing unchanged, the change in back wall thickness also affects the height of the ribs and therefore their mass. With the maximum compared back wall thickness of 2,5 mm the mass of the ribs decreases down to 195 g.

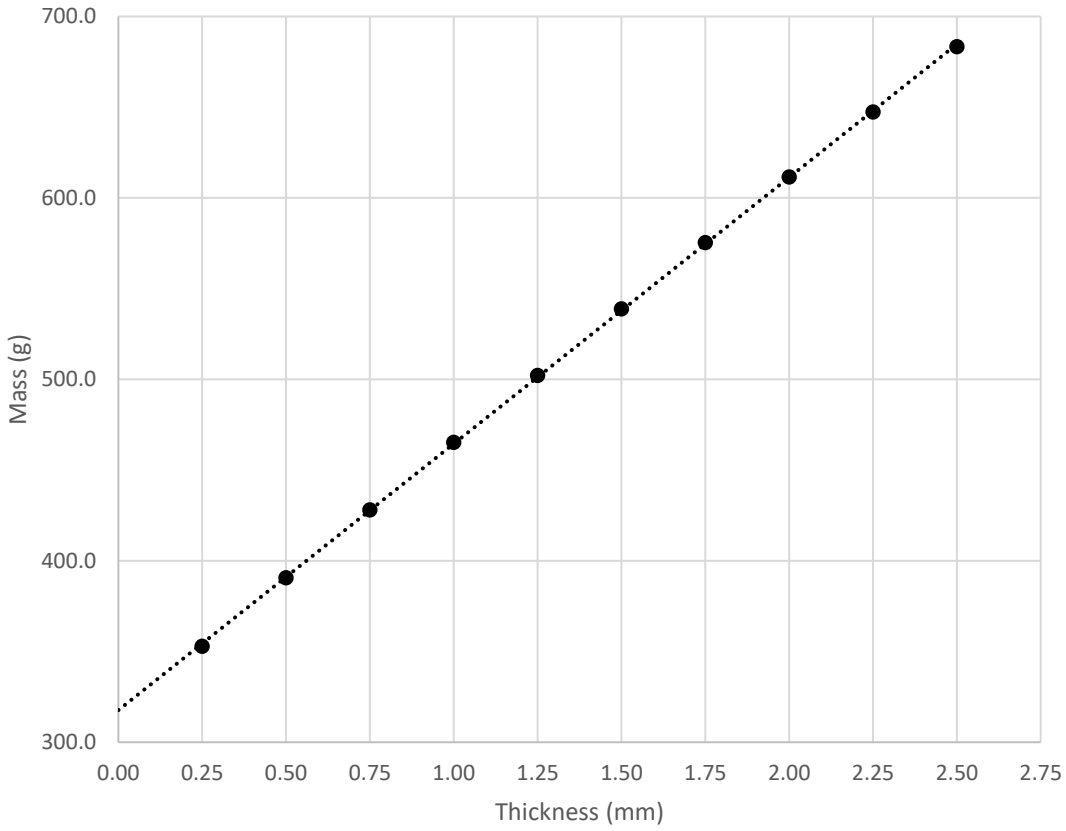

Figure 15. *Housing mass related to back wall thickness*

Figure 16 visualizes the logged simulation results of maximum von Mises stresses and displacement values shown in Table 8. Their development is not that linear as for the mass and a s-shaped trendline can be fitted to both data sets. For both trendlines their slope decreases around the same back wall thickness which is 1,5 mm. This can be determined as the optimal back wall thickness for the design as with smaller values the von Mises stress and displacement values start to grow exponentially.

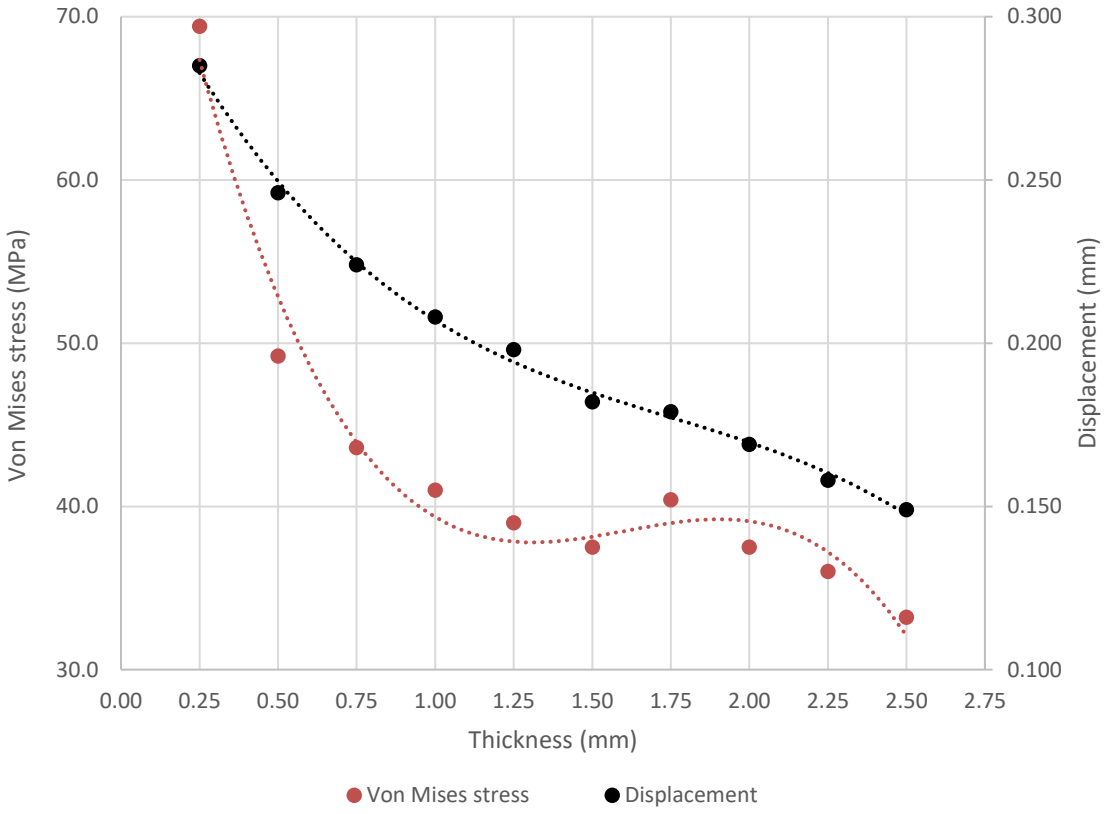

Figure 16. *Maximum von Mises stress and displacement values for variable back wall thicknesses*

The optimal rib shape and back wall thickness being found, the design can now be optimized to match the stiffness requirement while minimizing mass. This can be done simply by adjusting rib thickness until the stiffness meets the required target level. Initial rib thickness was 1,5 mm and it was increased to 2,3 mm for the design to match with the stiffness requirement. After the modification the mass was found to be 626,2 g compared to the original 683,7 g honeycomb design which is an 8,4 % decrease.

Optimized dimensions are transformed into the proposed patent design with separate rib structure and sheet metal back wall. Manufacturability of the rib part was assessed using Altair Inspire Cast simulation tool. Runner, gating and overflow systems were designed for the part using Catia V5. HPDC process parameters were assigned, and simulation was run for filling, solidification and demolding steps. Initial honeycomb design was used as a benchmark to evaluate castability of the updated designs.

Complex weblike structure creates a narrow and a long route for the melt to fill the mold cavity. The simulation reveals issues with cavity filling, mold erosion, air entrapment and cold shuts. Large part surface area to casting volume ratio and complicated filling route causes melt to cool rapidly and therefore cavity cannot be filled completely with feasible casting parameters before solidification. Even if filled successfully, separated flow fronts

would meet in each horizontal rib causing cold shuts as presented in green colour in Figure 17.

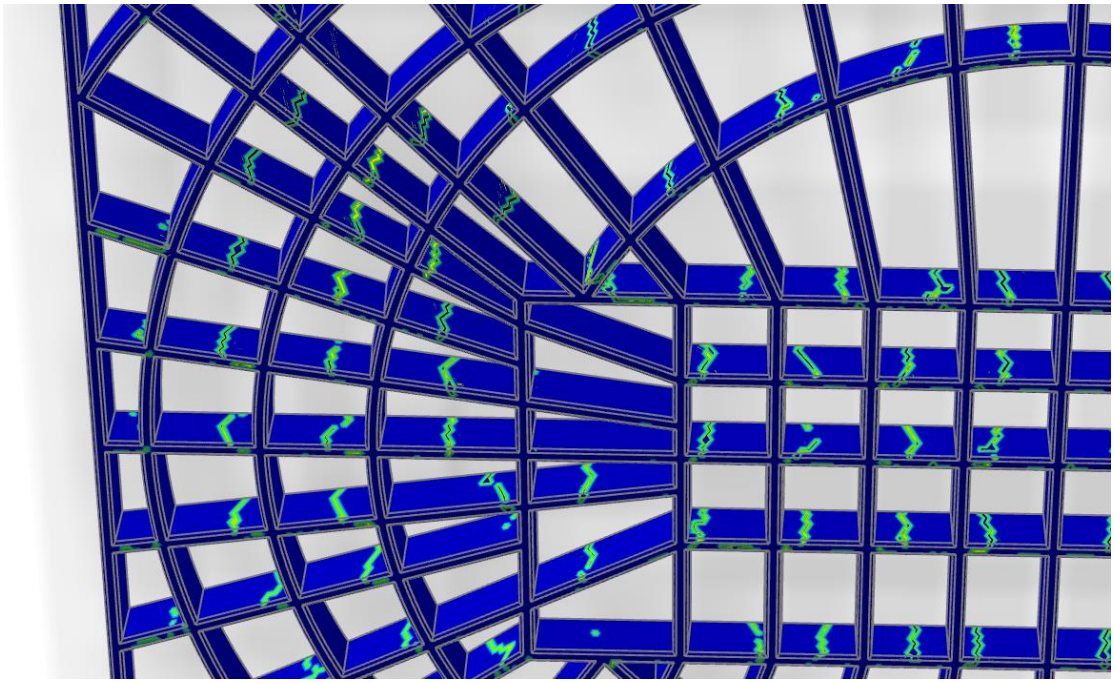

Figure 17. *Rib structure cold shuts*

The solidification pattern for this type of a web structure is also problematic. Figure 18 illustrates how solidification occurs after filling where blue and white areas represent solidified and liquid material. Intersections of the ribs create hot spots where solidification occurs last. These spots are vulnerable for porosity defects and are also placed critically in the intersections of the ribs which should be creating the structural integrity of the design. The solidification pattern can be manipulated using overflows in addition to the actual design of the final part. With problematic areas in each intersection this solution is not feasible.

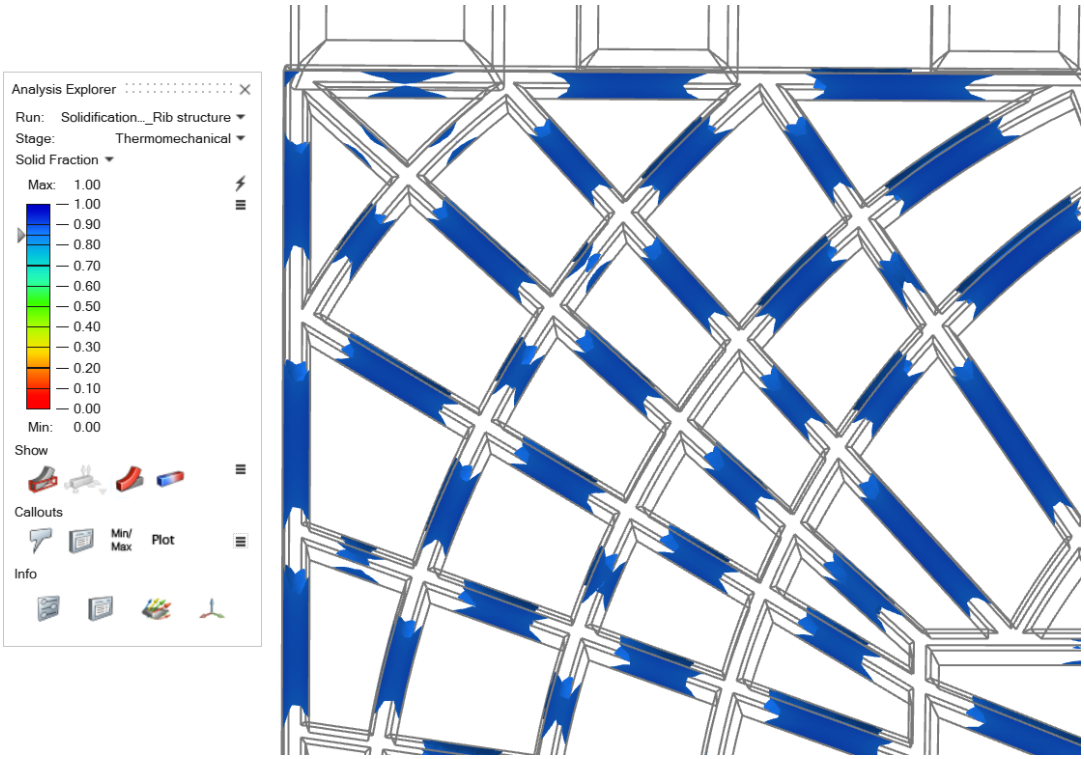

Figure 18. *Rib structure solid fraction*

The analysis step for round 1 is illustrated in Figure 19. The weight reduction of 8,4 % for the design upgrades the overall weight evaluation score to 8. The stiffness being kept the same as original, also the score is kept the same at 7. Issues with the rib design sets the score for manufacturability to 0.

