Evaluation of AI-driven Generative Design and Redesign of a MINI-LINK Mounting Kit

Master's Thesis in Product Development

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2023
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Cover:
[Rendering of a redesigned mounting kit using generative design, further explained in section 5.3.7]
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ABSTRACT

This master’s thesis is a partial fulfillment for the degree of Master of Science in Product Development and aimed to assess the viability of incorporating AI-driven generative design within Ericsson’s mechanical design department. In this study, Ericsson’s specific needs and requirements for generative design were explored and identified through a series of interviews and a comprehensive user study. Subsequently, the identified needs were transformed into benchmarking criteria for evaluating the capabilities of different software in performing generative design or topology optimization. The primary objective of the benchmarking phase was to evaluate the extent to which various software options aligned with the benchmarking criteria and their proficiency in executing generative design or topology optimization tasks. Following evaluation against the benchmarking criteria, PTC Creo Parametric emerged as the highest scoring software and was consequently employed in the redesign of an existing mounting kit for a MINI-LINK radio. The outcomes of the redesign phase revealed promising advancements in the form of improved design that surpassed the performance of the pre-existing solution in terms of weight reduction, increased stiffness, and a lower total cost. As the complexity of the model, load cases and constraints increased in the redesign of the mounting kit, limitations with the current version of Creo were revealed. A potential explanation is the difficulty to combine a generic method as the contextual complexity and detail imposes specific constrains.

Concluding the thesis report, a revised and improved workflow proposal for product development process within the mechanical design department was presented, in addition with the insights and findings obtained throughout the study.

Keywords: Artificial Intelligence, Benchmarking, Deep Learning, Generative Design, Needs Identification, Redesign, Topology Optimization

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Jim Alanko & Mattias Wallin
Göteborg, June 2023

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LIST OF ACRONYMS

The following is a table of acronyms that have been used in this thesis, arranged alphabetically:

Acronym:	**Description:**
ABS	Acrylonitrile Butadiene Styrene - a common plastic for AM
AI	Artificial Intelligence
AM	Additive Manufacturing
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAGR	Compound Annual Growth Rate
FDM	Fused Deposition Modeling
FEM	Finite Element Method
SLM	Selective Laser Melting - a method used for metal AM
.STEP	Standard for Product Data Exchange
.STL	STereoLithography - File Format Family

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1. INTRODUCTION

This master’s thesis has been conducted by the authors in collaboration with Ericsson’s department of mechanical & thermal design at Lindholmen, Göteborg. Ericsson has expressed interest in better understanding and exploring the feasibility of integrating generative design, belonging to the realm of Computer Aided Design (CAD), into the mechanical design department’s workflow. The background, aim, limitations and the specification of issues under investigation are described in this chapter.

1.1. Background

Ericsson is a global corporation that specializes in offering telecommunication products, software, and services to customers around the world. The company is actively engaged in developing cutting-edge technologies like 5G, IoT, and cloud computing. A notable achievement of Ericsson is the creation of a microwave transmission system known as MINI-LINK, which facilitates high-capacity and low-latency communication links between base stations and other network components [1] [2].

Traditionally, hardware components at Ericsson have been developed by designers using CAD software and experience gained through individual and organizational learning. Recently, Ericsson’s mechanical design department has expressed interest in exploring the adoption of generative design, which is to utilize artificial intelligence to optimize product design by creating designs that meet set requirements and restrictions in product development [3].

During a generative design development process, the engineer specifies the objectives and limitations, assesses the outcomes, and modifies the parameters to achieve the desired design results [3]. Ericsson’s intention with this master’s thesis is to evaluate the potential and limitations of generative design and compare different software that offer this or similar technology, as well as to propose an optimized redesign for an existing mounting kit for the MINI-LINK radio mentioned previously, using generative design.

1.2. Aim & Purpose

This master’s thesis report aims to study the possibility of implementing generative design into the workflow of the mechanical design department at Ericsson. The purpose is to enable Ericsson to stay current with the latest technological advancements in their field of operation, ensuring that they remain competitive while also facilitating the development of novel modeling techniques that enable the creation of revolutionary designs. Investigating this in a thesis project is a means to learn about generative design in advance of decisions regarding mainly tool adoption and financial incitement. Furthermore, a benchmark analysis that compares different CAD software providing generative design is conducted. Lastly, an exploration of how generative design can be employed in redesigning a mounting kit that enables separate installation of a MINI-LINK outdoor radio in a telecom tower is conducted.

The master’s thesis project is concluded in a report and prototypes are presented to the Ericsson team. The work is supervised by mechanical design engineers and simulation engineers at Ericsson ensuring that many aspects of a true design process are accounted for.

1.3. Limitations

The thesis will be limited to 30 HP/ECT during the spring semester of 2023, which consists of 20 weeks. Following this constraint, are several other limitations for the report that are listed below.

- The benchmark will be limited to a selection of available software and should not be considered as an exhaustive or complete benchmark.
- The variety of geometric parts for the benchmark is limited in complexity and variation.
- The report will not cover code-programming in the generative design modules.
- The benchmarking will only consider the design constraint of maximize stiffness.
- Only one existing Ericsson product will be redesigned using generative design.
- The benchmarking and redesign will only account for studies using a static load case.
- Manufacturability of generated designs are restricted to the design criteria in the software.
- AM prototyping will only be conducted with an FDM printer available at Ericsson.

- The thesis does not intend to monitor the effects of generative design after it may have been implemented within the design process of the Ericsson team.

1.4. Research Questions

To fulfill the aim and purpose of this report, five research questions have been formulated to guide the thesis work:

RQ1: What are the advantages and limitations of generative design?

RQ2: Is generative design feasible to implement within the existing design procedure of the mechanical design department at Ericsson?

RQ3: How does the functional capabilities of generative design in different software vary?

RQ4: What are the potential savings in cost when utilizing generative design instead of traditional modeling?

RQ5: What are the critical factors to redesign on the MINI-LINK mounting kit?

These issues will be answered by carrying out the following activities:

- Literature review of the present state-of-the-art in AI driven generative design
- Customer needs identification and analysis
- Workflow analysis
- Benchmarking
- Requirement specification and functional analysis of a MINI-LINK radio mounting kit
- Redesign process of MINI-LINK radio mounting kit using generative design
- Cost calculations of manufacturing and product assembly
- Proposed implementation strategy of generative design in current workflow

2. LITERATURE STUDY

In the literature study is the evolution of CAD, including its integration with generative design, explored. The comparison between generative design and topology optimization, examining their respective methodologies, are delved into. Additionally, design optimization theory, design evaluation techniques, as well as the incorporation of AI and deep learning within CAD systems are investigated. By addressing these key aspects, the outcome of the literature study provides the necessary background and understanding of the thesis's focus, enabling a critical evaluation of generative design's applications across various fields.

2.1. Evolution of Computer Aided Design

The discipline of CAD has undergone a constant progression since its inception in the early 1960s [4]. The development of CAD systems had its roots in the need to automate the creation of two-dimensional drawings, which were previously done manually on a drawing board. These systems aimed to make the drafting process more efficient and convenient, allowing for easy changes and the reuse of created geometries. The drawing library feature of these systems also facilitated more organized administration of the drawings.

Many industries had an early requirement for the ability to handle three-dimensional geometries with complex, double-curved shapes, this particularly applies to the mobility industry which includes all means of transportation. This led to an evolution of CAD systems, enabling them to handle three-dimensional geometries. However, due to the limited computational power of computers at the time, the systems were initially limited to handling three-dimensional wire models, which represented the geometries using curves defining their contours in space [5].

With the introduction of powerful computers, this limitation has been overcome, and modern CAD systems can handle fully defined three-dimensional geometries in the form of surface and solid models. Additionally, today's CAD systems allow for the creation of both static and parameterized models, where the latter can be adapted to different variants using varying parameter values. This affords the user greater flexibility and the ability to work with generic models.

2.1.1. Generative Design in CAD and its Underlying Process

Generative design is a method of design optimization that utilizes AI algorithms to create an array of design options. In recent years, the introduction of more powerful computing systems and the availability of generative software as plug-ins for CAD systems have made it possible for designers to generate designs that are lighter, stronger, and in some cases, more subjectively aesthetically pleasing than those created using traditional methods [6].

The generative design approach is different from traditional design techniques and consists of a set of activities that are carried out in sequential order. One of the first activities are to set up limitations and specifications in the chosen software. The user indicates to the program about the current load case, and in which regions material can or cannot be created, by designating a starting geometry, one or several preserved geometries and eventual excluded geometries. Additionally, choice of materials must be specified as well as the manufacturing techniques to be employed, and their restrictions.

The functionality of generative design software includes the implementation of a preserve geometry function, which specifies the requirement for the selected geometry to be maintained. The subsequent generation of variations is based on these geometries, which serves to protect critical features such as surfaces, points of force application, screw holes, and bolts. Additionally, an excluded geometry feature prohibits the software from generating material in or through designated volumes, thereby ensuring proximity of components to existing details [7].

After completing the preparatory steps, the software initiates the generation of concepts of the specified section. This stage is managed by the program, with the duration of completion dependent on the established mesh size, maximum number of iterations and the computational power of the computer. The generated concepts can then be evaluated by the user, with information provided regarding material consumption, approximate production cost, volume, mass, safety factor, and maximum permissible stress in accordance with the von Mises criterion among other.

The user has the option to assess the efficacy of the generated variants and make a final selection by weighing the relative merits of each. Further editing or refinement may be necessary to achieve the desired performance. The user also has the ability to eliminate undesirable or unattractive geometry before exporting the final version, which can then easily and preferably be imported into a program for AM setup and subsequent printing [8], if desired.

One key advantage of generative design is the ability to generate designs that the designer may not have thought of, or even do not have the capability to design manually. The models generated often have a complex organic shape which would take significantly longer designing by hand in a CAD software. Furthermore, due to the use of machine learning techniques, the software can assist in the construction of a mathematical model of the optimized product, taking into account important parameters such as manufacturing processes. Simulations are often run with cloud-based systems, allowing even demanding generative design studies to be carried out, regardless of the performance of the designer's computer [9]. However, even though the shift from the local computer calculations to cloud computing has many advantages, there are also disadvantages such as loss of security and control. Users are exposed to risks related to data availability, confidentiality, and integrity when entrusting important data to a service provider. Another critical factor to consider is the matter of fact that cloud services utilize a two-way interaction between providers and subscribers which further amplifies security concerns due to the two-way movement of information [10].

Overall, generative design is a powerful tool that is gaining increasing attention from industrial manufacturing companies looking to redesign products or create new concepts. The ability to generate designs with improved performance, combined with the ease of use and accessibility of generative software, make generative design a valuable tool for modern designers [9].

2.1.2. Generative Design & Topology Optimization Comparison

Barbieri and Muzzupappa [9] compared generative design against topology optimization as two alternative geometry strategies, focusing on the similarities and differences of the two different approaches.

The primary distinction is that topology optimization is mostly employed by engineers specialized in computer aided engineering (CAE), as opposed to generative design which is being applied more by product design engineers. Various topology optimization methods have been developed throughout the years, two of them are Solid Isotropic Material with Penalization (SIMP) which is a density-based method and the other one called the level-set method [11]. In the SIMP method, material density values are assigned to finite elements, while in the level-set method, a continuous level-set function is used to separate the design domain into solid material and void space [12].

The need for optimization in the product development cycle encourages simulation driven design methodologies, which call for a considerable shift in the designer's responsibilities. This is because these optimization methods may be used to help engineers define the geometry of 3D models early on, at the conceptual and modeling phases of the design process. However, when using these methods, it is crucial to have in mind the available production technologies for the part that is being designed. Most often, the optimization software produces organic shapes which can be difficult to produce with subtractive manufacturing. A much more suitable production technology is AM because of its possibility to a larger extent realize the advantages provided by generative design and topology optimization. The study carried out by Loris Barbieri and Maurizio Muzzupappa [9] showed that both topology optimization and generative design tools may be effectively used early in a design process that is oriented to AM to generate geometry that is driven by functional needs or to redesign components to make them lighter and stronger in the quest for improved performance.

Another aspect in the comparison of the two methods are generative design's ability to be integrated in CAD, enabling designers to model, optimize, and ultimately modify the component's shape within a special design and simulation environment without suffering data losses from translation and redesign procedures. In fact, designers can directly alter and refine the geometries produced by the generative design tool's algorithms during the post-processing stage.

An additional important consideration is that generative design tools allow users to provide an initial design space that will be optimized, and that doing so has no impact on the algorithm's output. In the topology optimization approach, on the other hand, various beginning design spaces result in various solutions.

In conclusion, as a consequence of the two methods being similar, generative design is in many instances referred to as re-branded topology optimization. CAD tools are being made available that use topology optimization for design exploration, and efforts of using it in product development are intensifying [6].

2.2. Design Optimization Theory

Optimization is described by Cavazzuti [13] as a systematic process of determining the optimal values of a set of decision variables in order to maximize or minimize a given objective function, subject to a set of constraints. The utilization of optimization ranges from several application and can for instance be found when improving design [14] or when optimizing industrial processes [15]. Optimization problems can be formalized mathematically and solved using advanced algorithmic approaches, such as gradient-based methods, linear programming, and stochastic optimization techniques, among others. The goal of optimization is to find the best possible solution within a defined set of constraints and considerations [13]. As described by Papalambros [16] an optimization problem can be defined in canonical form as shown in Equation 1. The objective is to minimize the function represented by f, while h and g are vectors denoting the equality and inequality constraints respectively. The values for the variables contained within the vector x must be determined to resolve the equation problem.

$$\begin{aligned}&\min f(x)\\&subject\ to:\\&h(x)\ ?\ 0\\&g(x)\ ?\ 0\end{aligned}$$

Equation 1 - Optimization problem in canonical form

The integration of optimization into the generative design process can greatly enhance the efficiency and effectiveness of the design process. The utilization of optimization algorithms and simulation tools in conjunction with generative design allows designers to rapidly study many design possibilities and identify the optimal solution that at the same time satisfies both performance requirements and product constraints [17]. The combination of generative design and optimization can result in products that are lightweight, durable, and efficient, providing substantial benefits to both manufacturers and end-users.

2.3. Design Evaluation

When evaluating designs, one must carefully consider the trade-offs between design parameters. For example, weight reduction is often a high placed ambition by designers, simply because of the fact that reducing weight in products, especially in the mobility industry, can lead to reduced costs through lowered fuel consumption, and reduced material usage, thus also lowering the environmental impact. When using generative design to model products, mass is an objective that users can choose to minimize, according to Barbieri and Muzzupappa [9]. That is one of generative design's main advantages, to reduce weight by only placing material where needed, according to the specified load case. On the contrary, generative design tend to generate organic and complex shapes which highly affect the manufacturing possibilities. The part seen in Figure 1 a) below, which is designed using traditional modeling, can easily be manufactured using subtractive and joining methods. This leads to a low manufacturing cost at a high production series. The part seen in Figure 1 b) have been designed using generative design and cannot as easily be manufactured using the same technologies as the first part. AM, however, would in many cases be a more suitable choice for this type of design [9]. The tradeoff between weight reduction and cost of manufacturing is therefore something the designer needs to keep in mind when evaluating different concepts.

a) Designed without generative design *b) Designed with generative design*

Figure 1 - Illustration of how generative design can be utilized (author's own pictures)

2.4. Artificial Intelligence and Deep Learning in CAD Systems

In the last few years, there has been a notable surge in the investigation of deep learning techniques, a subset of AI, within the realm of CAD [6]. There have been various studies conducted in the application of deep learning to generative design based on topology optimization. In the paper by O. Sangeun et al. [18], a "Deep Generative Design Framework" is presented as a design process consisting of nine different stages in which an Autoencoder [19] is used to learn about previous design outcomes, reconstruct errors and evaluate possible design options. N. Ath. Kallioras et al. [20] presents a novel approach to generative design by combining deep learning with topology optimization. The proposed methodology, named DzAIℕ, employs pre-trained deep networks to establish correlations between topologies of reduced order models and optimal topologies of large-scale models. These correlations enable the network to generate a substantial number of initial designs that satisfy user-defined constraints. The proposed methodology utilizes a structure that integrates Deep Belief Networks and Solid Isotropic Material with Penalization method (SIMP). By leveraging deep learning and topology optimization, DzAIℕ allows for efficient generation of initial designs that meet user-defined constraints [20].

Although the utilization of AI in CAD systems, most prominently generative design that has promising research, it is worth noting the challenges and opportunities the designers using the tool may face. In the paper by F. Gmeiner et al. [21] a study was conducted to investigate how designers better could be supported when learning to co-create with AI-design tools. In the study, 14 trained designers who ranged in age, work domain and experience were observed as they executed realistic design tasks and learned to work with the AI-based tools [21]. The study was conducted in two sessions, one individual and one guided session, the participants were then asked to discuss their experience. From the individual study, it can be concluded that there are several challenges when getting designers to co-work with AI. For instance, one of the participants expressed the difficulty of controlling the design tools, it seemed that the tool had more control of the design process than the designer himself. Further, several of the participants experienced difficulties in interpreting how to set both load cases and different design criteria. In the latter study, in which the participants were guided, the designers expressed a desire of the AI system being more of a collaborative work partner which could provide with insights and possible ways to create, not necessarily generating the whole design.

Additionally, the study found that experienced designers faced challenges beyond learning the AI tool's interface when co-creating with AI, despite having access to various support resources. Most designers struggled to produce satisfactory outcomes with AI assistance, and this was not solely due to tool limitations. The study identified new learning challenges, such as the need to specify all required parameters upfront, which requires a different design approach from the typical iterative process. These findings suggest the need for new support strategies, such as encouraging designers to reflect and suggesting alternative design goals that align with the AI's capabilities [21].

In recent years, it has been claimed that the application of AI has been increasingly integrated into CAD systems, specifically in the area of generative design. PTC, a company providing CAD solutions, has developed a generative design module in Creo. According to K. Brown-Siebenaler, [22], PTC claims that by incorporating AI into the generative design process, engineers can create designs that are free from human bias in regard to the optimization itself, yet not free from bias transported to the ability of setting up constraints and design criteria. The integration of AI techniques in this process follows a structured approach that closely resembles the human design process, thereby improving the scope and accuracy of the designs produced. AI-driven generative design software such as Creo [3] offers designers the ability to define tasks through geometric constraints and loads, which subsequently generates optimized designs within specific parameters. It is worth noting that the precise methodology by which AI is employed in Creo's design software remains undisclosed, including the specific type of AI system utilized. The undisclosed utilization of AI in the software results in knowledge gaps of the actual degree of learning incorporated within the algorithms, introducing a potential risk of varying performance across different generations. Thus, this uncertainty in the algorithm's level of learning can lead to challenges in terms of quality control and certification.