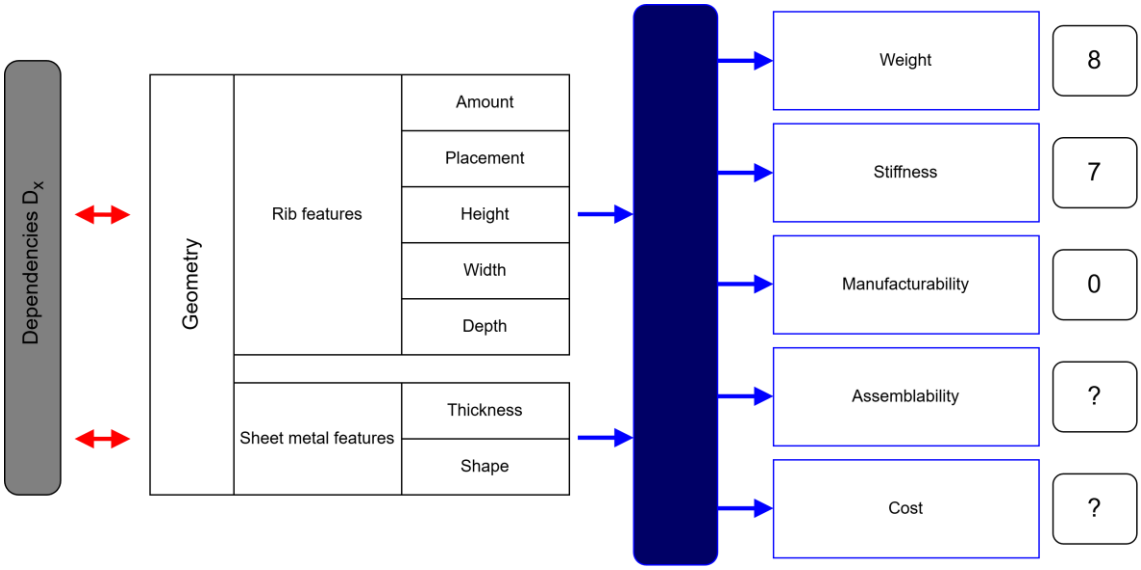

Figure 19. *Round 1 analysis*

Round 1 analysis step will be terminated after the found issues with the rib structure manufacturability. Scoring for the assemblability and cost are therefore irrelevant and

are left unknown for this round. They will be refined in later rounds while other properties are found to be feasible again by updating characteristics.

6.3.2 Round 2

The second development round focuses on manufacturability of the part as the first development round found the cast rib design to be unfeasible to manufacture. The design solution is revised back to a single cast part as in the initial design but the rib design and back wall optimization from the first development round are included as a starting point for this round. Figure 20 recognizes modifiable characteristics for the second development round.

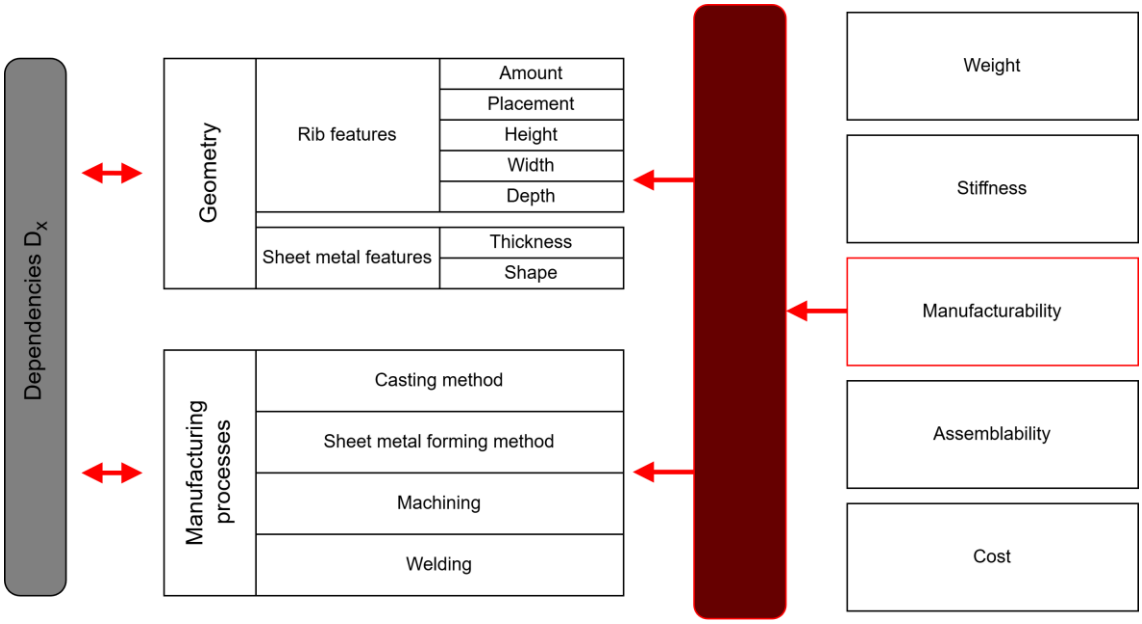

Figure 20. *Round 2 synthesis*

Manufacturability of the optimized design in the first development round is evaluated again using Altair Inspire Cast but as a single cast part. Back wall and rib thicknesses are gradually being developed towards rib thickness being smaller fraction of the back wall thickness. Each step's castability was simulated and assessed. Table 9 includes used thicknesses and percentual rib thickness' fraction of the back wall thickness during the second development round.

Table 9. *Back wall and rib thicknesses*

		Back wall thickness (mm)	Rib thickness (mm)	Rib-%
(A)	Honeycomb, round 1	2,5	1,5	60,0
(B)	Freeform, round 1	1,5	2,3	153,3
(C)	Freeform, round 2.1	2,0	1,8	90,0
(D)	Freeform, round 2.2	2,4	1,5	62,5

The first reviewed simulation result is cold shuts as it was a major issues with the rib design in the first development round. The single part design with back wall allows the melt to flow more freely through the part. The freeform rib design seems to perform even better than the honeycomb design even with smaller back wall thicknesses as seen in Figure 21. The simulations show no issues with cold shuts and the design can be approved from this point of view.

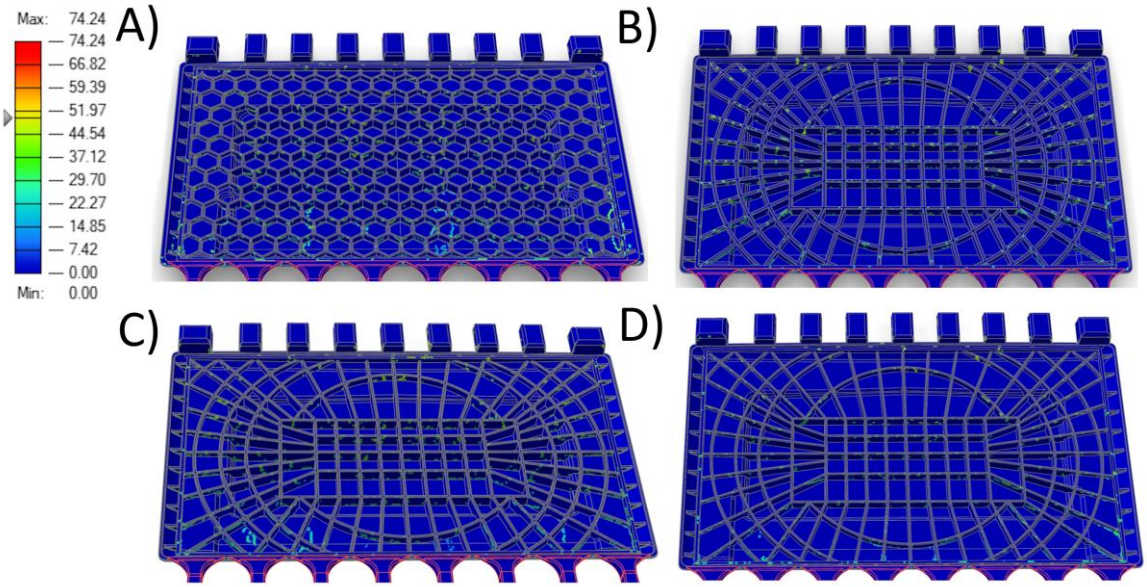

Figure 21. *Cold shuts*

Next the design was assessed by looking at the solidification times. Uniform solidification times for the cast part is crucial to reach the quality requirements of the part. Hot spots in the part can be identified clearly by inspecting the solidification times. These thermal concentrations lead commonly to defects such as shrinkage cavities, micro-porosity and local structural weakness. Too rapid cooling can also cause feeding issues. Development of solidification times between design iterations is visualized in Figure 22 below.

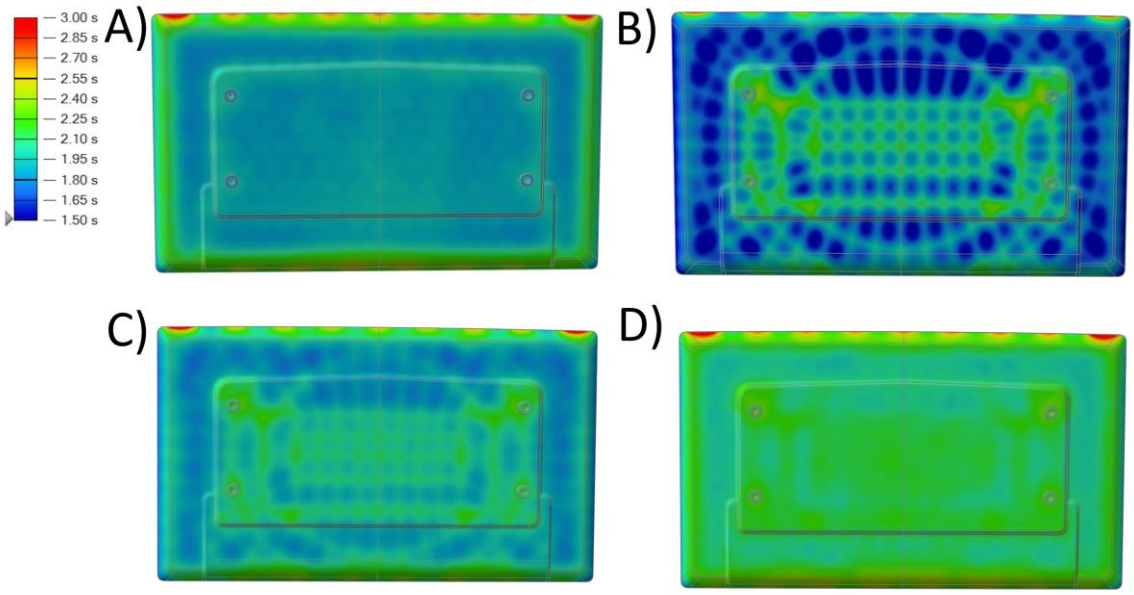

Figure 22. *Solidification times*

Design iterations were made again so that the corner displacement values should stay unchanged. Reviewing the refined FEA-study results in Table 10 it can be noted that the design updates have virtually no effect to the corner displacement values and the von Mises stress values have stayed at an acceptable level. Also, the centre displacement values, and their changes are so incremental that they have no effect on the parts performance. Table 10 summarizes FEA-study results for the second development round.