3. MARKET RESEARCH

The following chapter reviews an existing comparative report of different CAD software solutions in regards to various aspects of design optimization, including but not limited to: user interface, design flexibility, computational power, and generative design algorithms.

In addition to the report review, this chapter provides an overview of the current market size of generative design, including a thorough examination of industry trends. Furthermore, based on the information, the predicted future market size of generative design will be presented, considering factors such as technological advancements, increased demand for efficient and innovative design solutions, and market saturation.

Based on existing data, this chapter also explores ways in which generative design can be integrated into a typical design process. The focus is on understanding the benefits and potential challenges of incorporating generative design and various integration strategies, such as using it as a standalone tool or integrating it into a larger design workflow.

3.1. Market Size, Trends & Forecast

The generative design technology is a rapidly growing field with a significant potential for market growth in the coming years. According to industry projections, the global generative design market size is expected to reach USD7 billion by 2030, from its estimated value of USD2 billion in 2021 [23]. This represents a significant increase and is expected to be driven by a CAGR of 16% during the forecast period of 2021 to 2030 [23]. These projections highlight the increasing demand for generative design technology in various industries and its potential for continued growth in the near future.

The global generative design market is a highly fragmented and competitive landscape, with multiple regions contributing to its overall growth. According to recent market research, the North American region is projected to dominate the global generative design market, with a revenue forecast to grow at a CAGR of 15% to reach USD3 billion by 2030 [23]. The region's dominance can be attributed to its advanced technology infrastructure, high investment in research and development, and a large number of established players operating in the market.

In addition to North America, the European region is also expected to make a significant contribution to the global generative design market, accounting for the second-largest share. The region is forecasted to generate USD2 billion in sales by 2030, with a CAGR of 17% expected over the same period [23]. This growth can be attributed to the region’s increasing focus on sustainable and efficient product design, along with the growing demand for advanced manufacturing technologies.

The generative design market is characterized by various trends and prospects that highlight the benefits of using generative design software. In a recent report, published on Coherent Market Insights [24], it was highlighted that there are two main trends contributing to the growing demand for generative design. The first trend involves the utilization of generative design software to create multiple CAD designs and boost innovation and productivity, which is expected to play a crucial role in the expansion of the global generative design market.

The second trend in the generative design market is the growing demand for lightweight vehicle products, leading to an increased requirement for generative design technology. As an illustration, in 2019, the Volkswagen Group introduced a revamped vintage VW Microbus featuring various components created through the application of generative design technology [24].

Further, in the report, it is mentioned that manufacturers in the aerospace industry are presented with a significant opportunity to utilize generative design software to reduce the weight of aircraft, minimize environmental impact, and to enhance passenger safety. Additionally, the growing popularity of drones has spurred an increase in the utilization of generative design software to improve their aerodynamic efficacy, durability, and flight performance, which is anticipated to drive the growth of the global generative design market [24]. It is worth mentioning that the emergence of generative design happens to be within a period in which its capabilities and advantages, such as lightweight design, possibly can be realized to a large extent with the utilization of AM. Notably, AM already exhibits promising functional manufacturability and is undergoing continuous development [25] [26].

By acknowledging the aforementioned trends, they are reflected in the aim and background of this thesis. Ericsson has demonstrated an increasing interest in generative design, driven by a pursuit of lightweight design and enhanced product innovation. Nevertheless, it remains uncertain whether generative design will fulfill its anticipated potential and revolutionize the current design process, or if it will merely serve a niche position within the domain of CAD. This question is likely to be addressed when the application of generative design confronts more challenges, particularly in the creation of complex and realistic models.

3.2. Comparative Analysis of Generative Design Software

Recently, independent market analysis firm ABI Research conducted a competitive ranking of software suppliers providing generative design [27]. Segments from the market analysis are re-posted on several CAD software provider websites. The analyzed data in the following section is based on the market research posted on PTC's website [28]. The firm evaluated nine generative design software suppliers serving industrial and manufacturing customers and ranked them based on two criteria: innovation and implementation.

The innovation criteria used by ABI Research included:

1. Solution Accessibility
    - Vendors with user-friendly solutions that can be easily used by a recent graduate are favored.
    - Vendors who support remote work arrangements by making their solution available via cloud platforms are preferred.
2. Utilizing Selections
    - Vendors with solutions that integrate and exchange data with other software, such as CAD, PLM, IoT platforms, simulation software, and collaboration tools will score highly.
    - Vendors who support customers in creating a digital thread and sharing product information across the organization and other software applications will be favored.
    - Vendors whose solutions support turning geometric designs into VR or AR experiences and creating digital twins of the product will be highly rated.

3. Update Frequency
    - Vendors who frequently update their solution will be favored by designers who want new capabilities to be available as quickly as possible.

The implementation criteria used by ABI Research included:

1. Current usage levels and revenue: Vendors that demonstrate a growing installed base for their generative design solution will be favored.
2. Industry expertise: Vendors should show that their solution is being used across multiple industries and has notable customers.
3. Global availability: Vendors must prove that their solution is accessible to designers worldwide.
4. Go-to-Market strategy: Vendors that can engage directly with customers and have a broad partner network will be scored highly.
5. Educational initiatives and value-add services: Vendors should offer resources, tutorials, and consulting services to help customers get the most out of the solution.

ABI Research assigned scores to all software that were evaluated regarding innovation and implementation. The overall company score is established by combining the scores for innovation and implementation using the Root Mean Square method. This method calculates the square root of the mean of the squares of the scores, providing a single numerical value that represents the combined scores for innovation and implementation, as seen below in Equation 2. This value is then used to determine the overall company score and rank the suppliers in the market.

$$Score = \sqrt{\frac{innovation^2 + implementation^2}{2}}$$

Equation 2 - How ABI Research calculated the software total score

In Figure 2, all the scores for the nine evaluated software are presented in a graph, indicating that the top performing software by ABI Research’s criteria are Inspire by Altair, Creo by PTC and Fusion 360 by Autodesk.

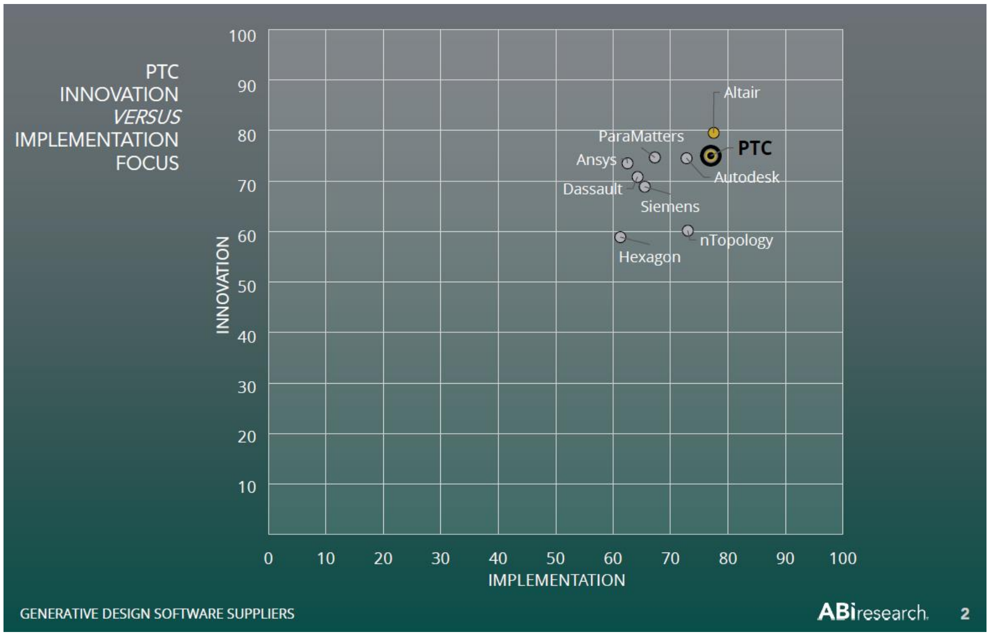


Figure 2 - ABI Research's result of the competitive ranking

3.3. Implementation of Generative Design

In the paper by G. Detlef et al. [29] the application of generative design is distinguished into two categories: "Assisted CAD modeling" and "Functional CAD programming environment." The former integrates a generative design component into conventional CAD as a workspace and features a user interface that resembles a conventional CAD tool, thereby making it user-friendly and familiar to engineers. However, its configuration options are limited and operates as a "black box", reducing the possibility of errors but also hinders comprehension and automation. The latter approach utilizes a low-code programming environment instead of predefined workflows and functions, giving the user complete control over the process but requiring knowledge of workflow generation and application, which could lead to errors. This approach supports integration with other tools and enables customizable parametric-driven generation, making it effective for solution space exploration and trade-off analysis. In the paper it is concluded that the potential for integration of the various features discussed in the product development process is extensive and varies in most cases between an individualized approach as well as between a manual process and an automatic process.

4. METHODOLOGY

In the following chapter, the methodologies, and their utilization to achieve the desired results are presented. These include literature study, geometric modelling using CAD, customer needs data collection, benchmarking, functional & requirement analysis, conceptual design and evaluation as well as physical prototyping. Each method plays a crucial role in the progress of the thesis project, contributing to the completion of the defined research questions.

4.1. Literature Study

To investigate the evolution and the current state of knowledge in the field of geometric modelling including both CAD and optimization methods, a literature review was conducted. Detailed examination of the existing published literature allowed to spot knowledge gaps within generative design and thus lay the groundwork for this thesis project. The process of conducting a literature review required multiple parts, which began with formulating a clear, and well-defined research topic that served as the basis for the literature search [30]. For this thesis, the research questions presented in 1.4 served as topics for investigation. Subsequently, the next step in the literature study was to look for relevant literature, which involves using numerous databases. Literature and studies were mainly gathered from Chalmers Database Library [31] and Google Scholar [32], additional complementary information was gathered from various websites and literature. The search for relevant literature was based on valuable insights gained through meetings and conversation with the thesis supervisors and other experts within the field related to the defined research questions.

The gathered data was reviewed regarding each source’s methodology and findings, as well as the author’s point of view, to establish each one’s applicability, credibility, and reliability [30]. Furthermore, during the literature review conducted for this thesis project, particular emphasis was placed on ensuring that the selected literature adequately covered the formulated research questions. After conducting the literature study, relevant findings for the project were synthesized and presented as done in chapter 2 of this report.

4.2. Geometric Modelling using CAD

The following section explains the utilization of both traditional geometric modeling and generative modeling in this thesis.

4.2.1. Traditional Geometrical Modelling using CAD

The thesis project heavily relied on CAD modeling which is a method that utilizes software to generate digital versions of physical objects. This process allowed for the creation and manipulation of 3D models that have a wide range of applications, such as product design, architectural visualization, and engineering analysis [33].

For CAD modelling, choosing between surface modeling and solid modeling was the initial stage. Surface modeling is a technique for producing 3D models that depict the outside of an object, as opposed to solid modeling, which represents the inside structure of an object. The choice of modeling technique was heavily influenced by what the model ultimately is used for. If the purpose, for example, is to create a stylish design in which dimensions and structure do not matter much, surface modeling is often the best option. Generally, one can reach more advanced and complex designs utilizing surface modeling, as opposed to solid modeling. On the other hand, if the model will be used for FEM calculations, a solid model is more compliant. In both the benchmarking and redesign phases of this thesis, the consideration of structural properties was important. Consequently, solid modeling was selected as the preferred approach for creating the starting, preserved, and excluded geometries, which were essential prerequisites for conducting generative design, which can be observed in section 5.2.2 and 5.3.

CAD modeling enables the construction of virtual prototypes that can be tested and analyzed. This can assist in finding and correcting design issues before they affect the final product [34]. Consequently, this was also the case for this thesis. Construction of several CAD models were conducted before deciding on the creation of physical prototypes, thus saving both time and resources.

4.2.2. Generative Design & Topology Optimization

Generative design is a systematic approach in which the form of a CAD object is generated by algorithms of software. This method allows the designer to explore several design options by specifying design parameters and constraints, rather than manually creating each design by itself [35]. Generative design and topology optimization share certain similarities, as presented in section 2.1.2. In this thesis, both generative design and topology optimization were evaluated, with a stronger emphasis on generative design as many of the software providers have re-branded their previous topology optimization as generative design. Therefore, regarding the benchmarking, the starting geometry used in generative design was equivalent to the component subjected to weight reduction in the topology optimization software.

In some instances, what enables the implementation of generative design is the utilization of AI software in conjunction with the computational capabilities of cloud computing [36]. The process, both generally and the one utilized in this thesis, begins by identifying the load cases, which represent the operating conditions that the model must withstand. In this case, the requirements and functionality originate from the existing mounting kit presented in 5.3. A design objective was then established, targeting a specified mass of 700 grams. Materials, design constraints, level of fidelity and optimization for an eventual manufacturing method, and its limits, was then specified. The subsequent phase involved the execution of the study, a process in which the duration varies according to the set level of fidelity. The results were then critically evaluated by the designer, and the most suitable designs were retained for further development [37].

4.3. User Needs Data Collection

A combination of data collection methods including process mapping, interviews, and user study were utilized to gather relevant information related to customer needs. By leveraging these data collection methods, critical information regarding user needs was comprehensively gathered and evaluated.

4.3.1. Process Mapping

Process mapping is a visual representation technique that is used to describe and analyze processes. It provides a clear illustration of the flow and various elements of a process, including steps, inputs, outputs, and decision points. Organizations can employ macro process mapping as a technique to identify areas that require improvement and eliminate operational inefficiencies in order to be able to communicate the process effectively, given that macro process mapping thoroughly covers the essential steps of the process [38].

In the context of this thesis, the development of an Ericsson product, specifically a MINI-LINK radio mounting kit, was analyzed using macro process mapping. The purpose of conducting a macro process mapping was to gain insight into the procedure of product development of Ericsson's mechanical design team and thus identify if and in which process step generative design can be implemented to optimize the development process. The process map was created using information gathered from interviews with three design engineers, two of whom were directly involved in the development of the mounting kit. The map was then subjected to a review and validation process by a fourth mechanical design engineer to ensure that all critical elements of the development process were captured accurately.

The final version of the process map underwent a final validation to confirm its completeness and accuracy. One way to map a process is to utilize the framework proposed by IBM in [39]. It is claimed one can expect benefits by utilizing this particular method. Some benefits, among others include "easier identification vulnerable aspects of a process" and "better enablement for scenario tests and assessments" [39]. These two benefits were particularly important for this thesis, as vulnerable aspects of the process possibly could be improved using generative design, additionally, testing and assessment is considered important when adopting a new method such as generative design. The proposed methodology of process mapping by IBM is divided into six different steps:

1. **Choosing which process that is to be mapped.** As previously mentioned in this section, the development process of a MINI-LINK radio mounting kit was analyzed.
2. **Involving the correct people.** To gain a comprehensive perspective of the development process, three design engineers from the Ericsson mechanical design team were interviewed, two of who were specifically designing the mounting kit.

3. **Outlining the process map.** The outline of the development process was based on the interview material.
4. **Utilizing symbols to enhance the process mapping.** The symbols which are depicted and described in Figure 3 were utilized to leverage the understanding of the process flow.
5. **Receiving feedback.** In order to confirm that the process is correctly outlined, it was cross-checked with a fourth design engineer from the Ericsson team. This ensured that no steps were missing and that all the parts of the process were covered.
6. **Implement process modifications and monitor their effects.** This is the purpose of process mapping. However, this thesis does not intend to implement nor monitor the effects of generative design in the design process due to time constraints. Instead, a new workflow is proposed in addition with important key points to consider when implementing.

To depict the different elements of the process, symbols were utilized, including rectangles for specific steps or activities, arrows for process flow, diamonds for decision points, ellipses for start and end points, and document or file symbols for inputs and outputs. The symbols are depicted and described in Figure 3.

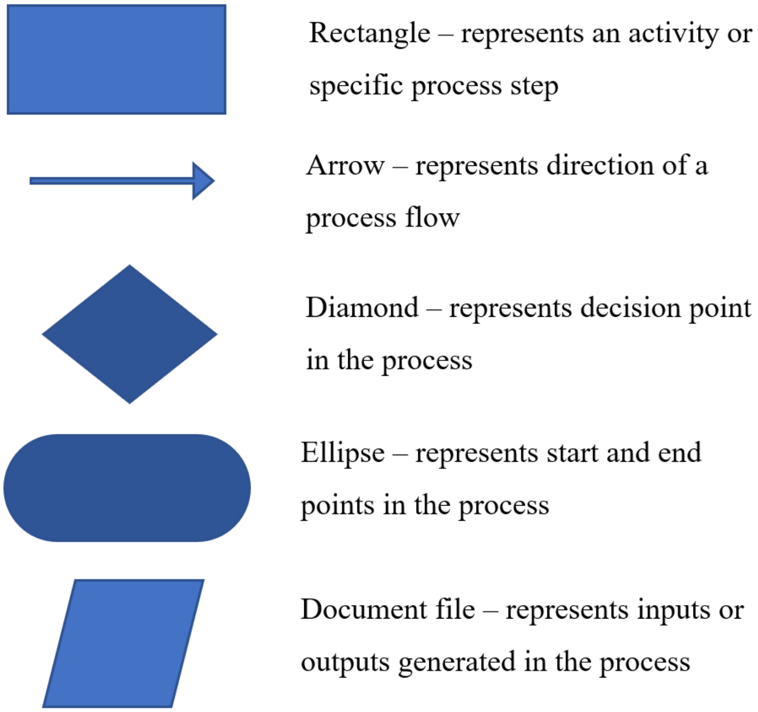


Figure 3 - Illustration of the different symbols proposed by IBM to map processes.

4.3.2. Interviews

Regarding the use of interviews as a data collection method, there are three common types: structured, semi-structured, and unstructured. Structured interviews involve verbally posing predetermined questions with little to no variation. Conversely, unstructured interviews use few to no predetermined questions, often beginning with an open-ended question, which allows the interviewee to lead the discussion in an informal manner. Semi-structured interviews provide a balanced approach among the two methods, utilizing predetermined questions to guide the conversation while allowing the interviewee to delve deeper into the topics as necessary [40]. Considering the aspect of gaining a precise understanding of customer needs based on specific questions, while also allowing interviewees to delve more deeply into the topic discussed, the use of semi-structured interviews was considered feasible.

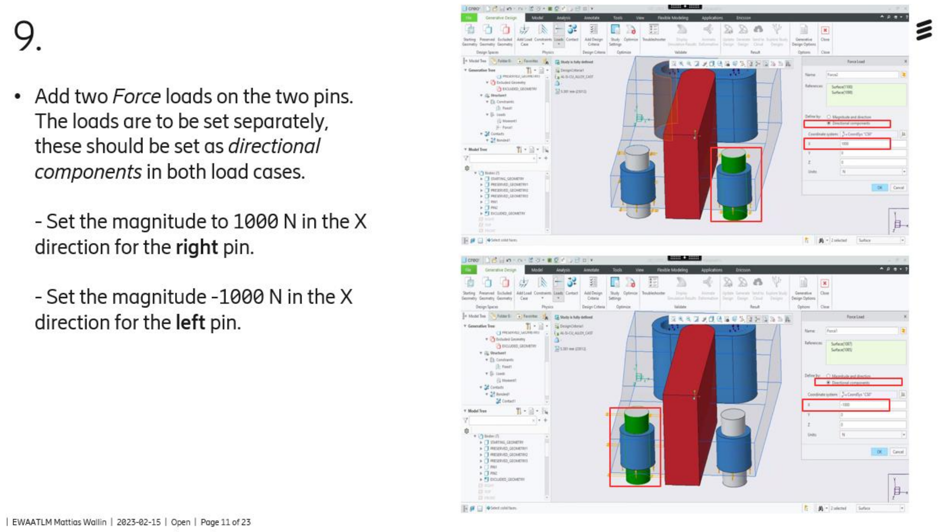
The interviews followed a predetermined structure, with specific questions that were identified and formulated in advance and then covered during the meeting. Among the three interviewees, the predetermined questions varied depending on what topics that was discussed. This approach ensured that the necessary information was gathered while also allowing the interviewee the flexibility to provide comprehensive and nuanced responses. During the interview, the answers from the interviewee were systematically noted by an assigned secretary. It was decided to not record nor videotape the interviews as a relaxed and informal approach was considered to be the best. The captured information from the interviews was analyzed and important highlights that refers to customer needs were systematically organized on a virtual white board as presented in Figure 7 in 5.1.3.

4.3.3. User Study

User studies are an effective approach of gaining insights into users and understanding their needs. By conducting user studies, one can gather valuable information about the user’s behaviors and preferences [41]. Further, user studies provide valuable insights into why a technique is effective by collecting user feedback and behavior data, enabling the improvement to better meet user needs [42]. In regard to this report, user studies were utilized with the purpose of discovering customer needs for generative design by allowing engineers at Ericsson to use the software and provide feedback based on their experience.

The topic of user studies is typically divided into two different segments, qualitative research studies, and quantitative research studies. Quantitative studies indirectly collect data through measurement methods like surveys or analytics, whereas qualitative studies directly collect data by observing actions and attitudes. Quantitative studies are better at addressing *how many* and *how much* of a certain attribute that is studied, while qualitative studies are better at addressing *why* or *how to* solve an issue [43]. The methodology employed in this report relied on qualitative studies, motivated by the lack of interest in quantitative data compared to the significance placed on qualitative data, particularly in the form of qualitative user feedback that could be translated into user needs.

In conducting the user study for this project, mechanical design engineers from Ericsson in both Gothenburg, Lindholmen and Stockholm, Kista were invited to participate, and the selection of participants was based on instructions from the industrial supervisor. The participating users were provided with a pre-structured case to experience the existing generative design module in Creo. The reasoning of choosing Creo for the user study was due to its availability for the employees. The provided case included a simplistic model to be optimized, along with clear instructions in a presentation with slides on how to use the generative design module to perform the optimization. In Figure 4 below, an example of a slide from the instruction presentation is shown.



9.

- Add two *Force* loads on the two pins. The loads are to be set separately, these should be set as *directional components* in both load cases.

  - Set the magnitude to 1000 N in the X direction for the **right** pin.

  - Set the magnitude -1000 N in the X direction for the **left** pin.

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Figure 4 - Presentation slide from instructions for the user study

Subsequently, after finishing the generative design study, the participants were asked to complete a survey to provide feedback and comment on their experience with the generative design module. The questions were stated as following:

1. What is your previous experience with generative design/topology optimization?

   Option 1: I have never used it

   Option 2: I have used it a few times, just for fun

   Option 3: I have used it a few times, and utilized the designs in my work

   Option 4: I use it frequently

2. Rate your overall experience with the generative design module (1 being very poor and 10 being excellent).
3. Was it clear for you how to assign all bodies and what each of them meant? Yes or No.
4. Was it clear for you how to assign all design criteria? Do you think there are objectives missing?
5. Do you think generative design could help you in your work and if so, in what way?
6. When you are designing a component in CAD, do you know the load case it is subject to? Do you estimate forces and constraints yourself?
7. What do you believe are the main **advantages** of generative design?
8. What do you believe are the main **disadvantages** of generative design?

4.3.4. Evaluation of Identified Needs

To evaluate the identified needs effectively, all the data gathered through interviews and user studies was analyzed and categorized to similar topics. To avoid any important information being overlooked from the interviews, the gathered responses were compared against the interview guide questions. Certain comments or citations from the interviews that were of interest were highlighted to later be categorized. Further, by analyzing and highlighting each one of the responses from the user study in regard to stated needs or specific comments that indicates a non-expressed need, all relevant information was considered to be covered. The collected sentences and citations that were of interest from the interviews and user study were subsequently distributed onto a digital whiteboard. To ensure a structured approach, similar sentences and citations were organized with each other, thus generating certain categories of captured data. The organized data was rephrased and transformed into specific customer needs. This approach allowed for a comprehensive analysis of the data and enabled the development of customer needs that accurately reflect user requirements.

4.4. Benchmarking

Benchmarking is a methodical approach used to evaluate the performance of a particular solution or product relative to a predefined standard or benchmark. The objective of benchmarking is to identify areas for improvement and to perform beyond the leading competitors in the market [44].

Throughout the course of this thesis, benchmarking was employed as a means to evaluate the performance of generative design and topology optimization within the designated software applications. The process began by identifying the specific needs of Ericsson for generative design, which subsequently served as the basis for establishing benchmarking criteria. These criteria were then assessed through the execution of case studies within each software, ensuring a consistent study setup for all parameters to facilitate a fair and unbiased comparison. This enabled the identification of the extent to which each criterion was satisfied, in addition with an analysis of the generated geometry with regard to its structural properties, such as stress and displacement.

Each one of the criteria were assigned a weightage, ranging from 1 to 5, that determined their importance. The evaluation for each criterion was subsequently performed on a scale of 1 to 5, with a score of 1 indicating that the software did not meet the criteria, while a score of 5 indicated that the software met the criteria in the most optimal way possible. The software were also evaluated based on criteria related to setting up the study, as well as the results from the generated design in terms of von Mises stress and displacement. The set-up evaluation was conducted based on how long it took to set up the study, how many clicks it took to set up the study, how long it took to generate the design, how long it took to post-process the part, and how many clicks were required for post-processing.

By assigning scores to the degree of fulfillment for each criterion, as well as applying weights to reflect their relative importance, a final score was calculated by multiplying the two and finally summarizing all terms, unveiling the highest performing and less successful contenders in the benchmarking process. However, it is important to note that since the criteria were formulated based on Ericsson's needs, the benchmarking outcomes may not fully capture the comprehensive capabilities of the software, as certain functionalities that were not specifically requested by Ericsson may not be emphasized. The results from the benchmarking are presented in section 5.2 and discussed in section 6.3.2.

4.5. Functional and Requirements Analysis

The Hubka Law posits that there exists a causal relationship between the functions and means of a product [45]. This principle can be applied to the process of decomposing product functions into a function means tree. The function means tree, following the Hubka Law, exhibits a hierarchical organization of functions and means that are arranged into distinct levels and linked together by relationships. At the top of this structure lies the purpose function, followed by means that propose a solution to realize the function [46]. Moreover, the function means tree is utilized to present alternative solutions, allowing for the identification of an optimal candidate solution.

The primary objective of employing the function means tree in this thesis was to identify and outline the various subfunctions of the mounting kit, thereby facilitating the identification of areas that required improvement during the redesign process. This analytical procedure was performed on the existing mounting kit that is utilized by Ericsson as of today. The functional analysis was employed in a methodological approach of investigating each one of the separate parts functionalities and subsequently installing the mounting kit with a MINI-LINK radio on an antenna pole. The component inspection and product installation were conducted in a lab environment at Ericsson to ensure the use of proper tools and instructions, thus achieving the primary objective of defining the functionalities of the mounting kit.

The analysis of the mounting kit's requirements was conducted through a comprehensive requirement specification process. A requirement specification is a document that consolidates requirements that a product's design and verification must satisfy. To identify the actual requirements, interviews were conducted with the designers of the existing mounting kit, and physical investigation of the mounting kit was performed. Additionally, certain requirements were derived from the standard requirements for Ericsson products installed in masts. These requirements were compiled into a list and assigned unique identifiers. For each requirement, marginal values and ideal values were established, representing the minimum acceptable limits and desirable targets for the product, respectively [47]. Due to updates of requirements and solutions to functions the requirement specification is to be considered as a dynamic document that evolves throughout the development process [48]. Each requirement was accompanied by a justification that outlined its purpose and significance. Furthermore, an evaluation method was described, delineating how each requirement was assessed and measured. Each requirement was categorized as either a mandatory requirement or a desirable attribute. The distinction lied in the fact that a mandatory requirement must be fulfilled, while a desire was not obligatory but would be advantageous if achieved.

4.6. Conceptual Design and Evaluation

This thesis heavily relied on conceptual design in the MINI-LINK mounting kit redesign phase, which involved treating both the existing solution and the solutions generated from the generative design software as concepts to be evaluated against each other. Rather than using conventional brainstorming methods, the generative design software was employed to generate concepts with different inputs provided for each run, considering manufacturing constraints, design constraints (such as symmetry), and variations in preserved geometries. The generated concepts did not incorporate specific details such as tolerances for dimensions and manufacturing considerations. These finer aspects, including tolerances, surface finishes, and other manufacturing-related specifications, were not explicitly included in the concept generation process. The focus of the generative design approach was primarily on the exploration and generation of overall geometric configurations and material allocations, while leaving out these specific manufacturing details that are typically addressed in subsequent stages of the design process. In conclusion, concept generation as of whole, is a relatively inexpensive and efficient phase compared to other stages of product development, and thus, should be executed with care and diligence [49].

The evaluation of concepts focused on structural properties, including von Mises stress and displacement, as well as mass and total cost. Von Mises stress was specifically observed as it is the only stress option available for evaluation in the utilized generative design module of the redesign and also simplifies stress analysis since it offers a convenient measure of overall stress intensity. Total cost was further subdivided into purchase cost, manufacturing cost, and assembly cost. As the existing solution's manufacturing is outsourced by Ericsson, the mounting kit is purchased at a fixed price, thereby making the manufacturing cost negligible and thus being replaced with a purchase cost. Conversely, the generated concepts consider a manufacturing cost that replaced the purchasing cost. The manufacturing cost was calculated using Equation 7, incorporating parameter values derived from ranges provided by Ansys Granta EduPack [50], as well as actual values for the concepts and estimates obtained from Ericsson.

4.7. Physical Prototyping

Physical prototypes help designers and engineers to test their ideas before committing to full-scale production, making it a crucial step in the product development process. Designers may discover and fix any design issues early on by making a physical prototype, which can help save time and reduce costs. It is also a powerful tool for the designer or producers to signal to their potential customers that progress is being made, since the prototype can be shown to customers, leading to their interest in the project to continue [51]. Prototyping played a significant role in both the benchmarking and redesign phases of this thesis. Within the essence of this thesis, prototypes were only manufactured with the AM process called fused deposition modeling (FDM). The decision to utilize FDM was primarily driven by the availability of a 3D printer at Ericsson that utilizes this technique, along with the high accuracy of the printed prototypes in replicating the designed geometry. The underlying method of FDM is that it builds objects layer by layer utilizing thermoplastic filaments. The filaments are heated and extruded through a nozzle, and the material is deposited in a precise pattern to form the desired shape. Each layer fuses with the previous one, resulting in a durable and robust object [52]. The purpose of prototyping the designs from the benchmarking was twofold: firstly, to enhance the visual representation of the designs and provide a tangible feel for their physical form, and secondly, to quantify the mass of the support material required for printing the design, thereby evaluating the effectiveness of the software in optimizing the design for AM.

Similarly, the generated concepts for the redesign of the mounting kit were also prototyped using 3D-printing. The objective of prototyping these concepts was firstly, to assess the feasibility of the concepts by mounting the MINI-LINK device to an antenna-pole using the prototyped mounting kit, and secondly, to identify any potential areas for improvement through physical testing and analysis of the prototypes.

5. RESULTS

The results chapter presents an analysis of various key aspects, including the identification and analysis of customer needs, software benchmarking, the redesign of the MINI-LINK mounting kit, the integration of generative design workflow, and the utilization of AI and deep learning in generative design.

5.1. Customer Need Identification and Analysis

The primary objective of the initial tasks undertaken in this thesis was to establish and define the customer needs related to generative design at Ericsson. To achieve this objective, several steps were undertaken, comprising of a workflow mapping, as well as interviews and a user study conducted by a team of mechanical engineers at Ericsson. Through these methods, a comprehensive understanding of the customer needs was obtained. Subsequently, the identified needs were subjected to a thorough analysis and categorized for further interpretation and use. The details of the identified customer needs and their corresponding categories are presented in the following subchapter.

5.1.1. Workflow Mapping of Current Situation

The process map presented in Figure 5 provides valuable insights into the development process of the MINI-LINK mounting kit and serves as a useful reference for further investigation about how generative design can be utilized in the development process.

The mechanical design process at Ericsson begins with the identification of a need for a product or mechanical component. In this particular thesis, as the initial design proposal for the MINI-LINK radio unit had been presented, the need of a mechanical attachment unit to connect the radio to the telecommunication mast became evident. The project was then assigned to the mechanical design department and further delegated to a designated mechanical design engineer. The *Pre-Study* phase involved exploring various design concepts and selecting the most suitable one for further development. During this phase, preparations were also made in regards to budgeting, scheduling, and risk management. The mechanical design department presented their design concepts through CAD models and physical mockups, providing a visual representation of the proposed solutions. As the pre-study is completed, there is a decision to be made in which it is decided whether the project should proceed. This decision is called *Start Implementation* and is based on the information concluded in the previous step.

Assuming the successful initiation of the implementation phase, the subsequent step involves conducting a thorough analysis of the requirements and establishing a conceptual design. In the development of the MINI-LINK radio mounting kit, the requirements were not clearly specified and had to be identified by the designers. The designers were provided with two key requirements: 1) ensuring the radio does not fall, and 2) positioning the radio at a specified distance from the mast. These requirements were further expanded to include additional factors such as the maximum weight and maximum vibration that the structure must be able to withstand.

During the *Conceptual Design* phase, the mechanical concept is decomposed into a structured design, with distinct mechanical components defined. These components are evaluated in terms of environmental requirements, usage, and production processes, to ensure the design will meet verification criteria in later stages. The mechanical design department presents the concept in the form of a CAD model and mock-up, providing a visual representation of the proposed solution.

The primary objective of the *Design & Design Verification Preparation* phase is to thoroughly document the mechanical design through the creation of technical drawings and CAD-models. This is a crucial step towards the fabrication of a prototype, which will be utilized in the subsequent *Design Verification* phase. Additionally, it is also imperative to initiate and thoroughly plan the necessary tests for the design verification process, ensuring a comprehensive assessment of the design prior to its implementation.

The *Design Verification* phase is centered around the verification of the prototype in accordance with the product specifications and documentation. It is essential to conduct a thorough evaluation of the design to confirm that it meets all the established requirements. This process can involve testing the design to its limits, either by exceeding the requirements or by subjecting multiple prototypes to testing. Upon completion of this phase, it is necessary to decide regarding the release of the product and adhere to the pre-determined release plan.

In the event that the design fails to pass the verification process, it becomes necessary to make adjustments and revisit the previous phase of *Requirements Analysis & Conceptual Design*. On the other hand, if the design successfully satisfies all requirements, it is deemed ready for the final phase of *Final Documentation & Product Release*. During this phase, it is imperative to complete any supplementary documentation that supports the system verification and future production efforts. This documentation serves to ensure the overall viability and sustainability of the product as it has reached the end point in the process and can be handed over to production in the final step *Handover to Production.*

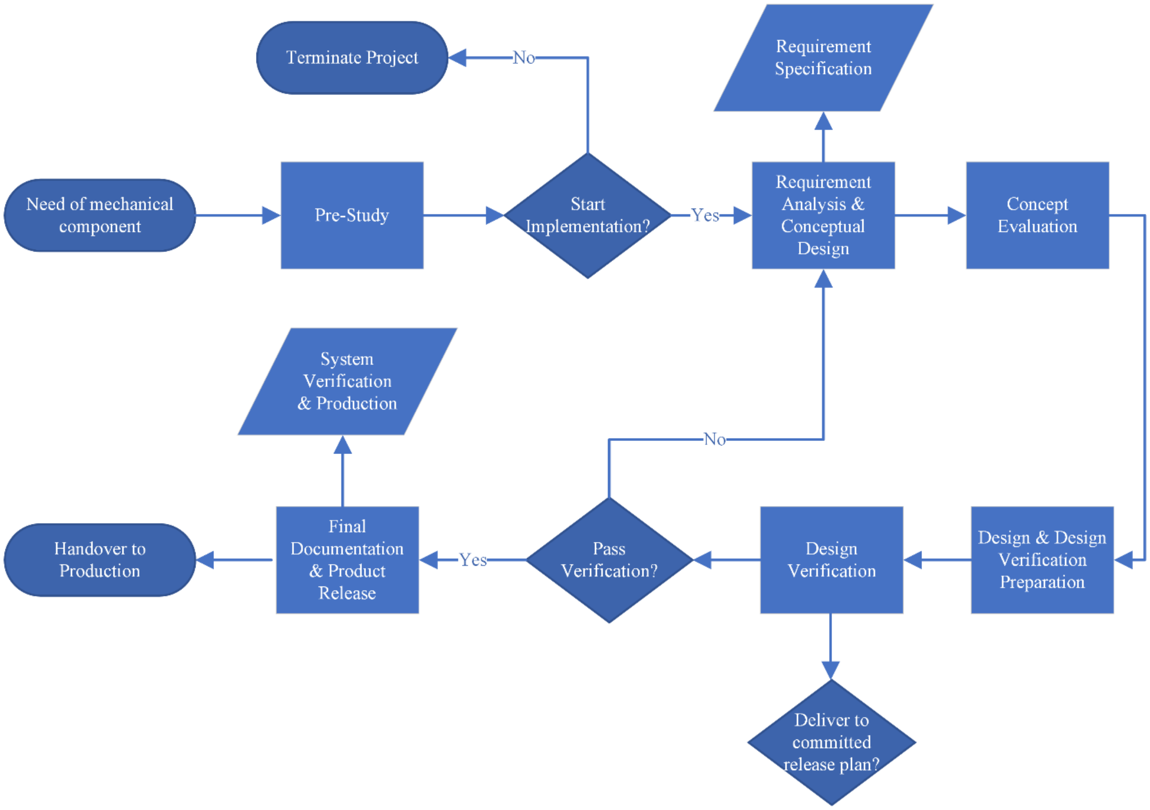


Figure 5 - Process flow of the Mechanical Design department at Ericsson

5.1.2. Underlying Need for Generative Design

In Figure 6 shown below, the needs are visualized in blue boxes and the attributes of generative design in orange boxes.