Table 10. *Updated FEA-study results*

			Von Mises stress (MPa)		Displacement (mm)	
		Weight (g)	Centre	Corner	Centre	Corner
(A)	Honeycomb, round 1	683,7	11,4	28,8	0,0869	0,156
(B)	Freeform, round 1	626,2	13,0	28,2	0,0545	0,156
(C)	Freeform, round 2.1	638,0	9,4	31,4	0,0595	0,156
(D)	Freeform, round 2.2	657,4	10,6	30,5	0,0635	0,155

Third iteration (D) of the freeform shaped housing design was found feasible for manufacturing. First iterations faced micro porosity and sinking defects due to too thick rib sections compared to the back wall thickness. The root cause of insufficient back wall-rib thickness ratio and its effect to solidification times inside the part was illustrated in B)-section in Figure 22. Refinements of the design during the second development round until finding a viable solution led to a new mass for the housing of 657,4 g which is a 3,9 % decrease compared to the original honeycomb design with a mass of 683,7 g.

The second development round is concluded with analysis step illustrated in Figure 23. Following the first development round it was known that the weight of the part needed to be increased to make it manufacturable again. Design iterations led to a point where the final mass of the part was 3,9 % lower than the original design but 5,0 % higher than the design in the first round. This sets the scoring for weight to 7. Goal for the stiffness was to be kept at least the same as in the original honeycomb design. The goal was achieved, and the stiffness values have stayed at the original level. Hence the scoring for stiffness is kept at 7. Manufacturability was the issue with the first development round and adjustments to part back wall and rib dimensions were made to regain manufacturability. The effects of the design changes on manufacturability were evaluated by simulating castability. After the design updates the part is castable, but the original honeycomb design outperforms it in some areas. The scoring for manufacturability is rated at 6. Assemblability stays unchanged as the integration features and their manufacturing methods were kept the same. Scoring for assemblability stays at 8. Cost has a similar situation as with assemblability and stays unchanged while no significant changes were made to affect the cost of the part. Lighter weight decreases material usage and therefore the overall cost, but the change is cost wise so slight that the score is kept at original 7.

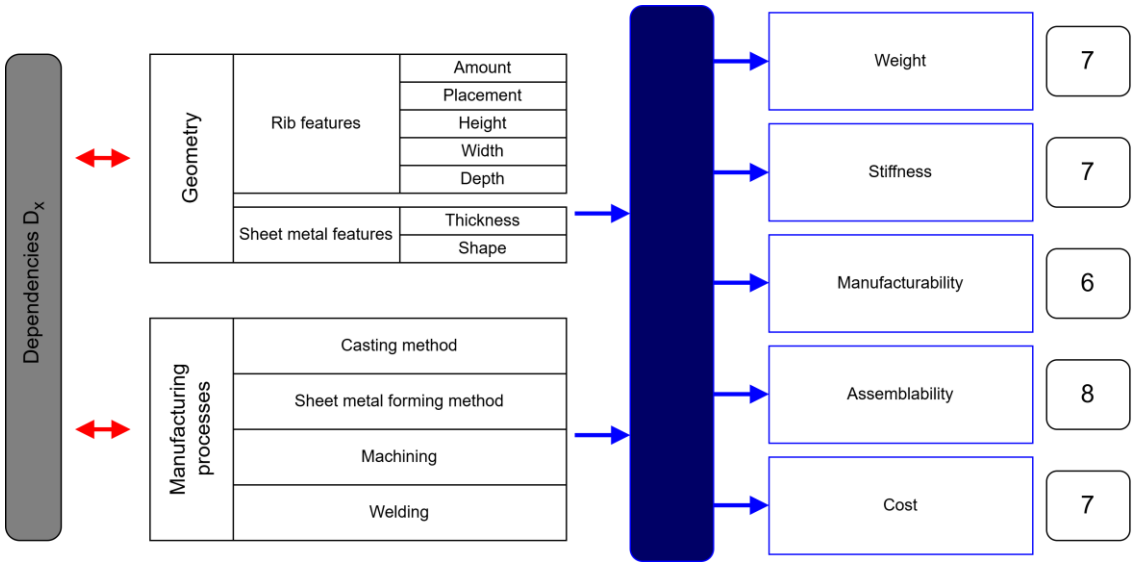

Figure 23. *Round 2 analysis*

After the second development round the process is terminated since the patent based separate cast rib and sheet metal back wall structure design was not feasible for manufacturing and feasible weight optimization was executed successfully during the second development round. The following section gathers the results found during the development rounds.

7. RESULTS

The total number of development rounds executed for the design was two. The first development round focused on mass and stiffness optimization as they were recognized as primary areas for improvement during the development process. Design changes made to optimize these properties had the most negative effect on products manufacturability estimation. The casting simulations performed on the rib structure adapted from the patent design idea during the first analysis step proved it to not be feasible for manufacturing. The structure faced issues with filling, constant solidification and cold shuts while using high pressure die casting process. This forced the development process to be continued by discarding the design idea adapted from the patent and to keep on with the original singular cast part design characteristics.

The second development round switched focus on manufacturability of the part as a single casting as the previous design changes had the biggest impact on it. To regain wanted level of manufacturability, in this case castability, the geometry related characteristics were refined to optimize the design by utilizing known dependencies, solution elements, between mass, stiffness and manufacturability. The outcome kept the stiffness properties similar to the original and upgraded the manufacturability to an acceptable level by sacrificing some improvement gained on the parts weight.

Assemblability and cost were found to be unchanged compared to the initial solution but also were not found to be sensible to focus development round on them as discarding the patent design idea changed the approach to the design process significantly.

7.1 Design evaluation

Discarding the patent design idea due to the manufacturability issue led the development process to be more like an optimization process with incremental advances in its evaluated and scored required properties. This section will walk through all five set required properties.

Weight

Minimizing weight of the product was one of the main goals of this thesis. The outcome of the design development process was a weight reduction of 3,9 %. One of the designs

had a weight reduction of 8,4 % compared to the initial design while maintaining its stiffness but it was not found manufacturable using investigated manufacturing methods. Main weight reduction was achieved by optimizing the back wall thickness and converting the rib shape from repetitive pattern to a freeform shape. Non-repetitive rib shape can handle the forces the housing faces more efficiently by placing them properly based on mounting features and known operating conditions. The reduction is quite incremental with presented display size in the context of a singular device on a passenger car. It is still notable that the impact of the weight reduction can become more significant if the device size gets bigger or if there are multiple devices in a single vehicle.

Stiffness

Stiffness values of the original design were determined by performing a FEA-study in the beginning of the development process. The results were used as a guideline that was followed as the required stiffness is legal based or sometimes defined by the customer if higher than the legal requirements. Updated design aimed to have the same stiffness as the original design as higher than required values do not bring any competitive advantage. The displacement values stayed practically unchanged during the development process. The von Mises stress distribution around the housing evolved between design iterations. The updated design has a bit higher maximum local stress values than the original, but the increases are moderate, manageable and do not cause any further actions. Hence the design goals stiffness wise were reached.

Manufacturability

Similarly to the stiffness values, the manufacturability of the original design was assessed by using simulation tools. This time a casting simulation tool was exploited. Evaluating manufacturability is not as straight forward as for the stiffness values earlier as the simulation setup and results both includes many parameters and need to be thoroughly evaluated to gain knowledge about the manufacturability of the part. It is also more or less iterative process to reach satisfactory results from the simulation. Manufacturability of the patent design was determined to not be feasible for manufacturing. Manufacturability was regained after design refinement. Various backwall thickness and rib shape combinations were simulated and that way optimized for manufacturability while maintaining as low weight of the product as possible. Found manufacturable design included back wall thickness nearly as thick as the original design and freeform rib shape formed during the first development round.

Assemblability & cost

These properties stayed unchanged during the development process. Assemblability and cost aspects of the design would have become significant if the design from patent proposal would have been applied to the part. This way the new solution would have possibly included also sheet metal forming and welding as manufacturing methods in addition to now used high pressure die casting. Now made design changes can be achieved while keeping the manufacturing process as with the initial design and therefore assemblability and cost stay unchanged. Required properties' scoring from the second and final development round is gathered to Table 11.

Table 11. *Updated design scoring* ***(RQ3)***

Property	**Score**
Weight	7
Stiffness	7
Manufacturability	6
Assemblability	8
Cost	7
Sum	35

The updated score for the design sums up at 35 points where the original design was rated 34 points out of the maximum score of 50. Figure 24 illustrates scoring changes on the designated properties.

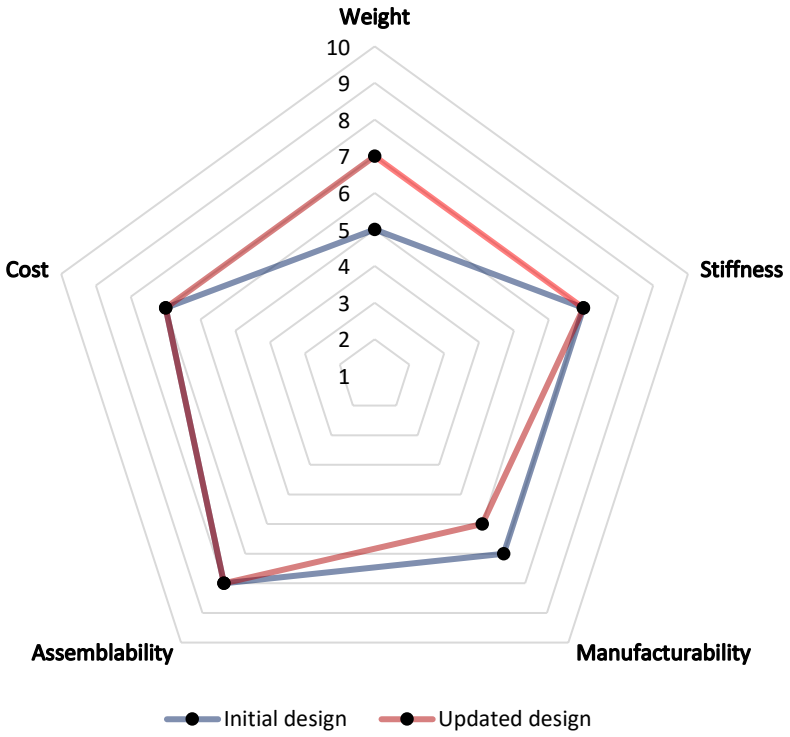

Figure 24. *Design scoring comparison*

It can be noted that the biggest improvement was made on the products weight where manufacturability faced some degradation. Other three properties were scored similarly as for the initial solution.

7.2 Research questions

In the beginning of this thesis four research questions defining its scope and objectives were formed. The following section summarizes the findings related to the research questions.

RQ1: Which characteristics of the current design affect its performance properties?

Product properties, characteristics, their relations in both analysis and synthesis directions and dependencies were recognized during the design process following Weber's CPM/PDD approach. The main characteristics affecting product's performance properties were found to be the geometrical dimension characteristics related to the rib and back wall features in addition to the manufacturing methods used for adapting the patent idea. All recognized characteristics are presented in Table 5 and underlined of those represent the modifiable ones following this thesis' scope respectfully.

RQ2: How can the found characteristics be developed?

During two development rounds product performance properties were developed by mainly refining the dimensions and shapes of the rib and back wall structures. To succeed in this optimization process, known solution elements were used to lead the design choices. Due to the dependencies of the established characteristics the development process could be described as an optimization process. The weight, stiffness and manufacturability properties have such dependencies that while you are improving one at least one of the remaining two will be compromised. Usage of topology optimization tools especially for the rib shape design is advised as it was proven that even the sketched freeform shaped design outperformed all the repetitive rib shapes.

RQ3: What is the impact of this development on the product's performance?

Initial solution model was scored with 34 points in the beginning of the development process. After the CPM/PDD development process using the same scoring system the product reached 35 points. Total improvement based on this scoring system was 1 point. This does not play a significant role on the product's performance. Though it is mentionable that the improvement was focused on the mass minimization of the product while sacrificing manufacturability. If the manufacturability can be held at an acceptable level, even smaller improvements in weight management will start to play a larger role when adapted to larger display sizes which is not too far-fetched looking at the automotive display trends.

RQ4: How suitable is the CPM/PDD approach for the company's product development processes?

The CPM/PDD framework was not found explicitly suitable for the company's needs in their product development process. Its benefits were recognized in its well-structured approach in defining product characteristics, properties and relations forming cross-department product knowledge and boosting product development efficiency. The need for systematic following of the framework was also found more beneficial for junior level engineers rather than more experienced ones.

7.3 Managerial impact

Main managerial impact of this thesis is how CPM/PDD framework can help in suitable resource allocation during the early development phase. The framework guides major design decision to be made during the conceptual phase of a product where they are the most cost-effective. This is also a recognized in literature. Ullman (2016) defines the goal of a design process to manage process in a way that the most engineering changes are

faced as early as possible during the process. Boothroyd et al. (2010) also recognize that engineering changes become more costly the later they are faced in the development process. Figure 25 presents ideal and actual working hour curves used in a development process.