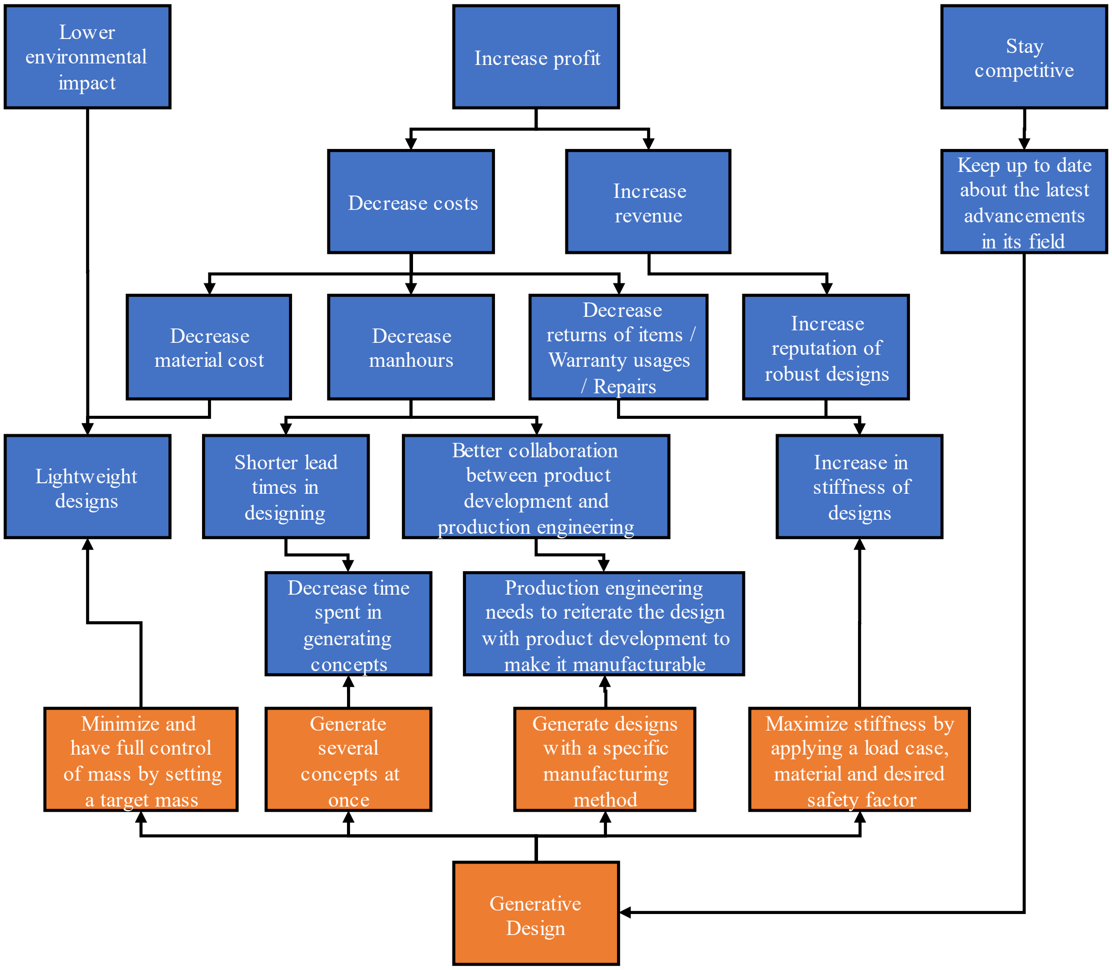


Figure 6 - Illustration of gathered results from interviews serving as underlying needs for generative design

Ericsson, like all companies that provide products and services, aim to increase profits. One way to achieve this goal is by decreasing costs or increasing revenue. When focusing on reducing costs, there are several measures that can be taken, such as decreasing material costs, labor hours, and replacement/repairs of faulty products. In the figure, it can be seen that these measures can be narrowed down to three areas: producing more lightweight designs, shortening the lead times in designing, and establishing better collaboration between product development and production engineering.

To address these needs, generative design is a promising solution. By using generative design, Ericsson can minimize the mass of designs, generate multiple concepts at once, reduce the time spent in the *Pre-Study* phase, and produce designs with a specific manufacturing method, as explained in section 2.4. Generative design can also address the need to reduce the number of replacement/repairs of faulty products. This can be achieved by maximizing the stiffness in generated designs by applying the correct load case the product will be subject to and its material. By designing products that are less likely to break or malfunction, yet without overdesigning and spending excessive amounts of resources, Ericsson may reduce their costs associated with warranty repairs or replacements, improve customer satisfaction, and enhance its reputation for robust designs.

Moreover, Ericsson aims to remain alongside of the most recent technical innovations in its industry to maintain competitiveness. In this regard, generative design clearly falls within the scope of Ericsson's strategic interests and to ignore its potential would be negligent. Failure to pursue generative design and assess its possibilities could result in a considerable opportunity cost, ultimately causing Ericsson to lose ground in the competitive landscape. Additionally, there is a need to utilize generative design as it has the possibility of providing optimal designs that are difficult to achieve using manual modelling. In addition to this, Ericsson also has the ambition to reduce their environmental impact, which generative design could help to accomplish by generating lightweight designs.

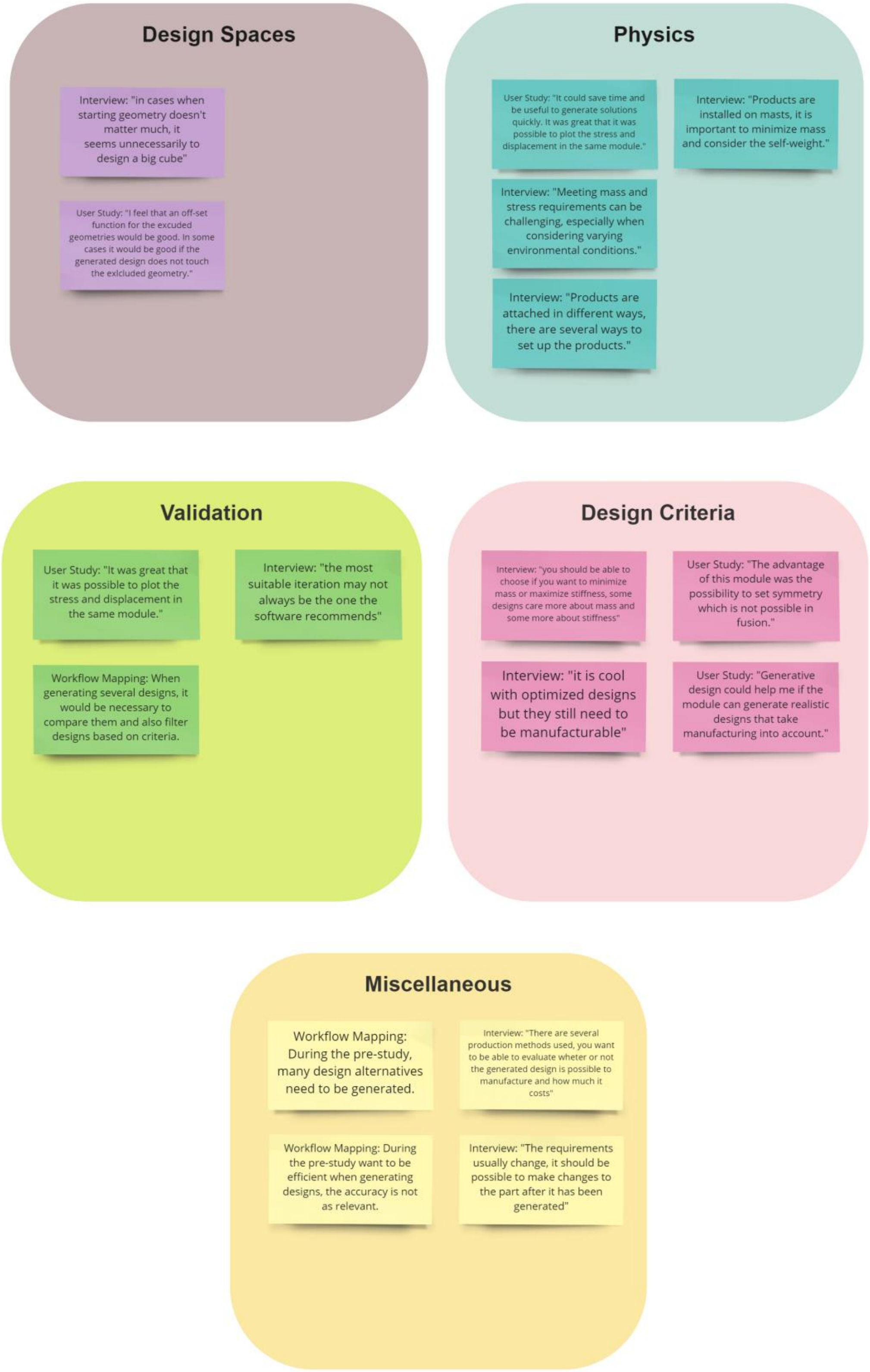
Based on the identified underlying needs for generative design, the software has the potential to address many of Ericsson's needs and help the company achieve its objective of increasing profits. By leveraging the benefits of generative design, Ericsson can produce designs with higher stiffness-to-weight ratio, shorten lead times in designing, establish better collaboration between product development and production engineering and reduce their overall environmental impact.

5.1.3. Identified Needs for Generative Design

To determine the requirements for a generative design software at Ericsson, a user needs identification was conducted. The collection of needs employed both interview and user study methods. The interviewees were mechanical design engineers, who are potential users of generative design at Ericsson. The user study involved participants testing the existing generative design module in Creo, based on a structured case.

A total of eight responses were collected, all from mechanical design engineers. Two-thirds of the respondents reported having no prior experience with generative design, while the remaining third had used it a few times for leisure. The average rating for the module was 7.4 out of 10, indicating a high level of satisfaction among the participants.

The responses from the survey and the interviews were analyzed to identify the key needs of Ericsson's mechanical design engineers regarding generative design. These needs were categorized on a digital whiteboard and presented in Figure 7, which provides insight into the primary advantages and disadvantages of generative design. The identified needs were deemed essential for continuous evaluation of an eventual implementation of generative design in Ericsson.



Design Spaces

Interview: "in cases when starting geometry doesn't matter much, it seems unnecessarily to design a big cube"

User Study: "I feel that an off-set function for the excuded geometries would be good. In some cases it would be good if the generated design does not touch the exlcluded geometry."

Physics

User Study: "It could save time and be useful to generate solutions quickly. It was great that it was possible to plot the stress and displacement in the same module."

Interview: "Products are installed on masts, it is important to minimize mass and consider the self-weight."

Interview: "Meeting mass and stress requirements can be challenging, especially when considering varying environmental conditions."

Interview: "Products are attached in different ways, there are several ways to set up the products."

Validation

User Study: "It was great that it was possible to plot the stress and displacement in the same module."

Interview: "the most suitable iteration may not always be the one the software recommends"

Workflow Mapping: When generating several designs, it would be necessary to compare them and also filter designs based on criteria.

Design Criteria

Interview: "you should be able to choose if you want to minimize mass or maximize stiffness, some designs care more about mass and some more about stiffness"

User Study: "The advantage of this module was the possibility to set symmetry which is not possible in fusion."

Interview: "it is cool with optimized designs but they still need to be manufacturable"

User Study: "Generative design could help me if the module can generate realistic designs that take manufacturing into account."

Miscellaneous

Workflow Mapping: During the pre-study, many design alternatives need to be generated.

Interview: "There are several production methods used, you want to be able to evaluate wheter or not the generated design is possible to manufacture and how much it costs"

Workflow Mapping: During the pre-study want to be efficient when generating designs, the accuracy is not as relevant.

Interview: "The requirements usually change, it should be possible to make changes to the part after it has been generated"

Figure 7 - Categorized customer needs

5.1.4. Analysis of Identified Needs

After the collection of needs for generative design software was obtained, as illustrated in Figure 7, the needs were subsequently subjected to analysis, as presented in Table 1. The identified needs were classified into distinct categories, namely, Design Spaces, Physics, Design Criteria, Validation, and Miscellaneous. Each identified need was accompanied by a justification, providing a clear explanation for its presence, along with an assigned weight on a scale of 1 to 5, representing the relative importance of the need. Moreover, each need was scrutinized in terms of its relevance to specific stages of the product development process. Lastly, the table includes a column denoting the origin of each need.

Table 1 - List of user needs

	No.	Need	Justification	Weight (1-5)	Origin
Design Spaces	1.1	Automated creation of starting geometry	Not wasting time on modelling starting geometry	3	Interview
	1.2	Be able to select an offset for the excluded geometry	This is sometime desired and if not possible, manual modelling is necessary	4	User Study
Physics	2.1	Be able to define several load cases in one study	This makes it easier to simulate different situations	4	User Study
	2.2	Different load selections	Products are exposed to different kinds of loads in real environements	4	Interview
	2.3	Different constraint selections	The attachments of products varies	4	Interview
	2.4	Possible to define contact	Loads may be applied to bodies other than preserved geometry	4	Interview
	2.5	Possible to apply gravity	Products are mounted on a altitude	3	Interview
Design Criteria	3.1	Possible to set various objectives	The aim of the product objective varies	5	Interview
	3.2	Utilize generative design for different manufacturing methods	Different manufacturing methods are utilized	5	Interview / User Study
	3.3	Generate designs based on geometry constraints	Designs often needs to have specific geometry constraints	5	User Study
Validation	4.1	Possible to plot the simulation of stress and/or displacement	Initial visual check if the generated design is feasible	4	User Study
	4.2	Compare generated alternatives	Finding the most suitable design	4	Workflow Mapping
	4.3	Filter different alternatives	Save time if several designs are generated	4	Workflow Mapping
	4.4	Display and use iterations from the generation process	The most suitable model might not be the final generated one	2	Interview
Miscellaneous	5.1	Several generated design alternatives	Being able to evaluate several design alternatives simultaneously with only one generation saves resources	4	Workflow Mapping
	5.2	Cost estimation for manufacturing	Being able to evaluate concepts in regards to total cost in an early stage	4	Interview
	5.3	Selection for generation accuracy	Being able to run with varied accuracy for *quick and dirty* runs and for detailed runs	5	Workflow Mapping
	5.4	Iterate generation when geometries are out of date	Designs are often iterated	5	Interview

5.2. Software Benchmarking

The software evaluation was undertaken with the objective of comparing various software programs that offer generative design or topology optimization. The evaluated programs were Creo Parametric by PTC, Fusion 360 by Autodesk, Inspire by Altair, 3DExperience by Dassault Systèmes, Ansys Mechanical and Ansys Discovery. All software programs were assessed on an equal footing against the same set of objectives. These objectives encompassed the use of an identical part for all software programs, along with the application of equivalent load cases, material properties, design constraints and level of fidelity for the generation.

5.2.1. Transformation of Needs into Benchmarking Criteria

To effectively evaluate the selected software in accordance with customer needs, it was imperative to translate the identified needs described in section 5.1.4 into benchmarking criteria. This process involved converting each identified need into a specific evaluation criterion, which could be systematically assessed during the evaluation of each software. By establishing clear and objective criteria for evaluating the software, it became possible to objectively assess how well each option aligned with the identified customer needs. All criteria were sorted using the same categories as in the Customer Needs Identification, shown in Table 1. The full list of benchmarking criteria, as well as each software response to each criterion, can be found in Appendix 1.

5.2.2. Benchmarking Case

In order to ensure consistency in the software evaluation process, a standardized approach was adopted for evaluating different software. The same set of constraints and objectives were set for each one of the software, thus it was possible to achieve consistency and mitigate possible biases. Further, the same part was used for all software evaluations, with identical load cases and material properties. The material properties used were based on an aluminum alloy and are described in Table 2.

Table 2 - Material properties for aluminum utilized in benchmarking

Density	2,7 g/cm^3
Young’s Modulus	70 GPa
Tensile Yield Stress	225 MPa
Poisson’s Ratio	0,33

The part designed for the evaluation was a simple component with various features to challenge the software, while avoiding unnecessary computational time. The part is shown below in Figure 8, also showing the different regions of the study. The blue bodies are preserved geometries, the red body is the excluded geometry, the transparent body is the starting geometry, and the grey bodies are undefined geometries. To further study the part, see Appendix 2 for a drawing of the utilized part.

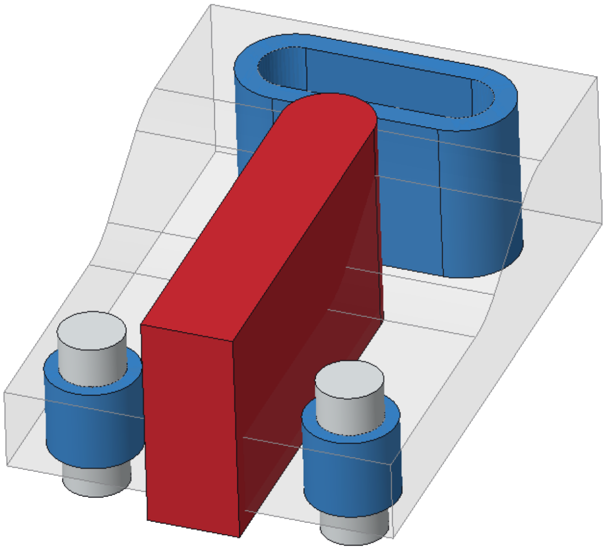
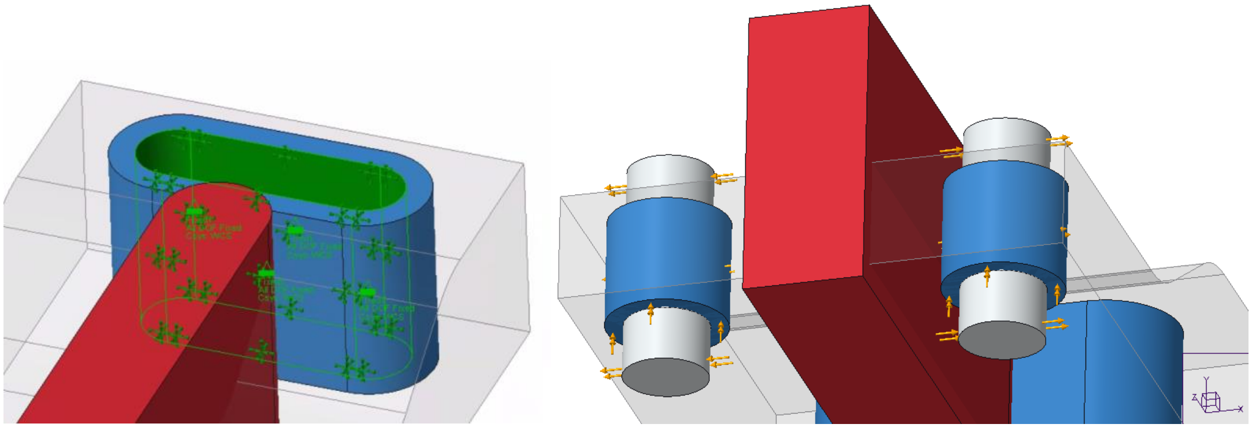


Figure 8 - The design used in the benchmarking case

The material properties previously described were kept constant for all software generations. The load case consisted of a fixed constraint in all degrees of freedom in the bigger preserved geometry, shown in Figure 9 a), two directional force loads of 1000 N in X and -X direction were applied on the pins, and -35 Nm of moment load in -X direction was applied on the bottom surface of the smaller preserved geometries, shown in Figure 9 b). It is noteworthy that the chosen load case was not intended to simulate an actual scenario, but rather serve the purpose of facilitating optimization while simultaneously providing outcomes related to stress and deformation which were to be evaluated. Regarding manufacturing constraints were two alternatives considered being unrestricted and AM-restricted optimization. The unrestricted alternative allows the software to generate material freely in accordance to set design criteria while the AM-restricted optimization aims to generate designs which minimizes the need for support material, thus minimizing overhang angles of more than 45°.

The design objective in all cases was set to *maximize stiffness* with a specific mass of 1,75 kg. Furthermore, the software programs were also evaluated against the same study settings, including the element size of 3,2 mm and maximum number of iterations. The aim of the evaluation was to gain a comprehensive understanding about the capabilities of each one of the different software.



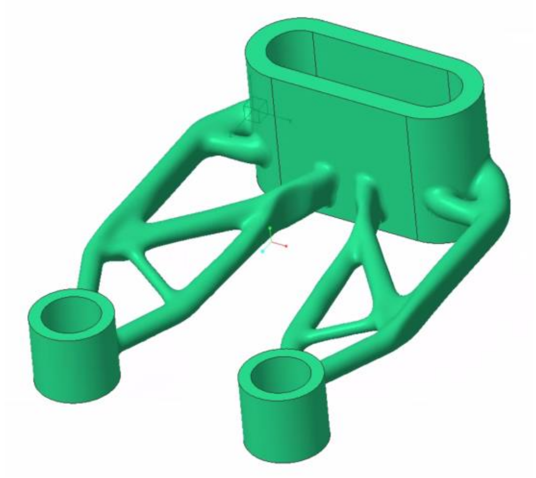
a) Fixed constraint

b) Forces and moment load

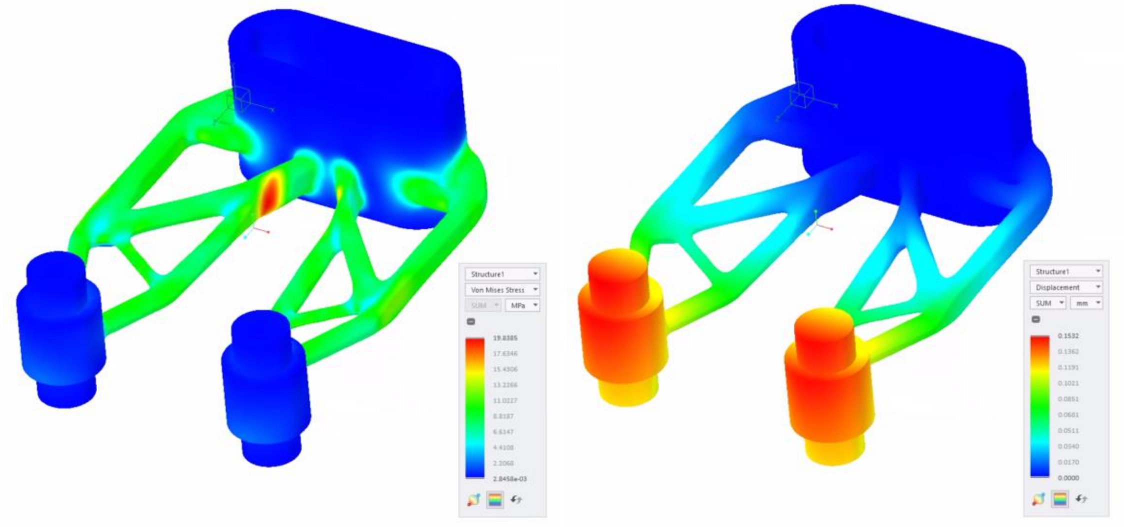
Figure 9 - Applied load case in the benchmarking case

5.2.3. Results from Benchmarking

During the study set-up in all the software, the criteria mentioned in section 5.2.1 were assessed, the number of clicks to generate the design were measured and the time it took to complete these steps were also noted. Additionally, the generated designs were analyzed regarding maximum von Mises Stress and displacement values. The outcomes from Creo in terms of the generated design restricted to AM, along with the corresponding von Mises and displacement plots, are shown in Figure 10 a), b) and c) respectively.



a) Generated design in Creo restricted to AM

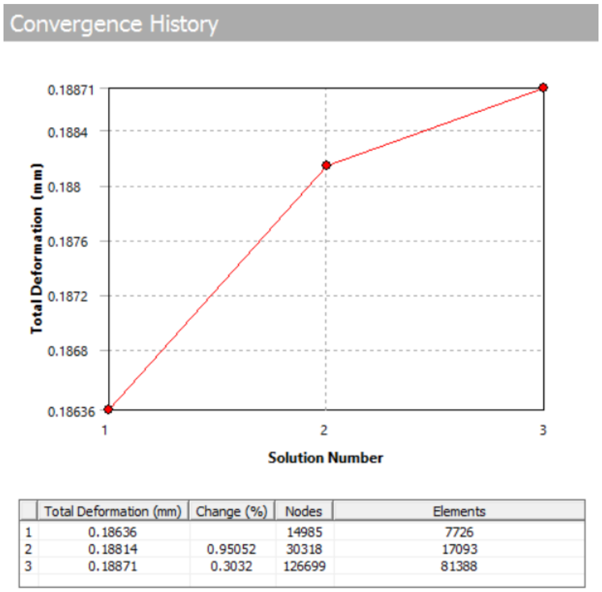


b) von Mises plot

c) Displacement plot

Figure 10 - Generated Design from Creo with corresponding von Mises and deformation plot

After generating all designs, their respective plots were collected, and each design was subsequently exported into a STEP-file for analysis in Ansys Workbench, which is a dedicated FEM tool. The purpose of this approach was to ensure a fair comparison across the software tools, accounting for potential differences in the way each software performs FEM. Stress and displacement plots, along with their respective maximum values, were recorded for each design. To obtain accurate results, a convergence analysis was conducted with an allowable change of 0,5%. Specifically, if an approximately four-fold increase in the number of elements in areas experiencing high stresses did not cause the maximum value to deviate by more than 0,5% from the previous value, the analysis was deemed to have converged, and the results were considered trustworthy. Figure 11 below displays a graph illustrating how the total deformation has converged with respect to the increase in the number of elements utilized in the analysis.



	Total Deformation (mm)	Change (%)	Nodes	Elements
1	0.18636		14985	7726
2	0.18814	0.95052	30318	17093
3	0.18871	0.3032	126699	81388

Figure 11 - Convergence analysis graph

All software were evaluated based on how well their reported von Mises stress and displacement matched with the result from Ansys Workbench. Additional designs and their respective plots for the remaining software, both from the evaluated software and from Ansys Workbench, are presented in Appendix 3, Appendix 4, Appendix 5 and Appendix 6.

The designs optimized for AM, which were generated using Creo, Fusion 360, 3DExperience, Ansys Discovery, and Ansys Workbench were prototyped using FDM 3D-printing. The 3D-printed model, generated with Creo, is shown in Figure 12. Additional 3D-printed models for the remaining software are presented in Appendix 7.

Figure 12 - 3D-printed design of the generated design from Creo

Upon conducting the evaluation of all software in accordance with the criteria outlined in chapter 5.2.1, as demonstrated by the case study explained in chapter 5.2.2, the total scores were calculated. The results, depicted in Table 3, reveal that Creo emerged as the top performer with 675 points, with 3DExperience and Fusion 360 trailing closely behind. The full list of evaluated criteria and the result for each software can be examined in Appendix 1.

Table 3 - Ranking and total score of the software in the benchmarking

Rank	Software	Total Score
1	Creo	675
2	3DExperience	568
3	Fusion 360	560
4	Ansys Discovery	472
5	Ansys Mechanical	471
6	Altair	298

5.2.4. Resulting Takeaways from Benchmarking

When interpreting the results presented in section 5.2.3 it is essential to bear in mind that all software were evaluated based on the same criteria that were linked to a specific identified need by Ericsson. Therefore, these scores do not necessarily reflect the true potential of the software programs since there may be several more capabilities and parameters that were not evaluated as they were not required to fulfill the specified needs.

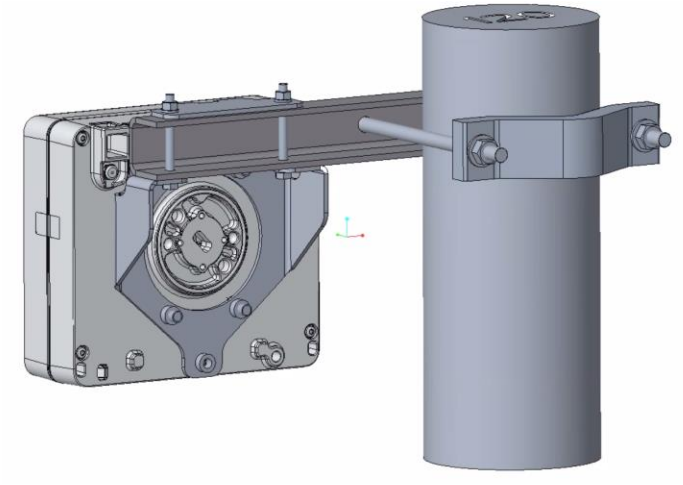
Based on the benchmarking results, it can be concluded that Creo is the most suitable software tool for the majority of mechanical design engineers, owing to its ease of learning, user-friendliness, efficiency, ability to generate realizable concepts, and lack of post-processing requirements. Moreover, since Creo is the software currently utilized for modeling by Ericsson, it eliminates any cross-software implications in a possible workflow adoption.

Conversely, Ansys Workbench emerged as the tool with the highest number of features and a big potential for parameter adjustment, thus making it a powerful design platform provided the designer has the necessary knowledge of the tool. Hence, Ansys Workbench may be deemed the most fitting solution for mechanical design engineers with a strong inclination toward optimization, or for designs that necessitate intensive optimization protocols or exhibit distinct constraints. Although it may be more challenging to learn, less user-friendly, and time-consuming, it provides numerous editable parameters, and its results are highly precise, giving users more autonomy in defining complex load cases and specifying criteria at a higher level. However, it is not suitable for multibody models.

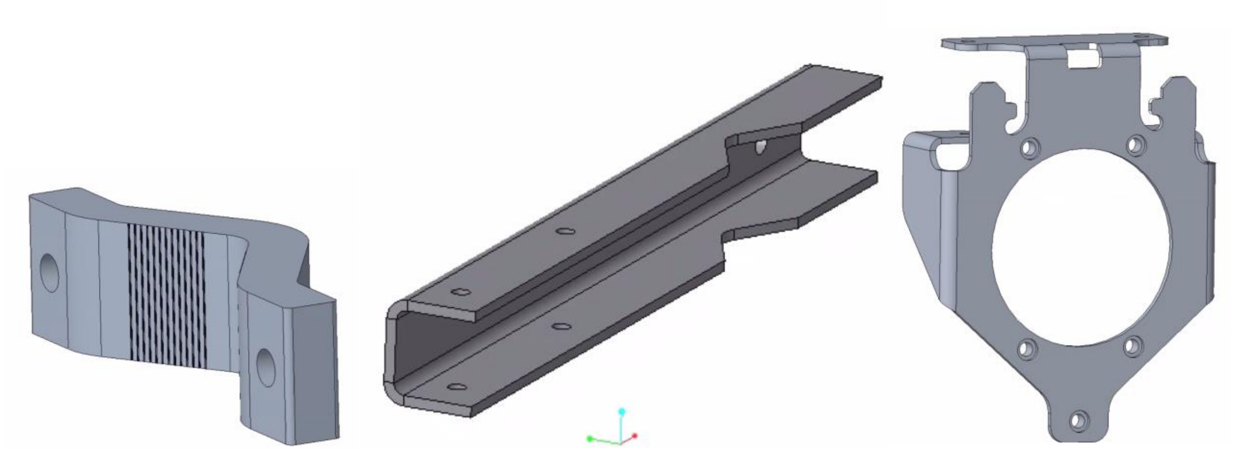
An additional noteworthy implication relates to the observation that numerous assessed software programs exhibited dissimilar maximum values for von Mises stress or displacement when compared to the identical design and boundary conditions evaluated in Ansys Workbench. This suggests that despite the apparent ability of the evaluated software to generate designs with low stress and displacement values, one must be cautious when interpreting these results. It is advisable to validate such values by employing a specialized FEM tool such as Ansys Workbench for cross-verification purposes.

5.3. MINI-LINK Mounting Kit Redesign

In order to confirm the results of the benchmarking and to clarify the feasibility of implementing generative design in a practical design scenario, a redesign of the mounting kit for a MINI-LINK radio was undertaken. The process involved an initial analysis of the current mounting kit, depicted in Figure 13, aimed at revealing the kit’s functional attributes through the development of a function means tree, as well as the establishment of a requirement specification. Subsequently, the load case to which the mounting kit is subjected was examined to ensure that the generations incorporated the correct load case. The generative design module in Creo was utilized to create the generations, as it emerged as the most effective tool in the benchmarking analysis.



a) MINI-LINK radio mounted on a Ø120mm mast



b) Clamp *c) Support arm* *d) Support plate*

Figure 13 - Existing mounting kit for the MINI-LINK radio

In the current implementation, the support arm and support plate are fabricated using hot dipped galvanized steel, whereas the clamp is composed of aluminum. In the forthcoming redesign, it has been determined that designs will be generated using aluminum as the primary material, owing to its reduced density and potential for manufacturing through both casting and AM, which will be the two methods used in the redesign. The material properties of the aluminum alloy utilized are detailed below in Table 4, which also coincide with the material used by Ericsson in the existing clamp.

Table 4 - Material properties of the aluminum used in the redesign

Density	2,7 g/cm^3
Young’s Modulus	70 GPa
Tensile Yield Stress	225 MPa
Poisson’s Ratio	0,33

A mesh size of 2 mm was implemented across all design generations, yielding an approximate total number of elements of 500 000. The utilization of a consistent mesh size enables a standardized analysis approach, ensuring reliable and accurate results across all iterations of the generative design process. The AM constraints aim to minimize the requirement of support material by diminishing overhangs with an angle exceeding 45°. On the other hand, the casting constraint develops a shape with a draft angle of 3°, thereby enabling an easy extraction of the design from the mold.

5.3.1. Function Means Tree

To attain a comprehensive understanding of the mounting kit employed for the MINI-LINK radio, a function analysis was conducted. This analytical procedure was performed on the current iteration of the product with the primary objective of delineating its diverse functionalities. The resulting insights from the analysis were utilized to inform future developmental efforts.

The primary function of the mounting kit is to maintain the MINI-LINK radio at a specified height. The means by which this function is accomplished are the fastening element and mast. The fastening element comprises three specific functions, namely, preventing the radio from falling, withstanding harsh weather conditions, and providing attachment between the radio and the mast. The proposed means can be observed in Figure 14.

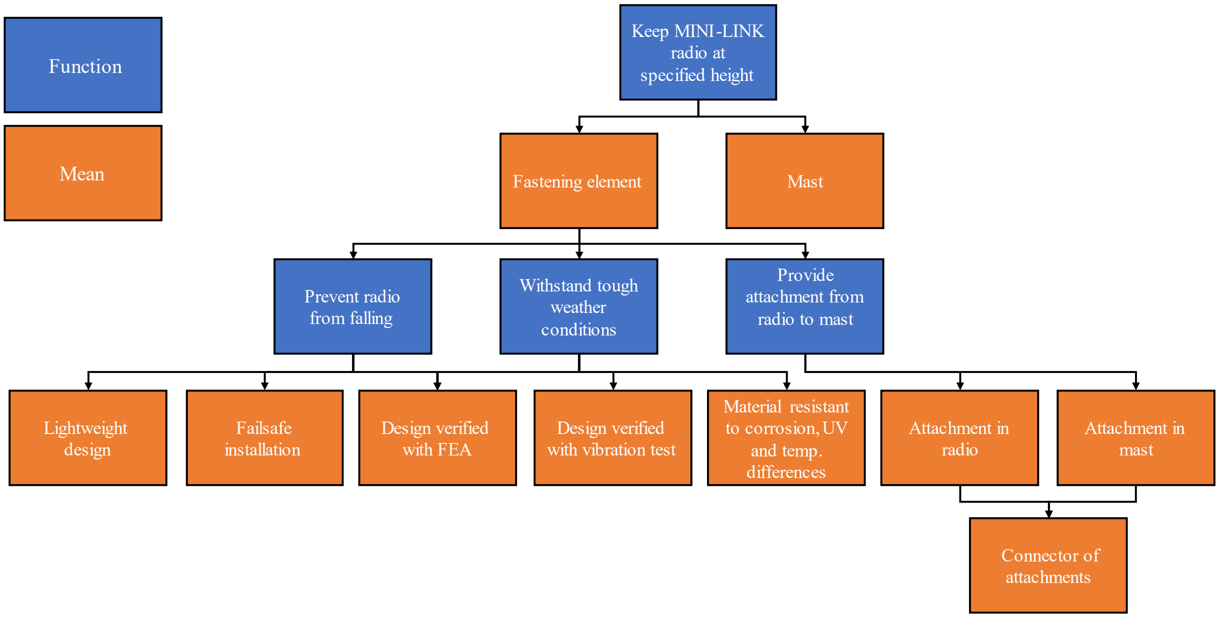


Figure 14 - Function Means Tree for the MINI-LINK mounting kit

5.3.2. Requirement Specification

The requirement specification presented in this report is based on an extensive research and analysis of functional needs and data for the existing product. The resulting document is presented in Table 5 and contains two categories, namely requirements and desires. The former consists of twelve requirements which represents the necessary conditions that must be met by the product. The latter consists of one desire which provides a recommendation, namely that the product should be easy to install. As illustrated in the table, each requirement and desire are accompanied by a specification that outlines the expected performance. The marginal value represents the minimum threshold that the product must satisfy, while the ideal value indicates the desired level, which is not mandatory.