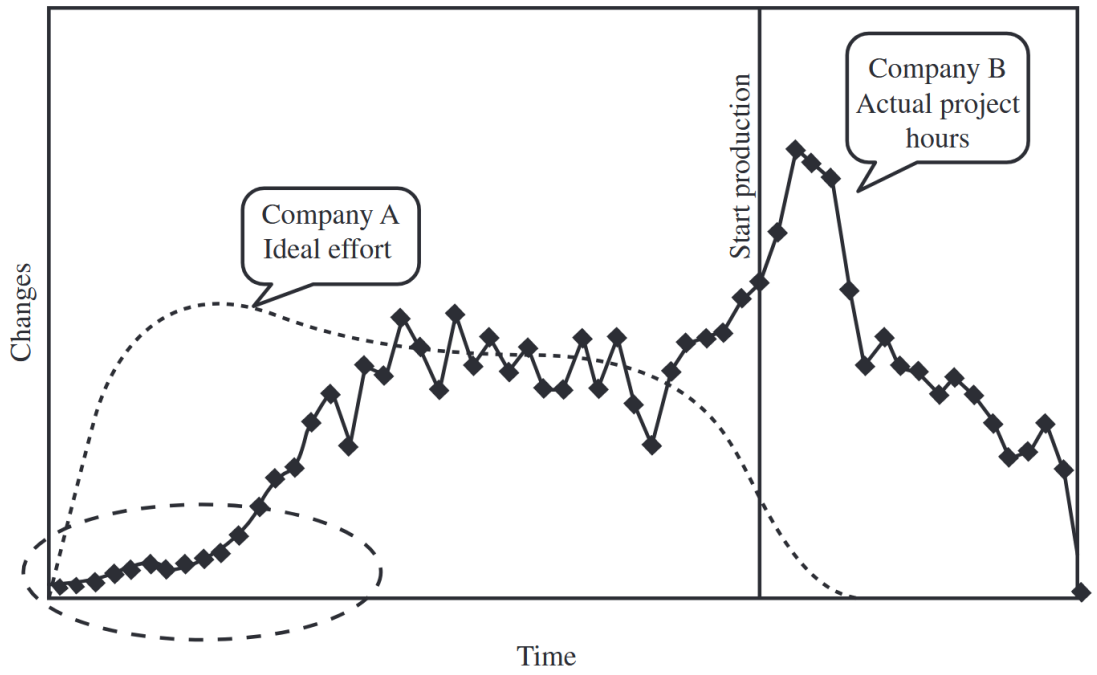

Figure 25. *Engineering changes during development process (Ullman, 2016)*

The product modelling aspect of Weber's CPM/PDD framework was found the most advantageous for the company's use. It is suggested to trial CPM framework for creating product or system level knowledge to create cross-department understanding on product characteristic relations. This could improve design process lead time as possible design limitations are recognized widely before clashing design solutions are proposed or developed even further.

The framework can also be seen beneficial in the context of competence development. Structured approach of the method forces designers to justify their decisions instead of relying solely on prior experience or intuition. This explicit nature of the framework makes it useful especially for junior level designers as it can prevent simple mistakes and creates a traceable reasoning path when mistakes happen.

7.4 Future development suggestions

Even though the proposed design idea from the patent was discarded in this study, it should not be left without attention. It has potential to help achieve major weight reduction in the display housing design. To achieve manufacturability for the product including

sheet metal back cover, alternative solutions for the now proposed cast rib part should be studied. High pressure die casting was not found to be a feasible manufacturing method for the rib part. Alternative solutions could include extremely reshaped rib designs, usage of sheet metal parts with perpendicular orientation compared to the back wall or parts created using additive manufacturing methods.

Regardless of the manufacturing method, the usage of topology optimization tools is recommended at least for the rib design. Done comparison on various rib shapes proved that repetitive patterns have weaker structural performance than more organic freeform shapes. In this study no topology optimization tools were adapted yet still the created design outperformed rib shapes generally used in the industry. Adaptation of a topology optimization tool should be quite straightforward as the external conditions and fixing points are generally well known for the housing during the design process. The tool could create preliminary rib designs which then could be approved and refined by the designer to be suitable for selected manufacturing methods. For cast parts it is suggested to include foundries in the design process as early as possible to claim as much beneficial process information, design guidelines, process limitations and possibilities.

8. DISCUSSION

Evaluating reliability of the research, following the CPM/PDD framework during the development process created a consistent base for the study. Usage of identical FEA-study parameters and comparable casting simulation parameters ensured the comparability of the results between development phases. The systematic relations between defined properties and established characteristics made design decisions easily traceable and helped maintain methodological continuity during the development rounds. On the downside, the lack of physical prototype leads the study to fully rely on simulation assumptions and simplifications.

Accuracy of the FEA-studies are considered to be on good level. Simulation parameters are well known, the setup of simulation is quite straightforward and given results from the linear structural analysis under load are directly comparable between design iterations. Accuracy of the casting simulation results need more consideration. The complexity of the process parameters and their dependencies need advanced knowledge on the topic to be perfected. This study aimed to create simplified yet accurate enough casting process which could be simulated in a reasonable time with available computational resources. These results could then be analysed and compared between the design iterations. The original series product was used as a benchmark device for both FEA and casting simulation studies. This was especially useful while designing the casting simulation as knowing it being manufacturable, the casting results on set parameters could be approved on higher reliability.

Internal validity of the research is considered strong as the required properties for the product are clearly defined and they are evaluated consistently using appropriate analysis tools. Observed outcomes based on used simulation tools correlated with theoretical expectations strengthening the confidence in made conclusion. Again, the lack of physical prototyping sets limits especially to the assessment accuracy of the products manufacturability. Therefore, the validity of the research is more robust for comparative analysis than for predicting the absolute behaviour of a real-world product.

Generalizability of the study is most evident in its methodology which combines the CPM/PDD framework to simulation-based validation tools. This can be applied to various types of structural components in addition to here used display housing. Established solution elements related to rib shapes, back wall thickness, structural performance and manufacturability can be exploited in broader catalogue of aluminium high-pressure die

cast products. Here shown results on the other hand are highly limited to this study with their numerical scoring. Therefore, the generalizability of presented results and exact geometrical guidelines for optimal design remain limited.

The possibilities for a substantial novelty for this research got highly reduced once the patent-based design idea was ultimately discarded due to manufacturability issues. This guided the study from conceptual innovation process to an optimization process of an existing design. The added value from this study focuses mainly on its focused methodological approach. Combining CPM/PDD framework with simulation tools offer a consistent cyclic development process to adapt in early-phase mechanical design.

9. CONCLUSION

This thesis studied the applicability of Christian Weber's CPM/PDD-method on improving mechanical design of an existing series-product by integrating proposed patent-based design features on the product. The aim was to construct a mechanical solution that is lighter in weight than the current mass-produced design while maintaining its stiffness and other required properties on an acceptable level. Utilizing CPM/PDD-framework the required properties for the product were defined, existing product characteristics were recognized, and their relations were analysed. This created systematically collected base knowledge on the product for the PDD-development cycles.

Defined required properties for the product were weight, stiffness, manufacturability, assemblability and cost. The first development round focused on weight and stiffness of the product. FEA-studies were performed for the proposed designs to verify their performance. The lightest design proposal had reduced weight by 8,4 % compared to the original design but during the first development rounds analysis step it was found not to be manufacturable. This led to discarding the patent proposed design with its manufacturability issues which were identified by utilizing casting simulation tools. The development focus got shifted on the manufacturability property for the second development round. With known solution elements and gathered knowledge from the first development round the geometry of the product was optimized to regain manufacturability with minimal increase in weight. The final design gained weight compared to the first development round and ended up being 3,9 % lighter than the initial design.

The most influential product characteristics for the design were found to be the rib geometry and back wall thickness. To optimize these an iterative development process was utilized, and the proposed design solutions were validated by using FEA-simulation and casting simulation tools. The final design solution gathered improvement in its weight performance but had a slight reduction in manufacturability. Total scoring for the original design was 34 points whereas the updated design was rated at 35 points. The differences were found in scoring for mentioned properties of weight and manufacturability. Scoring for stiffness, assemblability and cost stayed unchanged.

CPM/PDD framework was not found to be explicitly suitable design methodology for the company's usage. The systematic modelling of the product and recognition of computer-based methods usable during the development process were found to be advantageous creating cross-department product knowledge. The gathered product knowledge can be

useful in developing further revisions of an existing product or the established solution elements can be adapted on new products. The product development process was found to be more useful for junior level designers and less useful for more advanced level designers. The process is rather clunky and time consuming.

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APPENDIX A: FINITE ELEMENT ANALYSIS RESULTS

Corner displacement values

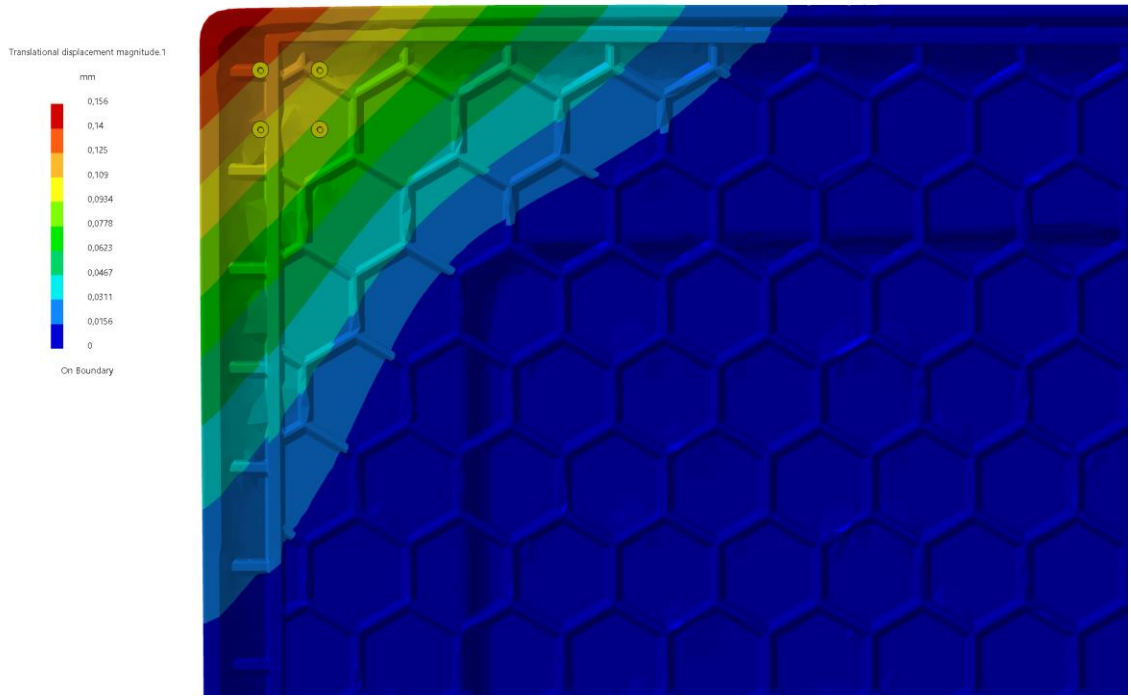

Figure A1. *Honeycomb corner displacement*

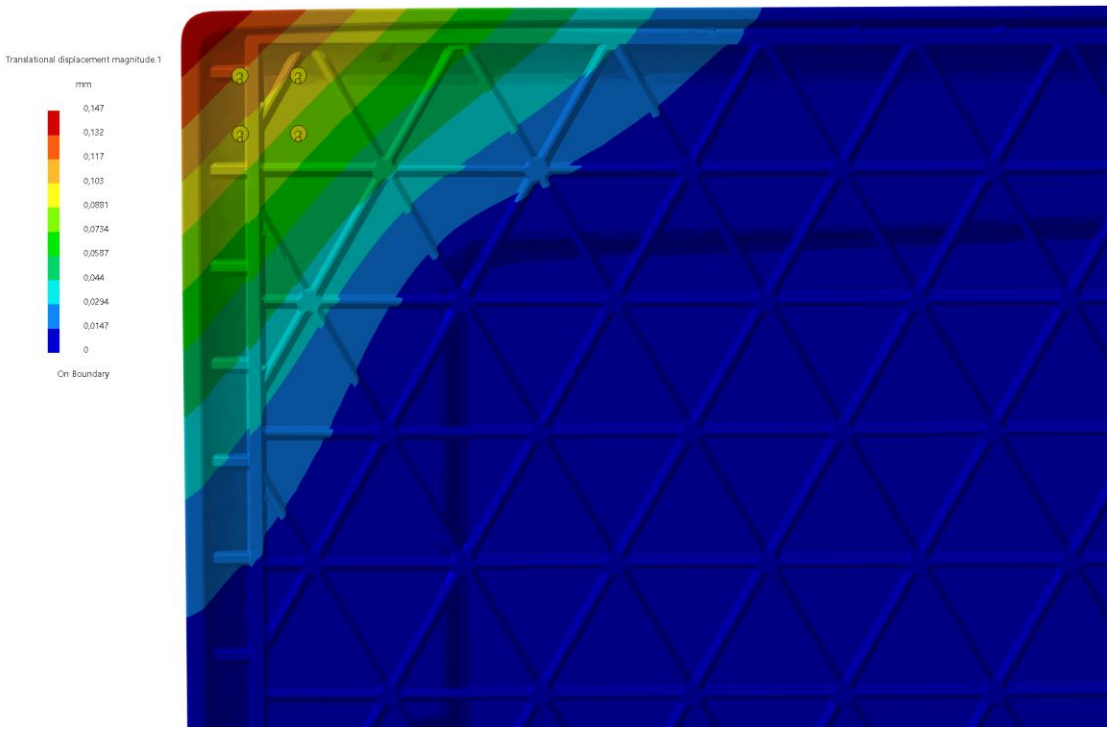

Figure A2. *Triangle corner displacement*

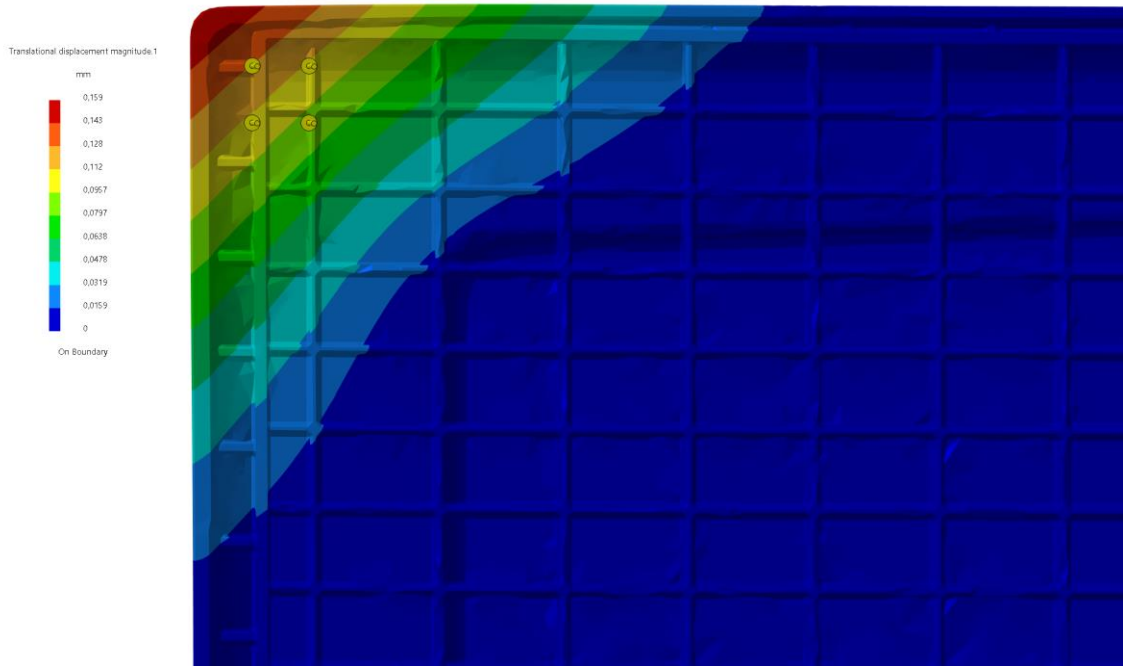

Figure A3. *Rectangle corner displacement*

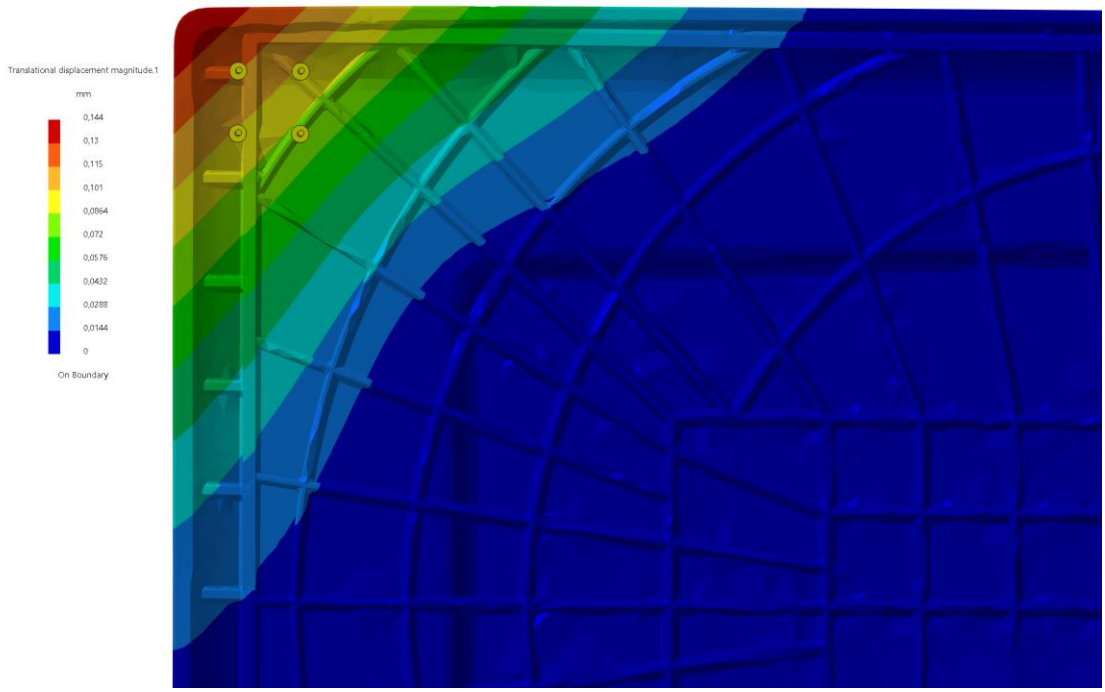

Figure A4. *Freeform corner displacement*

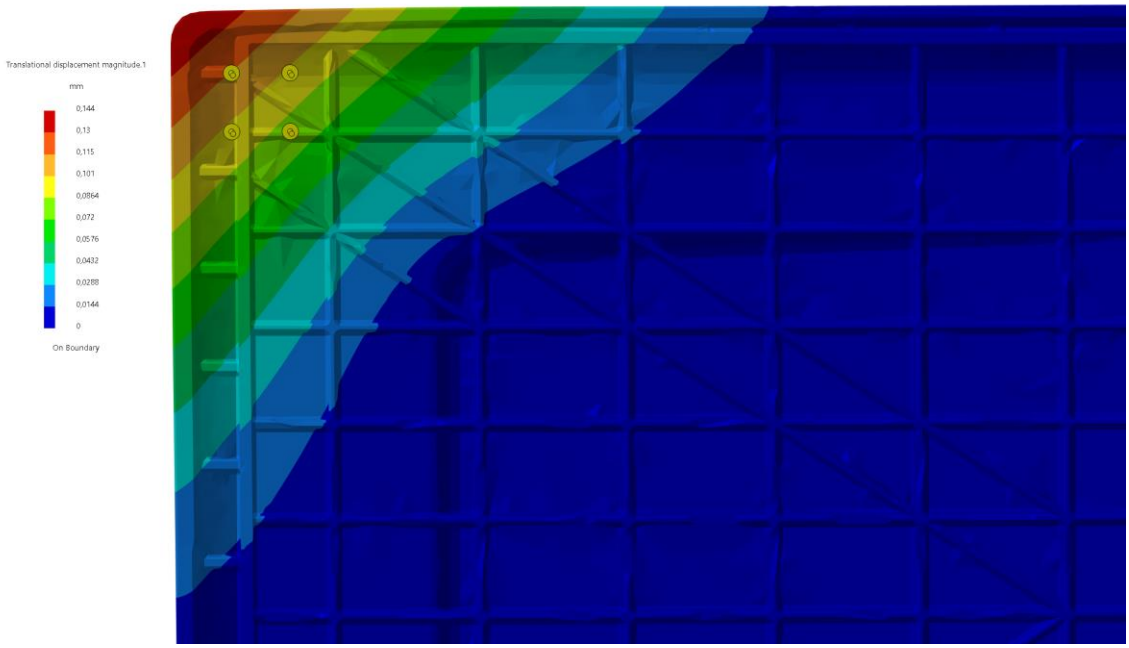