Moreover, the justification section presents the rationale for the inclusion of each requirement or desire, while the evaluation section outlines the intended approach to assess compliance. To prioritize desires, they are assigned weights ranging from one to five.

Table 5 - Requirement Specification for mounting kit

ID	Specification	Marginal Value	Ideal Value	Justification	Evaluation	Weight of desire (1-5)
R1	Total mass	1890 *g*	< 1890 *g*	Mass of new proposal must be less than or equal to existing solution / Minimize material cost & transport cost	CAD-assessment	N/A
R2	No plastic deformation	Pass	N/A	The radio must not fall down	FEM-analysis	N/A
R3	Manufacturing cost @5000 batch size	≤ Existing purchase cost	N/A	Cost of new proposal must be less than or equal to existing solution purchase cost / Minimize total cost	Granta EduPack and calculations	N/A
R4	Assembly cost for MINI-LINK installation with mounting kit	24 *SEK/pcs*	< 24 *SEK/pcs*	Cost of new proposal must be less than or equal to existing solution assembly cost / Minimize total cost	Timing	N/A
R5	Material must withstand temperature deviations	-50°C < x < 80°C	N/A	The mounting kit is used in different environments	Granta EduPack	N/A
R6	Material must not corrode	Pass	N/A	Corrosion weakens structural properties	Granta EduPack	N/A
R7	Mounting element for radio	Pass	N/A	The mounting attachment on the radio can not be changed	N/A	N/A
R8	Mounting kit must support various mast diameters	⌀ 50-120 *mm*	N/A	Telecom masts vary in diameter	CAD-assessment	N/A
R9	Mounting kit is subjected to weight of radio	2,5 *kg*	N/A	The radio must not fall down	FEM-analysis	N/A
R10	Structure is subjected to a perpendicular windload	90 *m/s*	N/A	The radio must not fall down	FEM-analysis	N/A
R11	Screws must be tightened with the torque of a M10 bolt	47 *Nm*	N/A	The radio must not fall down	FEM-analysis	N/A
R12	Mounting kit must pass Ericsson vibration test regarding eigenmode failures	Pass	N/A	Products are internally tested	Vibration test	N/A
D1	The mounting kit should be easy and safe to install	Pass	N/A	Installations might be executed on high altitudes	N/A	5

5.3.3. Load Case Investigation

In order to facilitate the generation of designs for the mounting kit, a thorough investigation of the applied load case was deemed necessary. Through this process, it was determined that the mounting kit is subjected to three distinct forces, namely the gravitational load exerted by the radio, the wind force resulting from external wind conditions, and the screw force originating from the tightening torque of the screws securing the mounting kit to the mast. All modal loads, such as vibration from the mast, were neglected since it is currently not possible to combine static and modal loads in Creo. Each of these forces was carefully evaluated and subsequently calculated to establish their respective magnitudes.

Gravitational load of the radio

The gravitational load exerted by the radio is a function of its mass (m) and the gravitational constant (g). This relationship can be expressed mathematically as shown in Equation 3.

$$F_{gravity} = m * g \approx 25\ N$$

Equation 3 - Function for gravitational load

The mass of the radio is 2,5 kg and the gravitational constant is assumed to be 9,82 m/s^2 worldwide. Based on these values, the gravitational load acting on the mounting kit is calculated to be 25 N.

Wind force

The wind force exerted on the mounting kit can be determined through the utilization of the wind velocity (v), air density (ρ), the angle of incidence (α), and the surface area upon which the wind is acting (A). The mathematical expression for the wind force is given by Equation 4.

$$F_{wind} = \frac{\rho\ * v^2}{2}\ * A\ * \sin\alpha \approx 174\ N$$

Equation 4 - Function for wind force

Upon analysis, the wind velocity utilized for structural calculations at Ericsson was determined to be 90 m/s, while the default air density was established to be 1,225 kg/m^3. For the most severe condition, an angle of incidence of 90° was assumed, and the rear surface area of the radio at this angle was found to be 0,035 m^2. Based on these parameters, the wind force acting on the mounting kit was calculated to be 174 N.

Screw force

The third force acting on the mounting kit, namely the screw force, was calculated based on several parameters, shown below.

$P = 1{,}5\ mm\ (threading\ for\ M10)$

$\mu = 0{,}25\ (friction\ against\ contact)$

$\mu b = 0{,}25\ (friction\ between\ threads)$

$d_2 = 9{,}026\ mm\ (mean\ diameter)$

$d_i = 10{,}5\ mm\ (inner\ diameter\ round\ washer\ M10)$

$d_y = 22\ mm\ (outer\ diameter\ round\ washer\ M10)$

$r_m = \frac{d_i + d_y}{4} = 7{,}625\ mm\ (mean\ radius\ of\ contact)$

$M_{tot} = 47\ Nm\ (total\ tightening\ torque, bolt\ strenght\ grade\ 8.8)$

The desired screw force (F_{ax}) was determined through the utilization of Equation 5. The formula, as well as screw data and friction estimates were found in [53].

$$M_{tot} = F_{ax}\left(0{,}16P + 0{,}58\mu d_2 + \mu_b \frac{d_i + d_y}{4}\right)$$

Equation 5 - Function for screw force

Using this equation, the axial force (F_{ax}) from the screws was found to be 13 128 N.

Based on the insights gained, a decision was made to prioritize the redesign of the clamp, as the screw force demonstrated significant superiority over the two other forces acting on the mounting kit. The knowledge and experience gained from the process of redesigning the clamp could then be effectively applied to the subsequent redesign of the support arm.

5.3.4. Set-up of Generative Design Study - Clamp

The present section serves to inform upon the set-up for the generative design study of the clamp, including the geometries under examination, the corresponding constraints and loads to which the geometries are subjected, as well as the design criteria related to manufacturing considerations.

The design objective in all generations was to *maximize stiffness* with a target mass of 309 g, which is the mass of the existing clamp.

Geometries

Figure 15 illustrates the geometries employed in the generative design investigation for the clamp. The blue bodies correspond to preserved geometries, while the red bodies represent excluded geometries. The transparent body is the geometry in which the software can allocate material. To enable the software to allocate material optimally, efforts have been undertaken to preserve as little space as possible. The preserved geometries include a thin plate that serves as the contact surface to the mast, similar to the existing clamp, as well as two cylindrical spaces where the screws will be mounted. The red cylinders have been excluded from the starting geometry to allow for space to mount and fasten the screws onto the clamp.

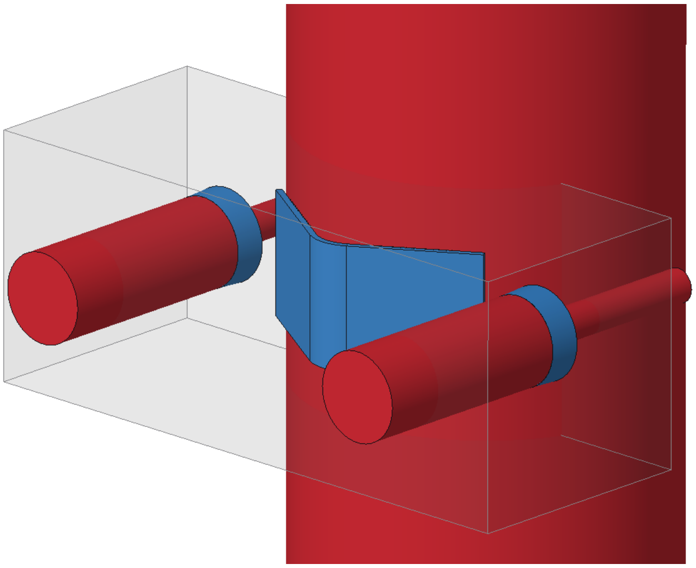
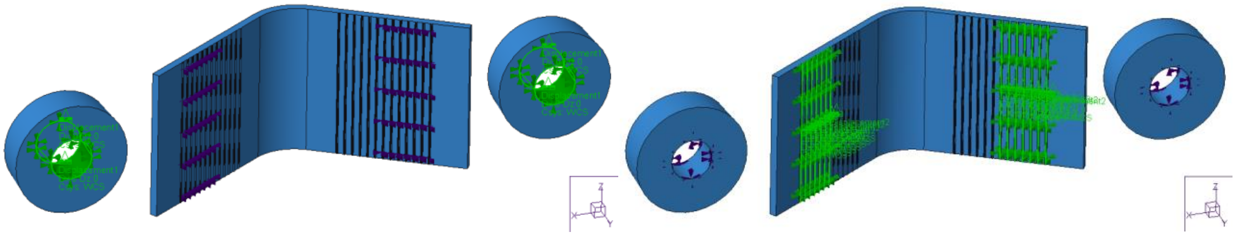


Figure 15 - Geometries of the generative design study for the clamp

Constraints

The constraints applied in the clamp redesign comprise of two primary components. Firstly, a displacement constraint is enforced in the two screw holes, where they are fixed in the X- and Z-directions, while being free in the Y-direction, as illustrated in Figure 16 a). Secondly, a displacement constraint is imposed on the edges that interact with the mast, whereby they are fixed in the X- and Y-directions while being unconstrained in the Z-direction, shown in Figure 16 b). Consequently, all frictional forces originating from the contact between the screws and the two circular preserved geometries, as well as those generated by the edges that interact with the mast, are disregarded. This approach assumes that the frictional effects are insignificant in comparison to other forces and are therefore negligible in the analysis.



a) Displacement in the screw holes

b) Displacement on the edges interacting with the mast

Figure 16 - Constraints of the generative design study for the clamp

Load case

The forces applied on the clamp entail the screw force that is implemented on both cylindrical geometries, at a diameter equivalent to the washer that will ultimately be assembled in that position, shown in Figure 17.

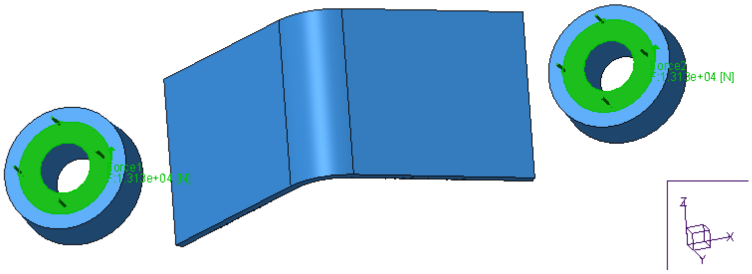
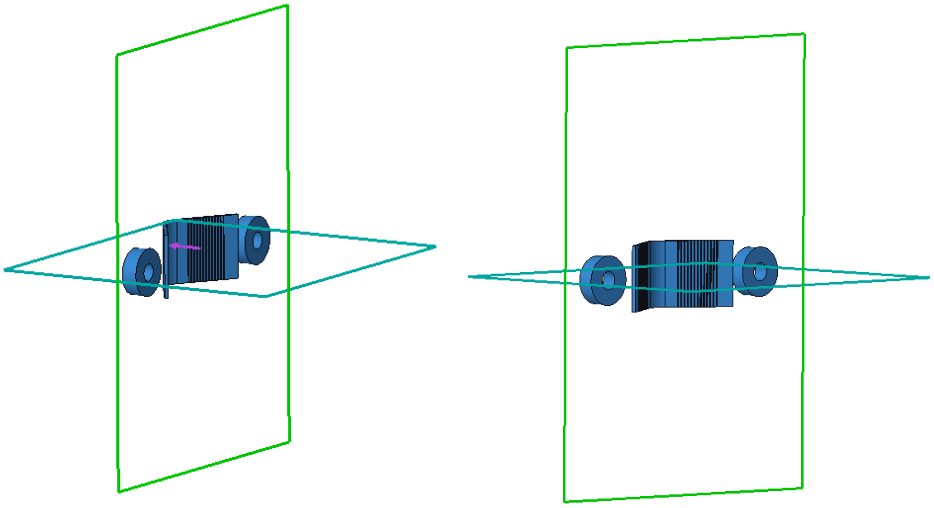


Figure 17 – Screw forces of the generative design study for the clamp

Design Criteria for Manufacturing

Figure 18 showcases the printing bed and printing direction for the AM-generation and the parting line for the casting-generation. Additionally, the blue plane showcases the design criteria for symmetry.

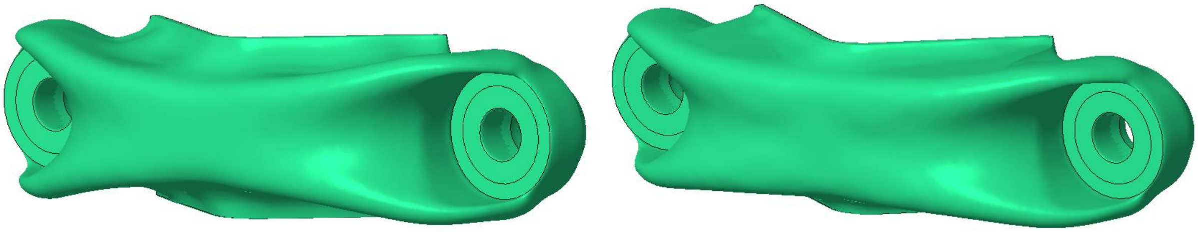


a) AM (green plane = printing bed, blue plane = symmetry) *b) Casting (green plane = parting line, blue plane = symmetry)*

Figure 18 – Illustration of the planes for the printing bed, parting line and symmetry used in the generative design study for the clamp

5.3.5. Results from Generations – Clamp

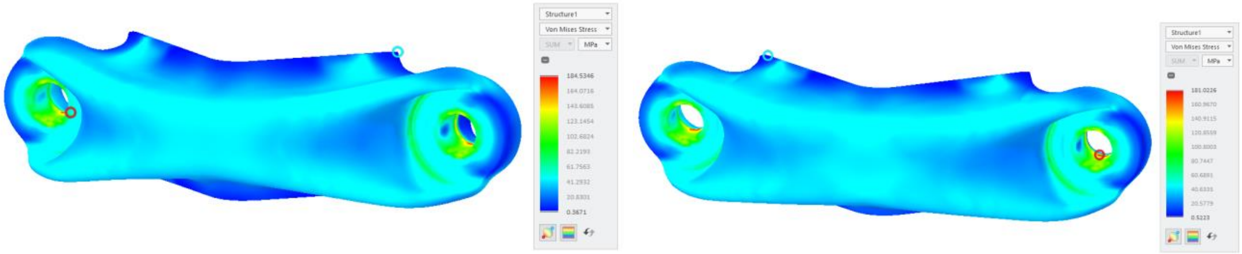
In Figure 19 below are the generated designs showcased using AM- and casting-constraints.



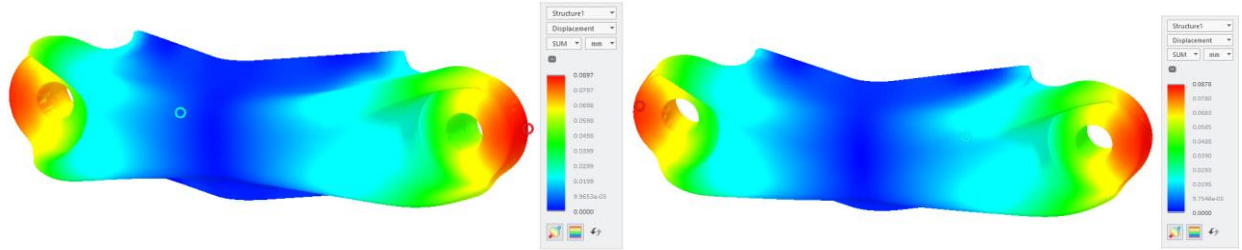
a) Generated design with AM-constraint *b) Generated design with casting-constraint*

Figure 19 - Results of the generative design study for the clamp

The two generated designs were analyzed regarding von Mises stress and displacement. The respective plots have been presented in Figure 20, with the maximum and minimum values of stress and displacement depicted by a red and blue circle, respectively. This analytical approach allows for a thorough assessment of the designs, aiding in the identification of potential areas of weakness.



a) *von Mises plot of generated design with AM-constraint* b) *von Mises plot of generated design with casting-constraint*



c) *Displacement plot of generated design with AM-constraint* d) *Displacement plot of generated design with casting-constraint*

Figure 20 - von Mises and displacement plots of the generated design for the clamp

Table 6 presents the outcomes obtained for the mass, maximum von Mises stress, and displacement values of the generated clamp.