Figure A5. *Combined corner displacement*

Centre displacement values

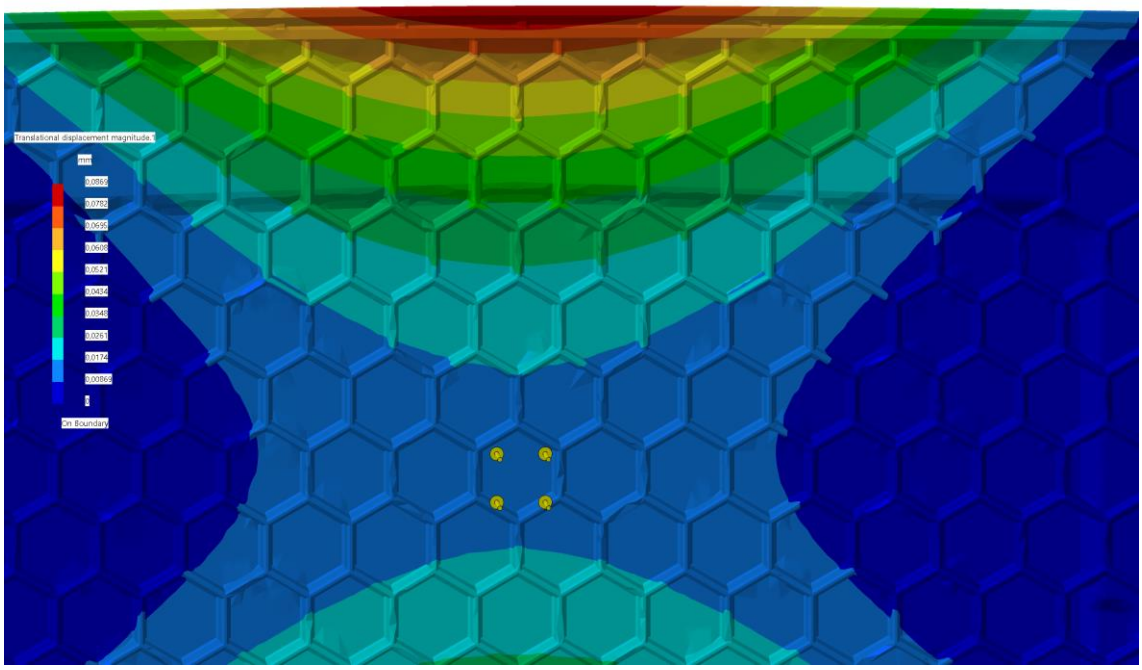

Figure A6. *Honeycomb centre displacement*

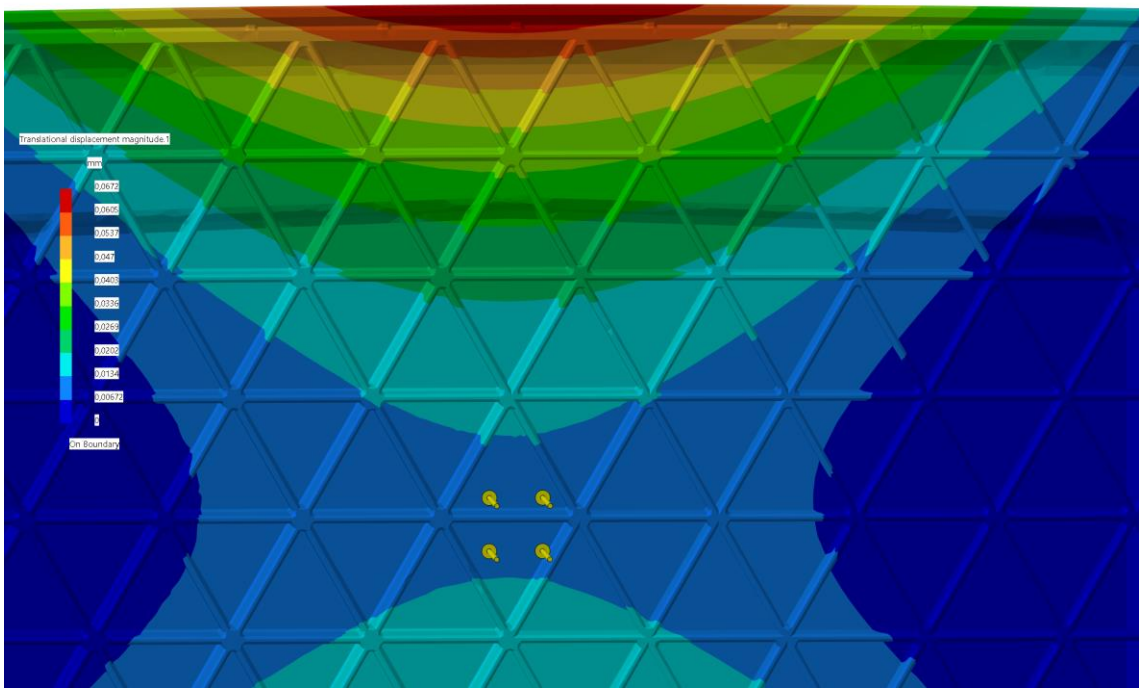

Figure A7. *Triangle centre displacement*

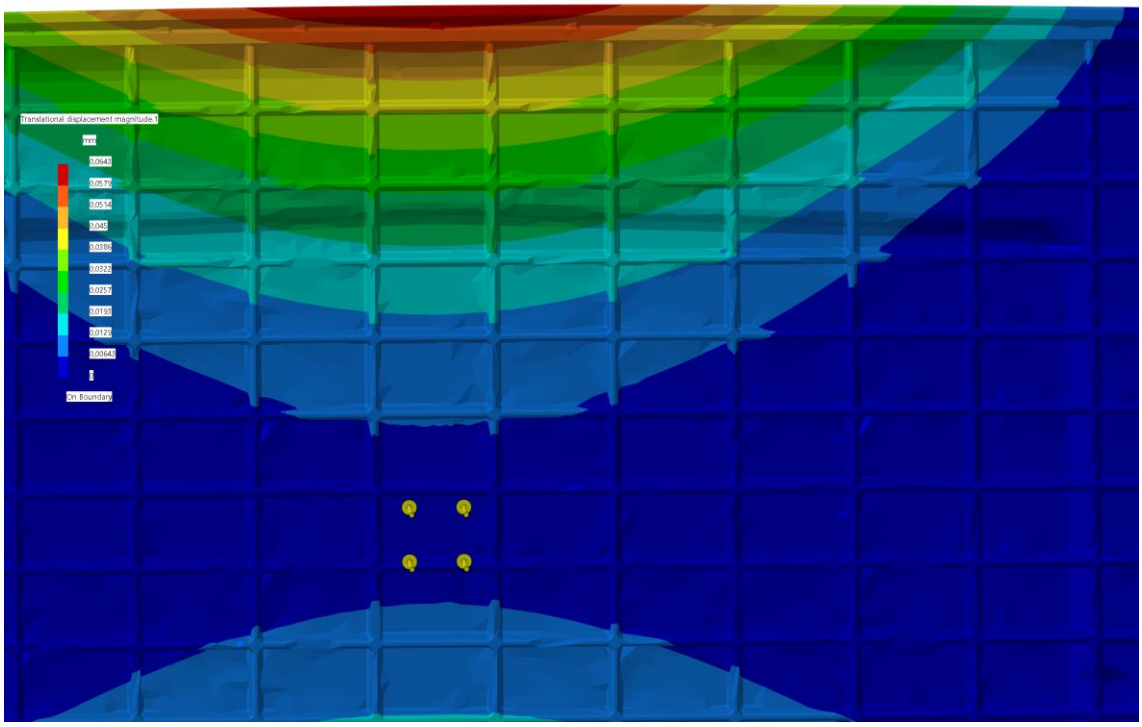

Figure A8. *Rectangle centre displacement*

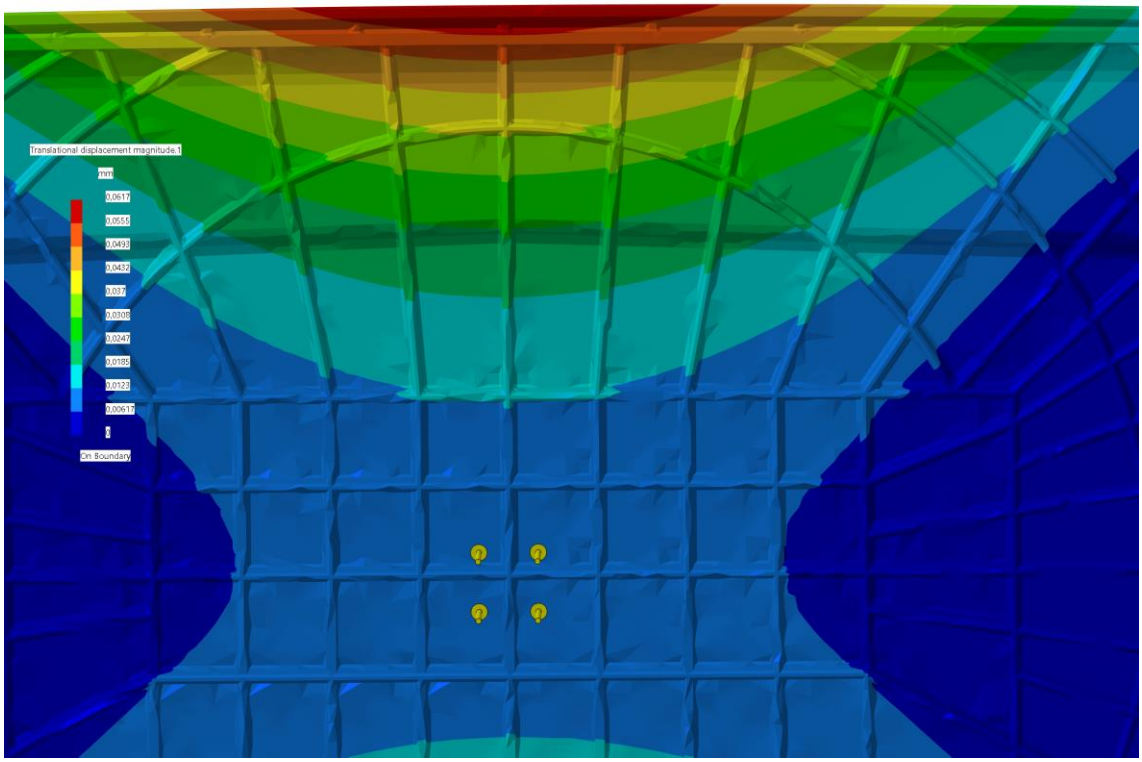

Figure A9. *Freeform centre displacement*

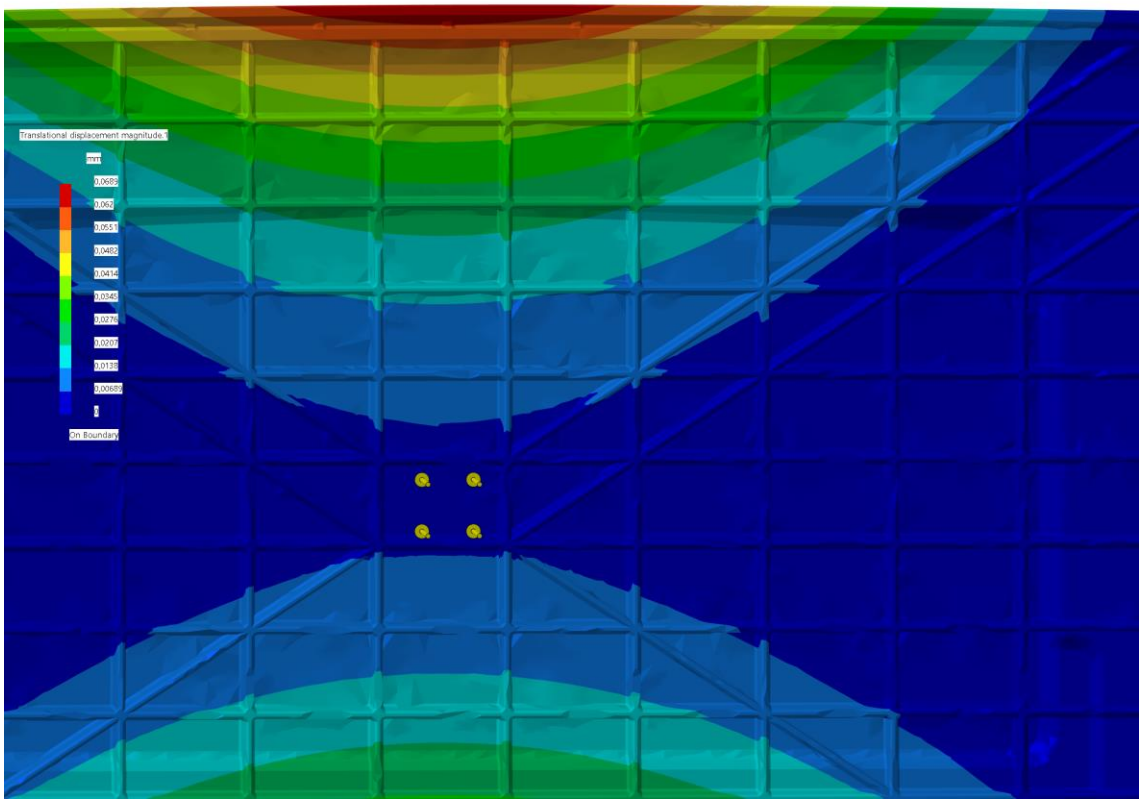

Figure A10. *Combined centre displacement*

Corner von Mises stress values

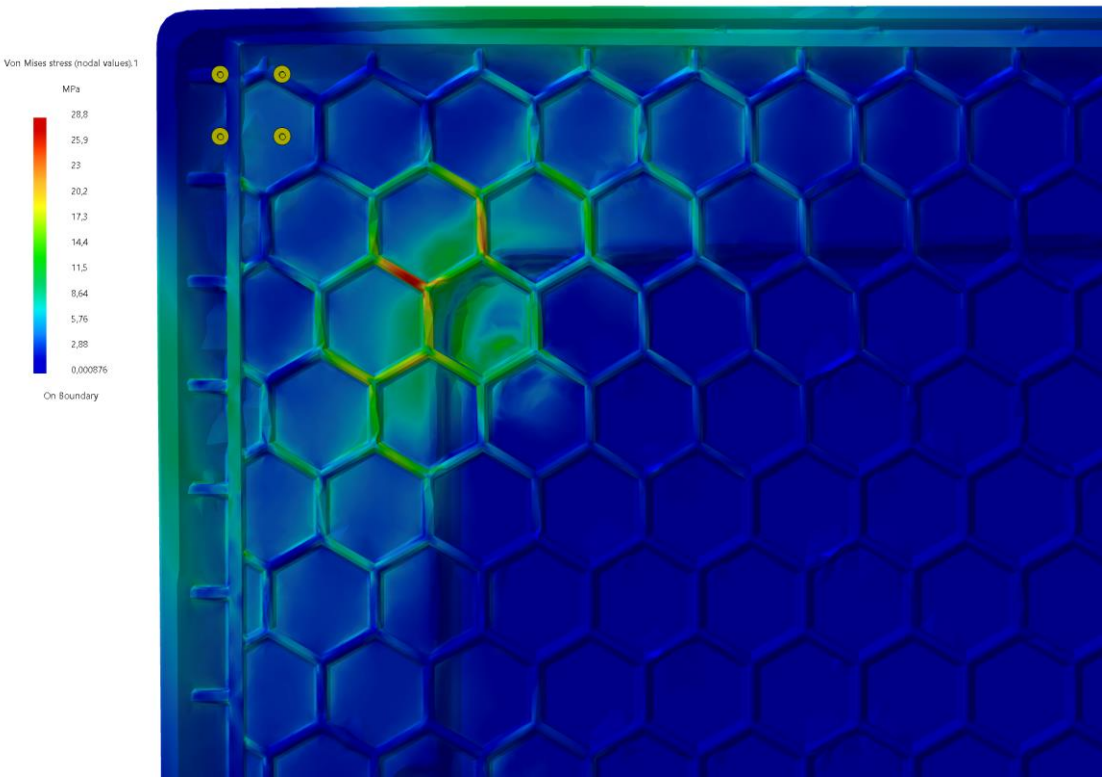

Figure A11. *Honeycomb corner von Mises stress*

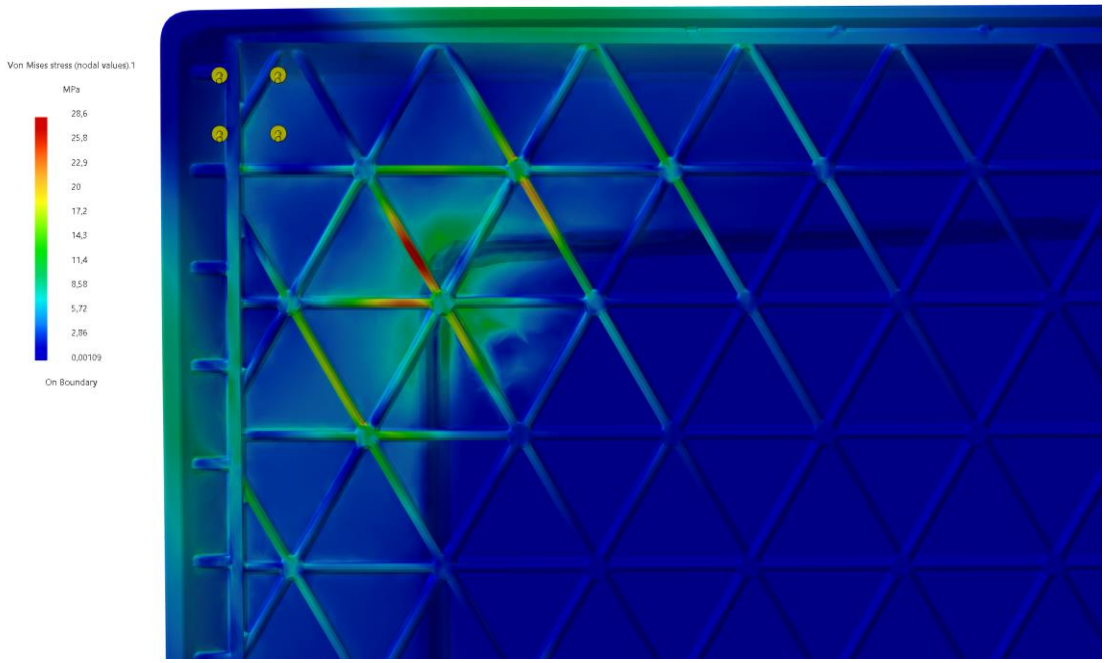

Figure A12. *Triangle corner von Mises stress*

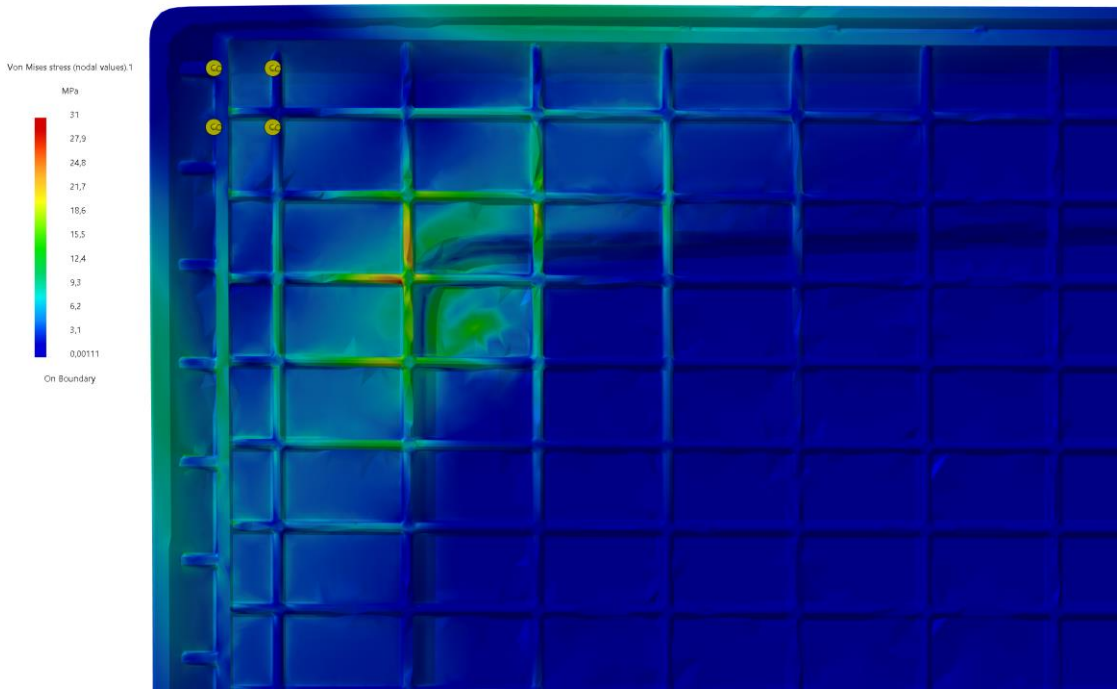

Figure A13. *Rectangle corner von Mises stress*

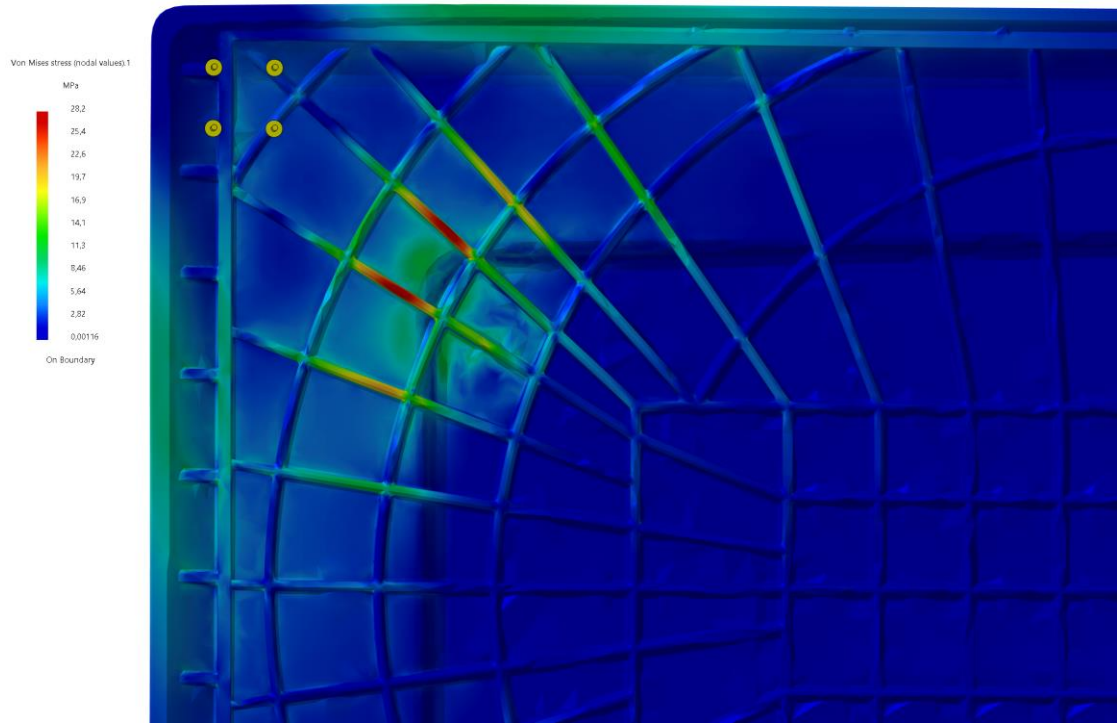

Figure A14. *Freeform corner von Mises stress*

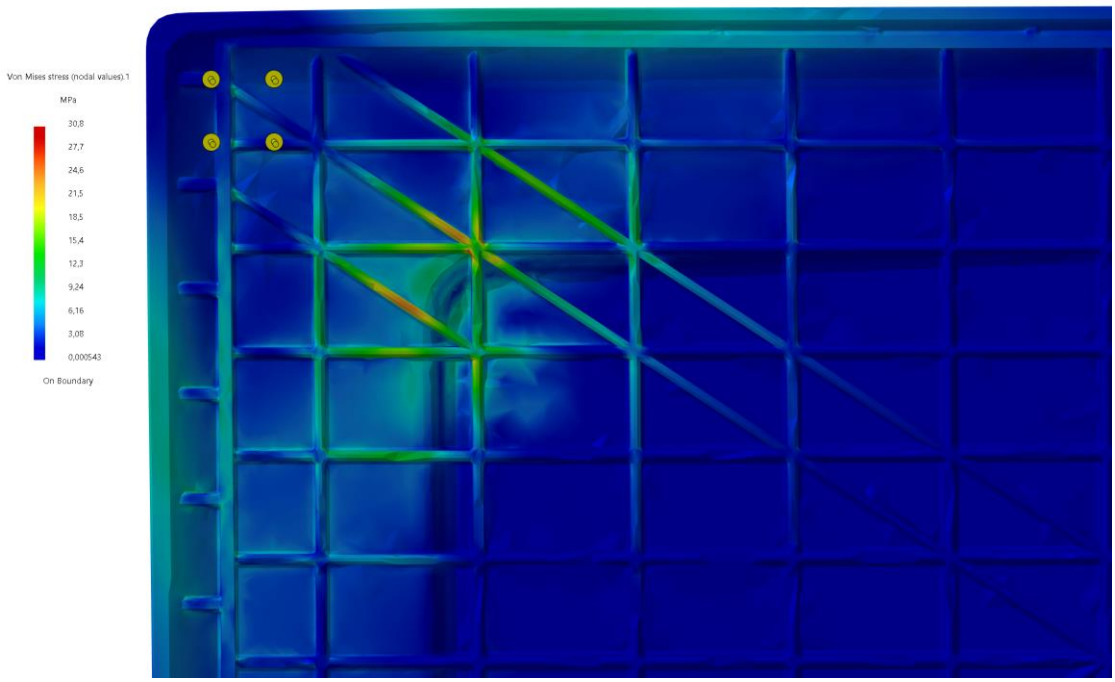

Figure A15. *Combined corner von Mises stress*