Table 6 - Values for mass, von Mises stress and displacement for the clamp

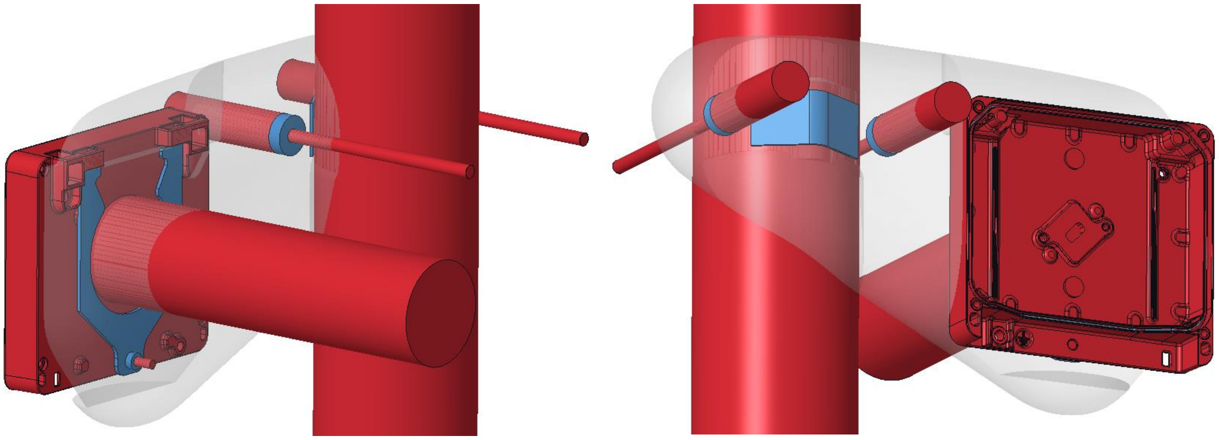
Attribute	**AM-constraint**	**Casting-constraint**
Mass (g)	305	306
Max von Mises stress (MPa)	184,5	181,0
Max Displacement (mm)	0,0897	0,0878

5.3.6. Set-up of Generative Design Study – Support Arm

The present subchapter serves to present the resulting set-up for the generative design study of the support arm, including the geometries under examination, the corresponding constraints and loads to which the geometries are subjected, as well as the design criteria related to manufacturing considerations. The support arm comprises of two distinct concepts, each characterized by unique preserved geometries, which is explained below. The design objective in all generations were to *maximize stiffness* with a target mass of 700 g.

Geometries – Concept 1

Figure 21 illustrates the geometries employed in the generative design investigation for the support arm. The blue bodies correspond to preserved geometries, while the red bodies represent excluded geometries. The transparent body denotes the initial geometry in which the software can allocate material. The preserved geometries include a thin plate that serves as the contact surface to the mast, similar to the existing clamp, as well as two cylindrical spaces where the screws will be mounted. Comparable to the existing solution, a plate has been preserved at the rear of the radio to ensure proper installation. To facilitate the mounting and fastening of screws onto the clamp and avoid material interference with cable attachment to the radio, the starting geometry has been modified to exclude the placement of the red cylinders. Additionally, both the mast and radio regions have also been excluded.

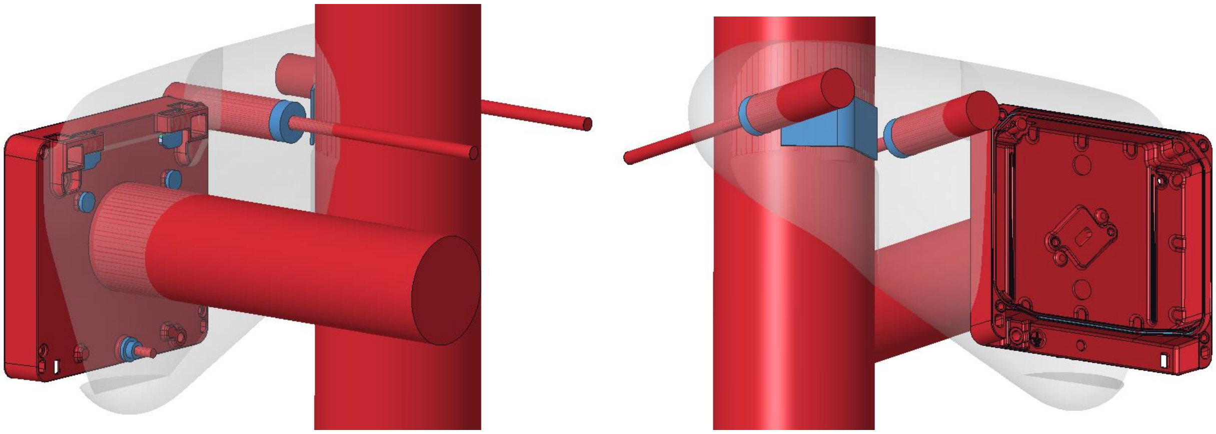


a) *Rear view* b) *Front view*

Figure 21 - Geometries of the generative design study for the support arm, concept 1

Geometries – Concept 2

The distinguishing feature between concept 1 and concept 2 lies solely in the geometries preserved at the rear section of the radio. In the latter concept, only the most crucial components of the plate have been retained, comprising the upper sheets of metal that fit into the slots of the radio frame, two circular sheets of metal that serve as support against the radio frame, and the lower cylindrical geometry into which a screw is fastened. By only preserving these geometries, which interact with the radio frame, the software is afforded greater flexibility in allocating material as needed, as a result of the reduced amount of material reserved for preserved geometries. All excluded geometries, along with the starting geometry, remain identical to those in concept 1. The geometries explained are found in Figure 22.



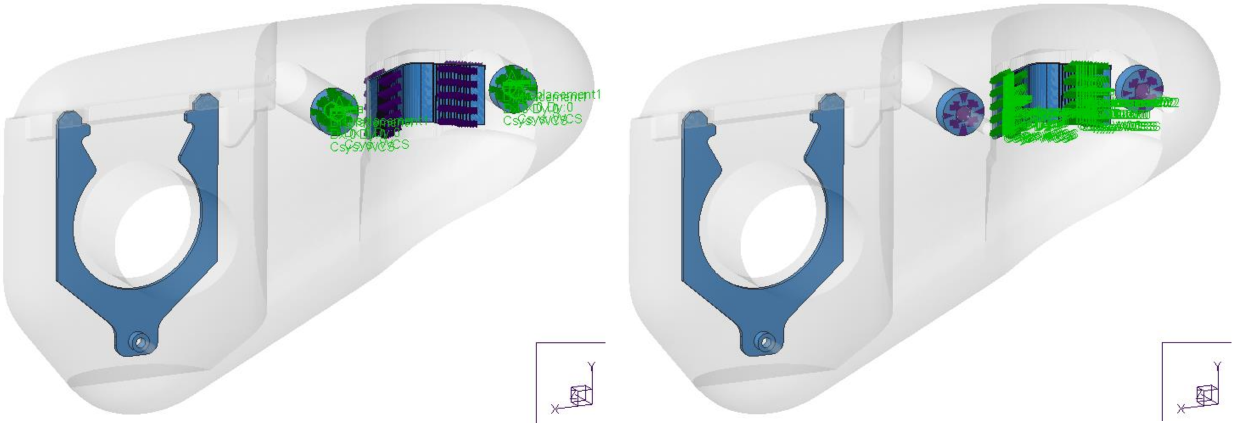
a) *Rear view*

b) Front view

Figure 22 - Geometries of the generative design study for the support arm, concept 2

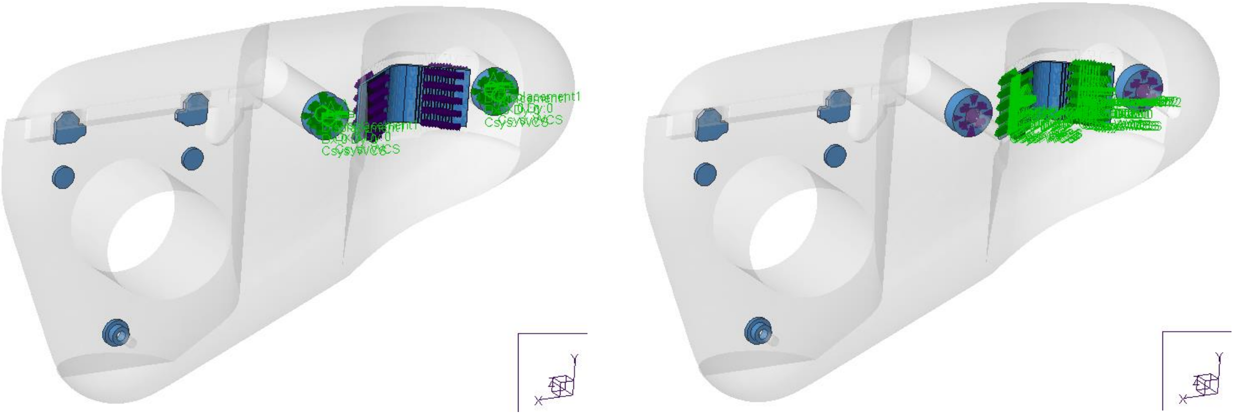
Constraints – Concept 1 & 2

The constraints implemented during the redesign of the support arm, which are identical to those employed in the redesign of the clamp, are demonstrated in Figure 23.



a) Displacement in the screw holes, concept 1

b) Displacement on the edges interacting with the mast, concept 1



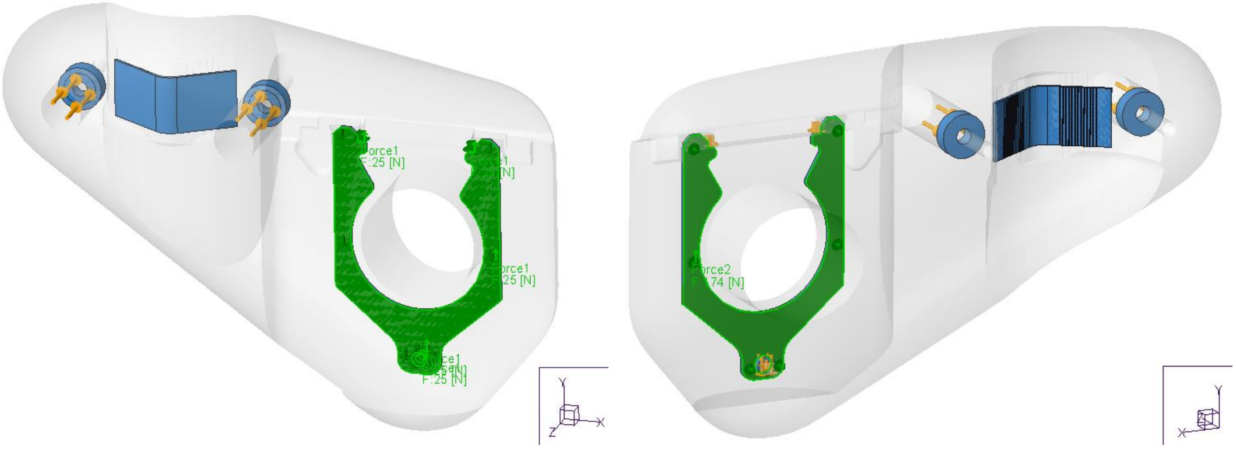
c) Displacement in the screw holes, concept 2

d) Displacement on the edges interacting with the mast, concept 2

Figure 23 - Constraints of the generative design study for the support arm

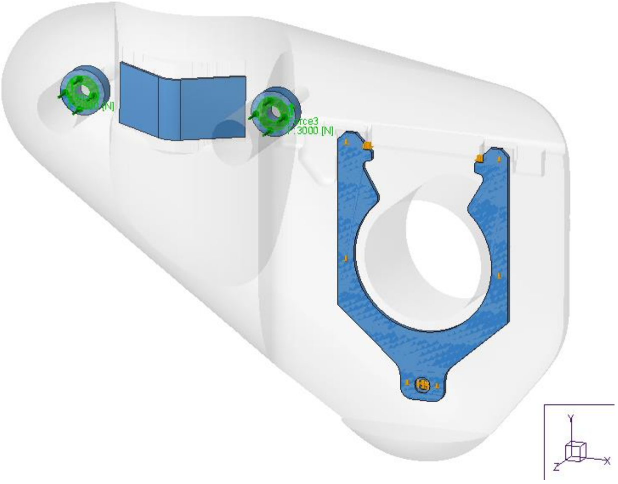
Load case – Concept 1 & 2

The support arm is subjected to a combination of forces, including the gravitational load acting on the preserved sheet metal plate mounted at the rear of the radio, the wind force acting perpendicularly on the front of the sheet metal plate, which represents the most extreme situation, as well as the screw forces acting on both cylindrical geometries at a diameter equivalent to that of the washer to be assembled in that position, all shown in Figure 24. However, the screw forces used in this study had to be decreased from the initial value of 13 128 N to 3 000 N, as the software prioritized the placement of material in response to the larger screw forces, making it difficult to connect all preserved geometries. Attempts were made to incorporate the original load for the screw forces, but the software failed to connect all geometries, as seen in Appendix 8. It was determined that sometimes one must use false loads to "trick" the software to generate a design that fully connects all geometries, which then should be verified using FEM to ensure its feasibility. The utilization of the false loads are further discussed in section 6.3.3.

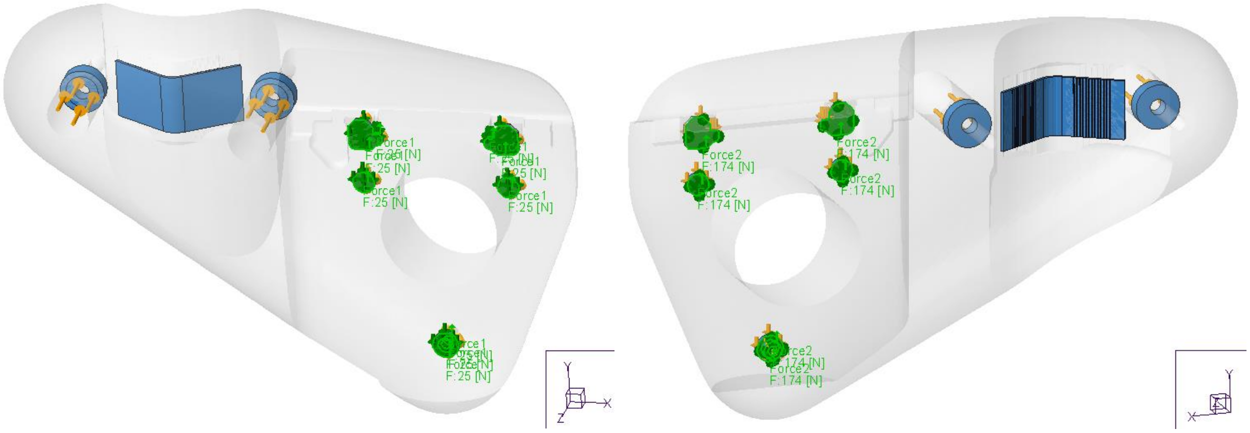


a) Gravitational force, concept 1

b) Wind force, concept 1

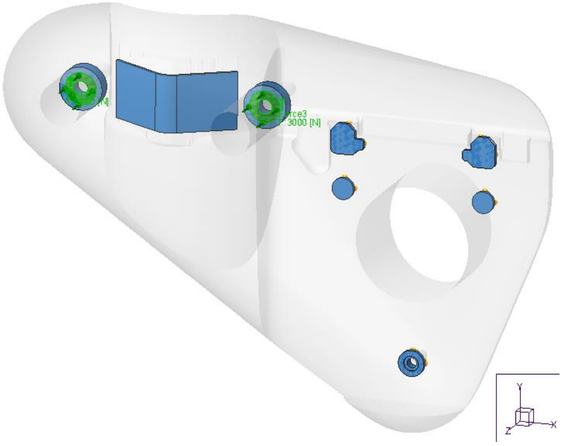


c) Screw forces, concept 1



e) Gravitational force, concept 2

f) Wind force, concept 2

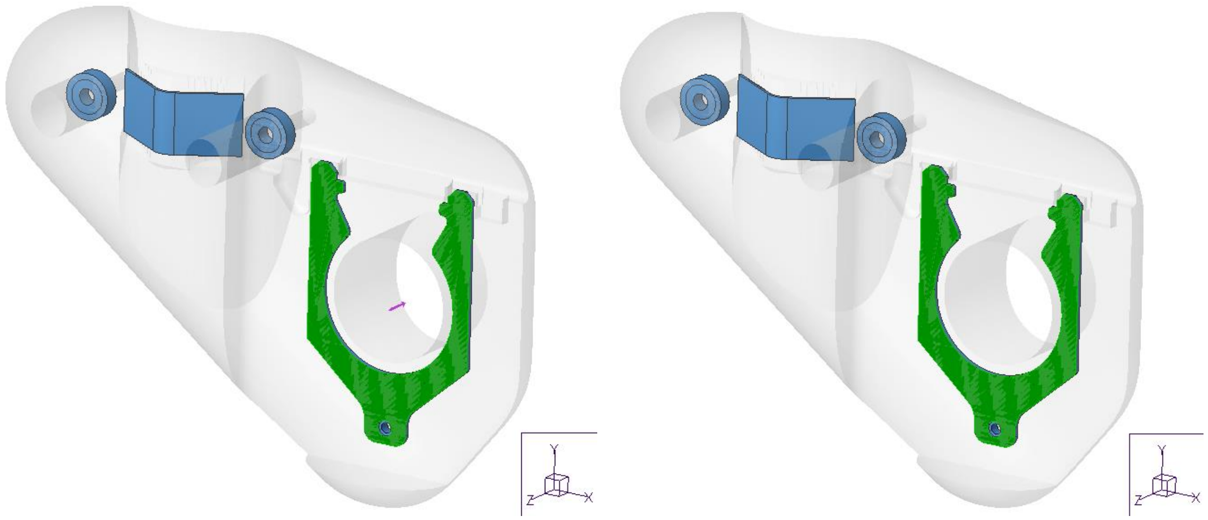


g) Screw forces, concept 2

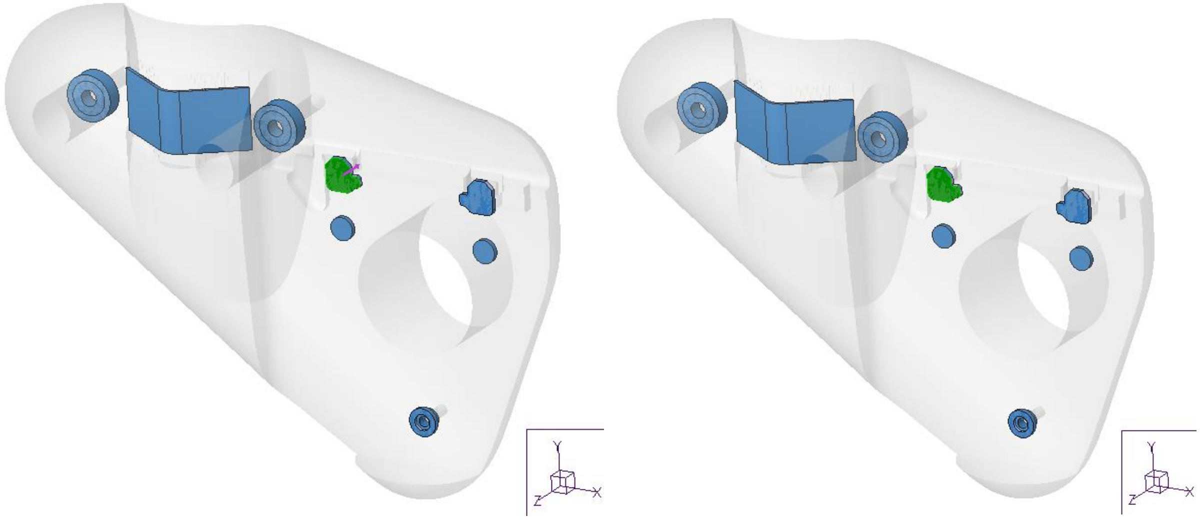
Figure 24 - Forces of the generative design study for the support arm

Design Criteria for Manufacturing - Concept 1 & 2

Figure 25 showcases the printing bed and printing direction for the AM-generation, as well as the parting line for the casting-generation for both concept 1 and 2.



a) AM (green plane = printing bed), concept 1 *b) Casting (green plane = parting line), concept 1*

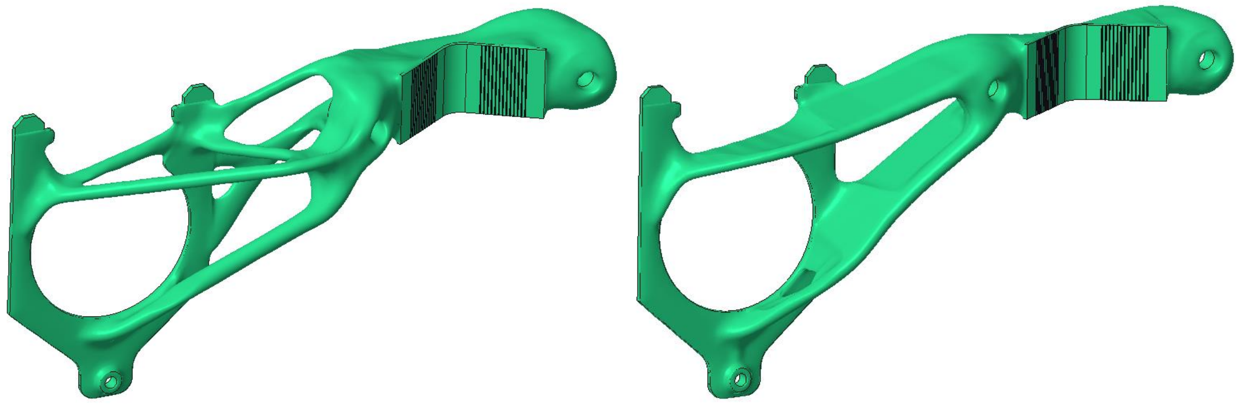


a) AM (green plane = printing bed), concept 2 *b) Casting (green plane = parting line), concept 2*

Figure 25 - Printing bed and parting line used in the generative design study for the support arm

5.3.7. Results from Generations – Support Arm

In Figure 26 below are the generated designs showcased using AM- and casting-constraints for both concept 1 and 2.