Centre von Mises stress values

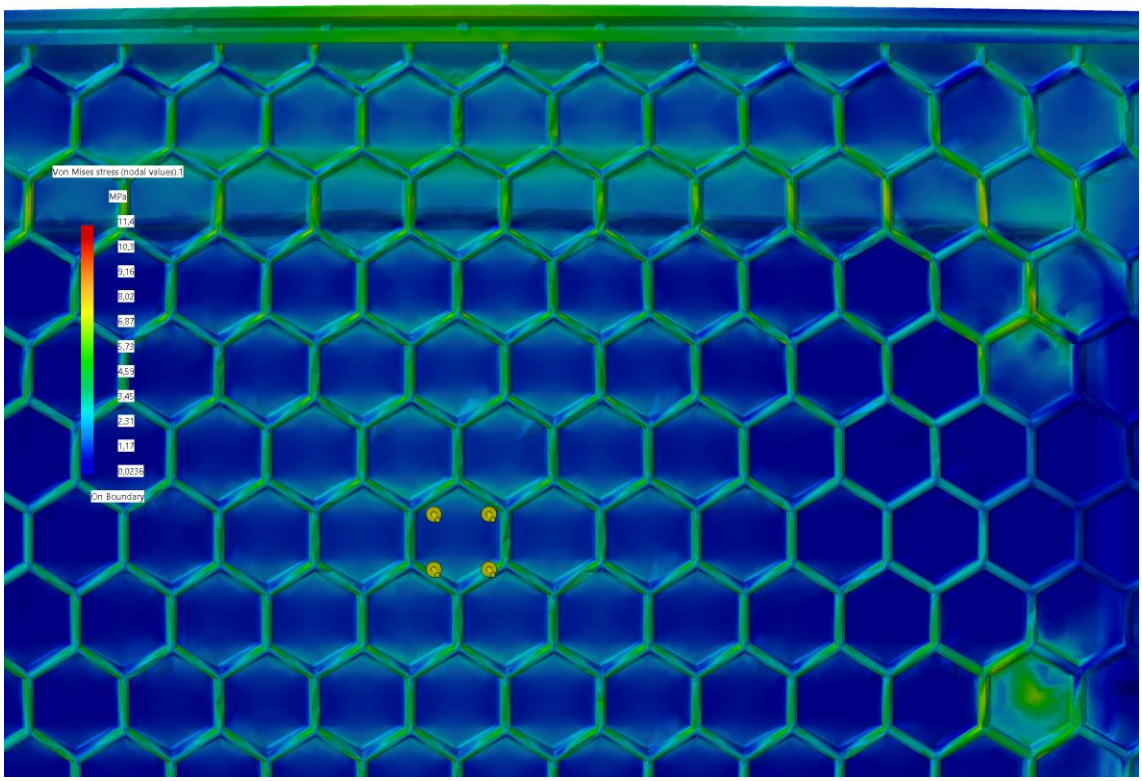

Figure A16. *Honeycomb centre von Mises stress*

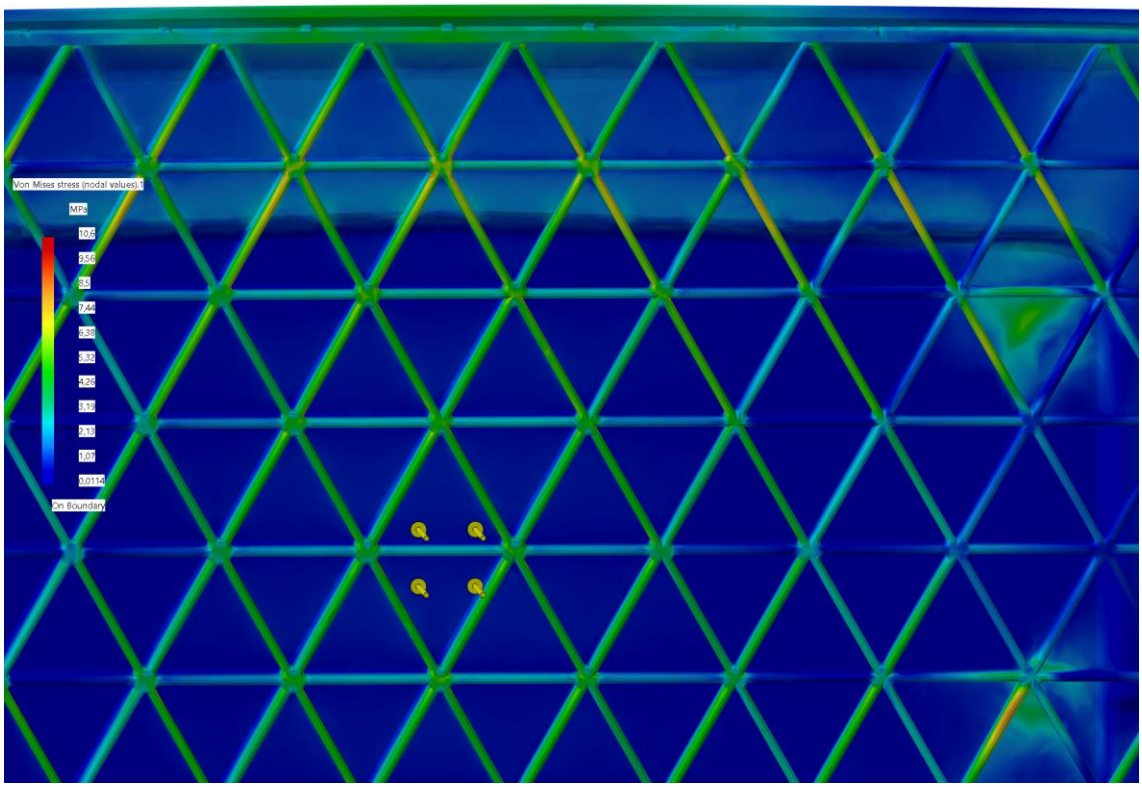

Figure A17. *Triangle centre von Mises stress*

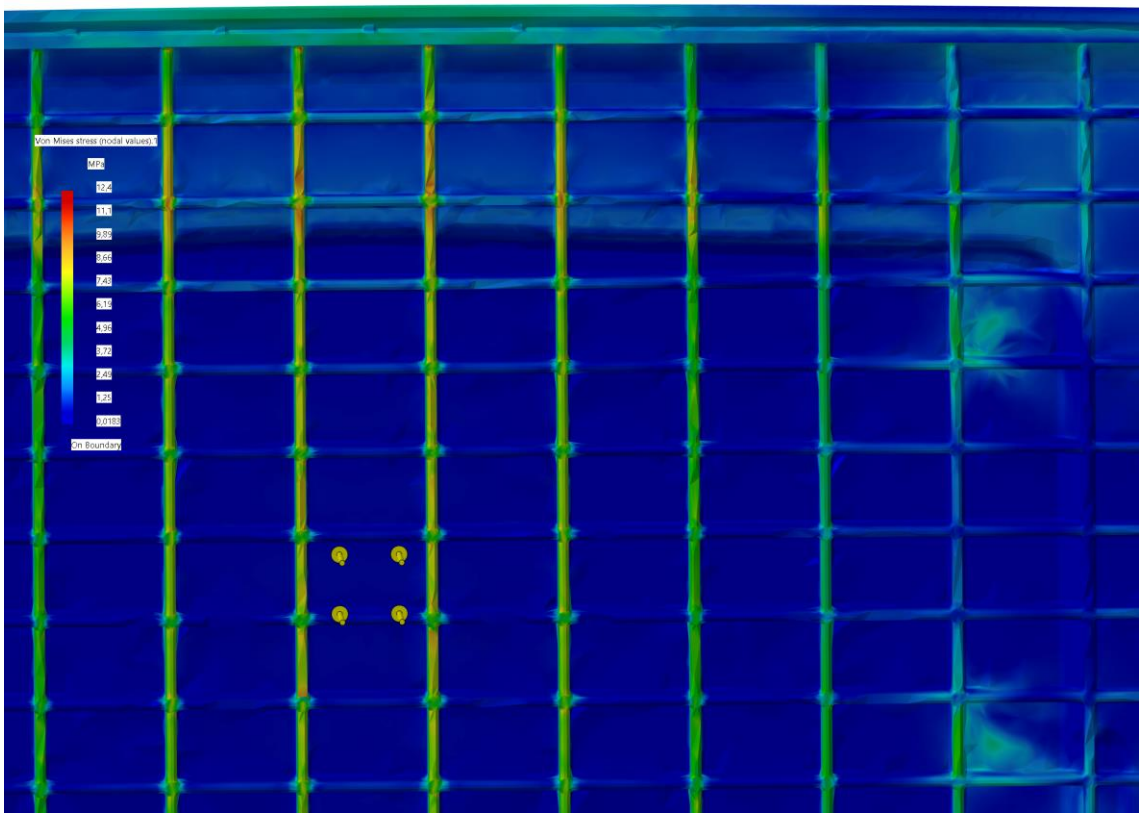

Figure A18. *Rectangle centre von Mises stress*

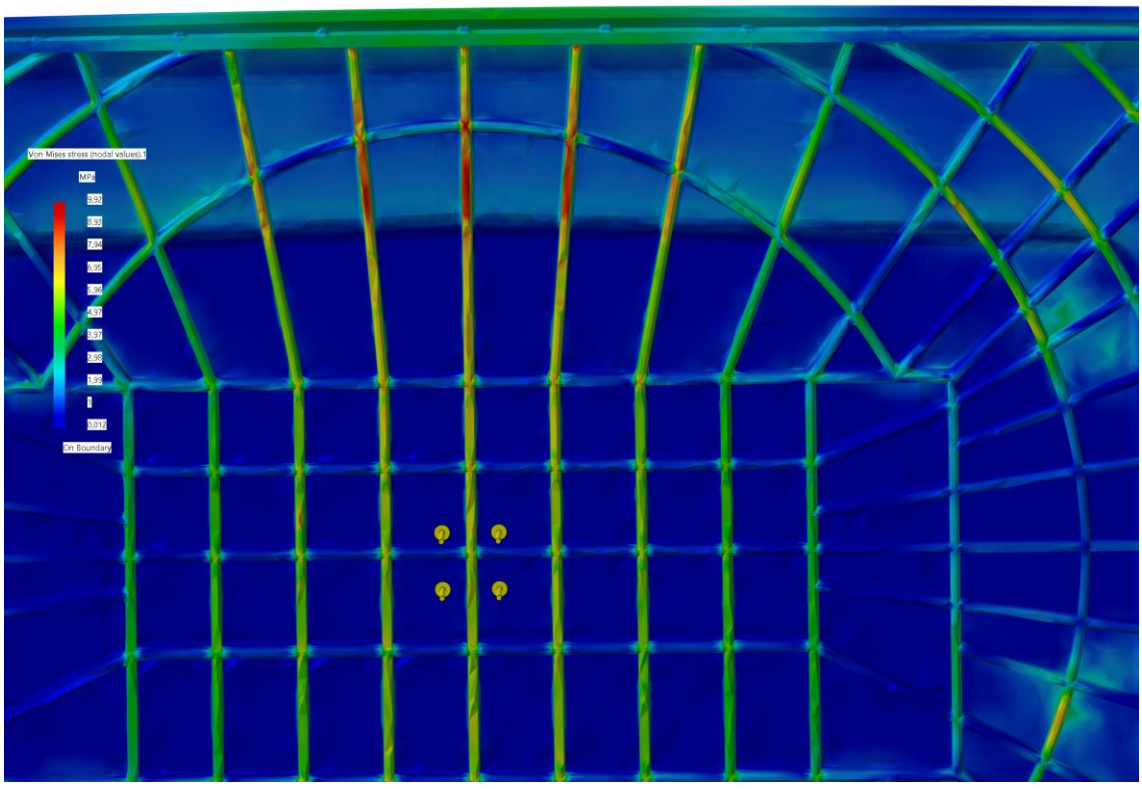

Figure A19. *Freeform centre von Mises stress*

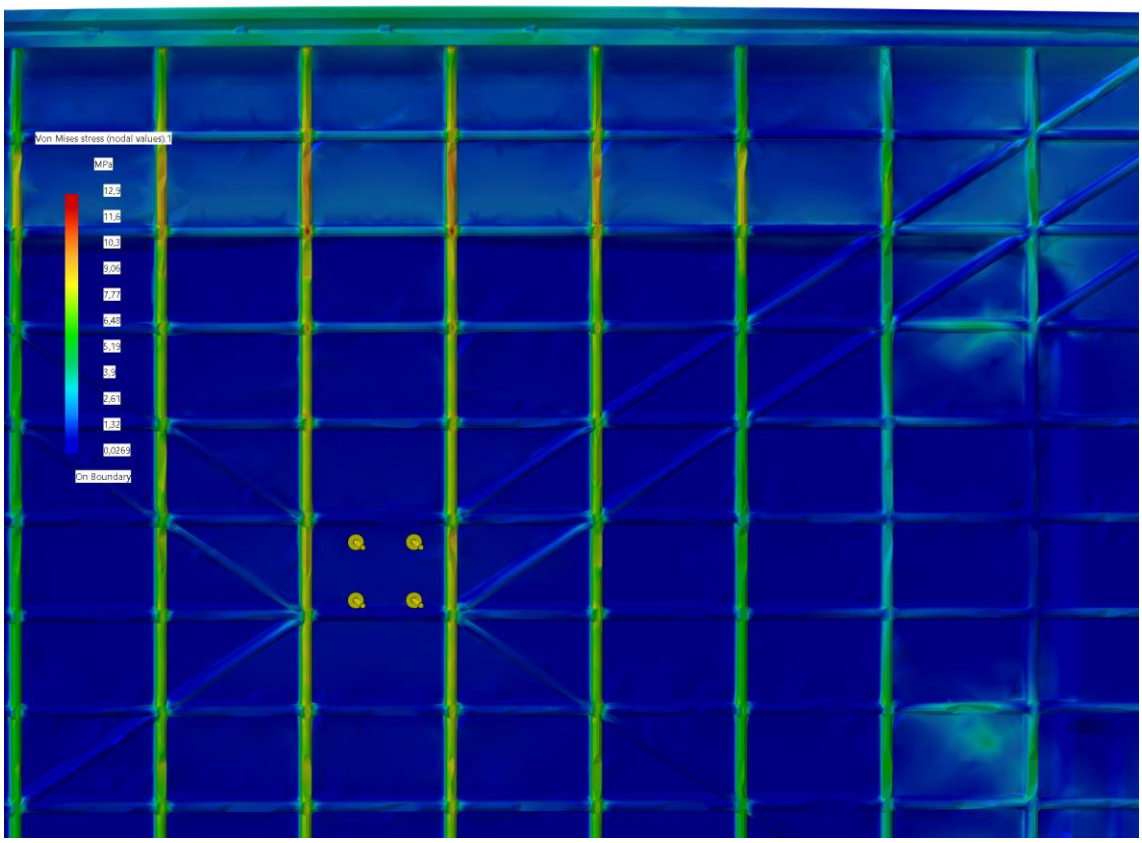

Figure A20. *Combined centre von Mises stress*