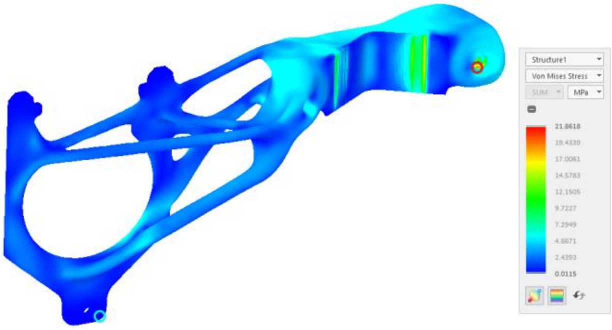


a) Generated design with AM-constraint, concept 1 *b) Generated design with casting-constraint, concept 1*

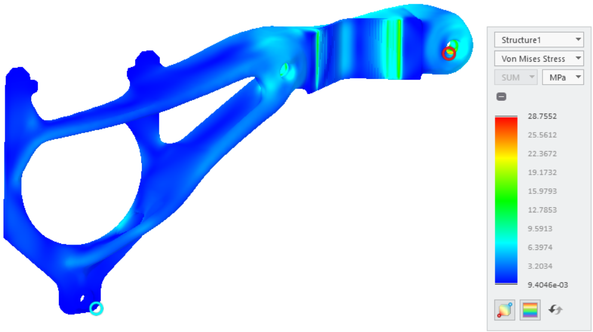
c) Generated design with AM-constraint, concept 2 *d) Generated design with casting-constraint, concept 2*

Figure 26 - Results of the generative design study for the support arm

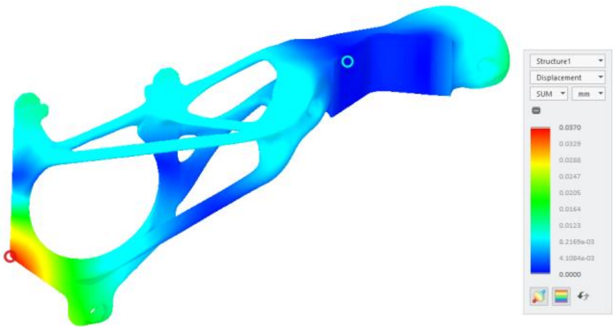
The generated designs were analyzed based on von Mises stress and displacement. The respective plots have been presented in Figure 27, with the maximum and minimum values of stress and displacement depicted by a red and blue circle, respectively. This analytical approach allows for a thorough assessment of the designs, aiding in the identification of potential areas of weakness.



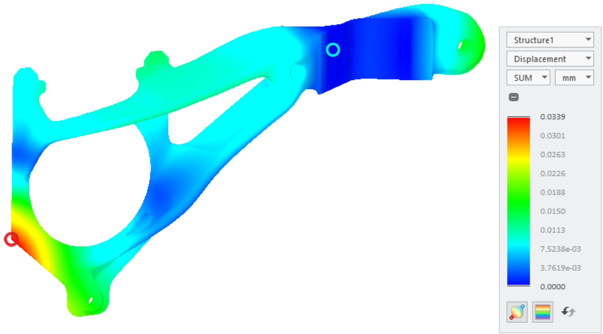
a) *von Mises plot of generated design with AM-constraint, concept 1*



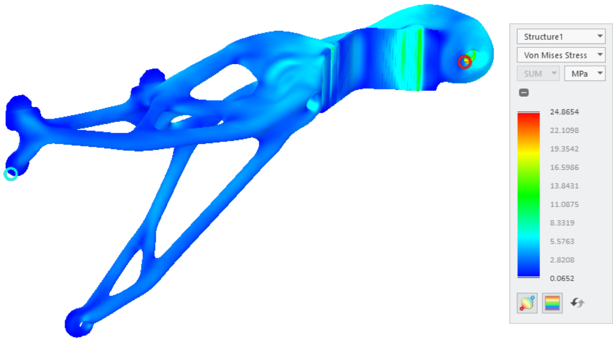
b) *von Mises plot of generated design with casting-constraint, concept 1*



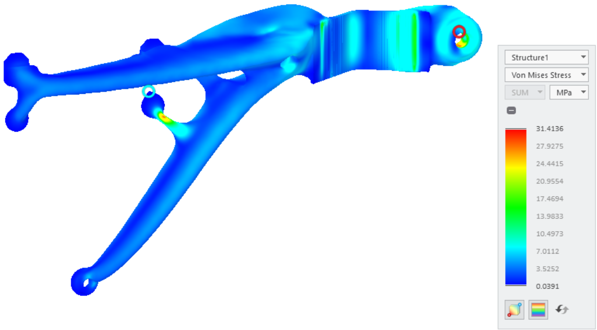
c) *Displacement plot of generated design with AM-constraint, concept 1*



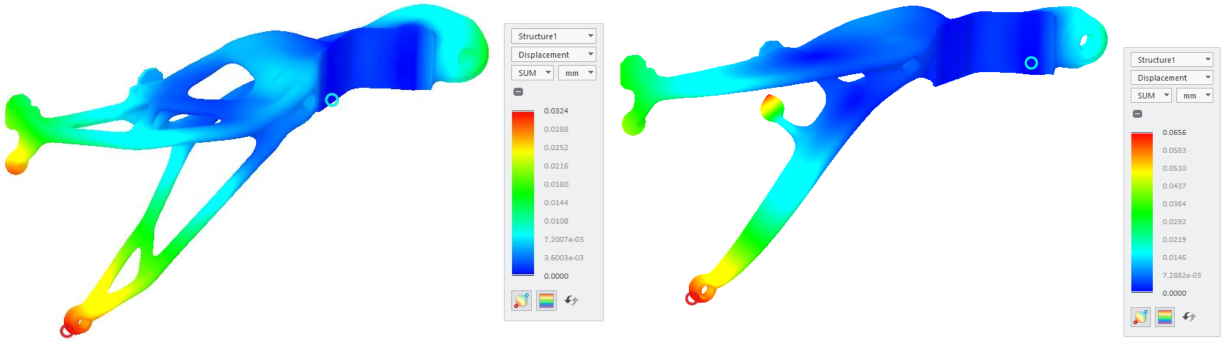
d) *Displacement plot of generated design with casting-constraint, concept 1*



e) *von Mises plot of generated design with AM-constraint, concept 2*



f) *von Mises plot of generated design with casting-constraint, concept 2*



g) *Displacement plot of generated design with AM-constraint, concept 2*

h) *Displacement plot of generated design with casting-constraint, concept 2*

Figure 27 - von Mises and displacement plots of the generated design for the support arm

Table 7 presents the outcomes obtained for the mass, maximum von Mises stress, and displacement values of concept 1 and 2.

Table 7 - Values for mass, von Mises stress and displacement for the support arm

Attribute	**Concept 1 - AM**	**Concept 1 - Casting**	**Concept 2 - AM**	**Concept 2 - Casting**
Mass (g)	733	764	730	764
Max von Mises stress (MPa)	21,8	28,8	24,9	31,4
Max Displacement (mm)	0,0370	0,0339	0,0324	0,0656

After completing the collection of the comparative data, all the generated concepts were rendered. This process was undertaken to facilitate a more immersive and realistic visualization of the different designs within a representative environment. Furthermore, the rendered outputs enabled a more informed assessment of the aesthetic qualities and overall visual appeal of each concept. In Figure 28, a rendering of Concept 1 – AM is presented from a front and rear view respectively. To observe the other generated concepts in rendered format, see Appendix 9.

a) Front view of Concept 1 – AM

a) Rear view of Concept 1 – AM

Figure 28 - Rendered illustration of Concept 1 - AM viewed from the front and rear in a realistic environment

Upon completion of the analysis, the two proposed concepts were presented to Ericsson supervisors for evaluation. Concept 1 is derived from an established sheet metal plate, specifically designed for numerous MINI-LINK radios. Concept 2, on the other hand, incorporates only the critical components of the sheet metal plate, enabling the generative design software to generate the design with optimal material allocation in accordance with the optimization criteria. The Ericsson supervisors emphasized their preference for manufacturability and easy integration of the new design with their existing product range. After a review of both concepts, it was concluded that Concept 1 was the more viable option. This was due to the relative ease of implementation afforded by the sheet metal construction, as well as the subjective opinion of one of the supervisors that it would be simpler to manufacture. Given the limited number of concepts evaluated and the performance of Concept 1 in terms of manufacturability and adoption, no formal evaluation matrix was employed to inform the decision-making process.

5.3.8. Fulfillment of Requirements

Table 8 presented below provides an evaluation of Concept 1's fulfillment of the requirements outlined in section 5.3.2. The total mass of both versions of Concept 1 was found to be significantly below the desired value. This outcome was attributed to the target masses established for the support arm and clamp in previous iterations, thereby satisfying requirement R1. The second requirement, R2, regarding plastic deformation, could not be assessed and therefore cannot be considered as fulfilled. The reason behind the inability to evaluate this requirement lies in the software incapacity to construct solid parts from the generated designs. Consequently, it was not possible to analyze the parts with the correct screw force.

The manufacturing cost for Concept 1 – Casting amounted to 152 SEK per piece which is lower than the purchase cost of the existing solution. However, the manufacturing cost for Concept 1 – AM was considerably higher, reaching a total of 19 947 SEK per piece, thereby failing to meet requirement R3. The assembly cost for both the casting and AM method was determined to be 17 SEK per piece, comfortably below the desired value for requirement R4. The cost calculations for Concept 1 are further explained in section 5.3.10. The chosen material for the support arm and clamp possessed a service temperature range that satisfied the specified interval in requirement R5, and it further demonstrated resistance to corrosion, thereby fulfilling requirement R6.

Requirement R7 was achieved by preserving the same piece of sheet metal from the existing solution within Concept 1, while requirement R8 was satisfied by utilizing the same interface geometry that interacts with the mast, as observed in the existing solution. The forces employed in the generation of Concept 1 originated from requirement R9, R10, and R11. The first two were successfully met as the generated geometry was subjected to those forces. However, since Creo was not able to generate any realistic geometry with the correct screw force, leading to it being reduced, R11 was not considered fulfilled. Requirement R12 was not realized as the consideration of a modal load case generation was unfeasible in Creo software. Further discussion on this matter is presented in chapter 6. Desire D1 was deemed successful following the installation of the prototypes, as illustrated in section 5.3.9.

Table 8 - Fulfillment of requirements for Concept 1

ID	**Specification**	**Marginal Value**	**Ideal Value**	**Concept 1 - Casting**	**Concept 1 - AM**
R1	Total mass	1890 *g*	< 1890 *g*	1066 *g*	1038 *g*
R2	No plastic deformation	Pass	N/A	Not tested	Not tested
R3	Manufacturing cost @5000 batch size	≤ Existing purchase cost	N/A	152 *SEK/pcs*	19 947 *SEK/pcs*
R4	Assembly cost for MINI-LINK installation with mounting kit	24 *SEK/pcs*	< 24 *SEK/pcs*	17 *SEK/pcs*	17 *SEK/pcs*
R5	Material must withstand temperature deviations	-50°C < x < 80°C	N/A	EN AW-6005 Max service temp. 130-160 °C Min service temp. -273 °C	EN AW-6005 Max service temp. 130-160 °C Min service temp. -273 °C
R6	Material must not corrode	Pass	N/A	Not suspictable	Not suspictable
R7	Mounting element for radio	Pass	N/A	Pass	Pass
R8	Mounting kit must support various mast diameters	⌀ 50-120 *mm*	N/A	Pass	Pass
R9	Mounting kit is subjected to weight of radio	2,5 *kg*	N/A	Pass	Pass
R10	Structure is subjected to a perpendicular windload	90 *m/s*	N/A	Pass	Pass
R11	Screws must be tightened with the torque of a M10 bolt	47 *Nm*	N/A	Not tested	Not tested
R12	Mounting kit must pass Ericsson vibration test regarding eigenmode failures	Pass	N/A	Not tested	Not tested
D1	The mounting kit should be easy and safe to install	Pass	N/A	Pass	Pass

5.3.9. Prototype Review

Concept 1 – Casting and Concept 1 – AM, were later prototyped using AM technology through the utilization of a FDM printer. ABS plastic was utilized as the material for the printing process. The prototyped mounting kit was subsequently mounted on a pole with a diameter of 120 mm, representing the maximum diameter of the pole which the radio is installed. Furthermore, a MINI-LINK radio was installed on the mounting kits, thereby ascertaining its practicality and efficacy, as depicted in Figure 29.

a) Rear view of Concept 1 - Casting

b) Front view of Concept 1 - Casting

c) Rear view of Concept 1 - AM

d) Front view of Concept 1 - AM

Figure 29 - 3D-printed prototypes of Concept 1 - Casting and Concept 1 - AM

5.3.10. Product Cost Calculations

The following section intends to present the total cost attributed to the existing solution, as well as Concept 1 - Casting and AM, with the purpose of comparing the different solutions. The overall total cost is further broken down into manufacturing cost, purchase cost, and assembly cost, with each aspect described in detail.

Manufacturing Cost

As a part of the total cost for the product, the cost for manufacturing is included. The calculation for the manufacturing cost is based on a model presented in Granta. The model consists of several attributes related to costs and production process factors which are listed in the Granta database. As detailed in R3 in Table 5, a batch size of 5000 pieces for manufacturing is considered relevant. The equation used for the calculation of the manufacturing cost can be observed in Equation 7. In Granta, the data concerning various attributes is presented in the form of ranges rather than specific values. As a result, assumptions have been made regarding the values of attributes in the calculations, with the exception of the tool cost for casting [54], component masses, AM material cost [55] and production rate for casting and AM. A complete list of the selected attributes can be observed below in Table 9. The calculations take into account that both manufacturing methods use an aluminum alloy, but in the case of AM, the alloy is in metal powder form. The manufacturing cost for concept 1 regards both the support arm and the clamp. For casting, “$Cost_{tool}$" presented in Table 9 considers two casting forms with two cavities in each form. The production rate for casting was internally provided by Ericsson and the production rate for AM was calculated with the use of Equation 6. Upon performing the calculations, the build rate was estimated to be 30 cm^3/h taking into account unique properties of the Selective Laser Melting (SLM) AM method and the selected material. The estimated build rate aligns with the data provided by SLM-solutions [56], thereby lending credibility to the estimate.

$$Production\ Rate_{AM} = \frac{Build\ Rate}{Volume} = pcs/hour$$

Equation 6 - Equation used to calculate production rate for AM

The imprecision of the estimation process can lead to small inaccuracies in the final results, as the selected values for the attributes stem from ranges used may not be entirely reliable. Despite this limitation, when the same assumptions are applied, this method can provide relatively fair comparisons between various manufacturing options and parts, assuming that no changes in factors affecting the estimation are known.

$$Cost_{manufacturing} = \frac{Cost_{material} * Mass_{component}}{Utilization_{material}} + \frac{Cost_{tool}}{Batch\ Size} * \left(1 + \frac{Batch\ Size}{Tool\ Life}\right) + \frac{1}{Production\ Rate} * \left(Cost_{overhead} + \frac{Cost_{capital} * \left(1 + \left(\frac{Discount\ Rate}{100}\right)^{Capital\ Write-off\ Time}\right)}{Capital\ Write - off\ Time * 24 * 365 * Load\ Factor}\right)$$

Equation 7 - Equation used for calculation model of manufacturing cost in Granta

Purchase Cost

In the present scenario, Ericsson has opted to outsource the manufacturing process of the existing solution. The purchase cost has been kept confidential throughout this report as requested by Ericsson.

Assembly Cost

After conducting an analysis of the assembly time for the existing mounting kit and the prototypes of Concept 1 – Casting and Concept 1 – AM, presented in Figure 29, it was observed that the total measured assembly time for the existing support arm was 4 minutes and 23 seconds. On the other hand, the total measured assembly time for the prototypes were 3 minutes and 4 seconds each. All the measured assembly times were based on installations conducted by one of the authors. To estimate the cost of assembling the mounting kit in Sweden, the average salary of an assembler in the electronics sector in Sweden was taken into account. It was found that the average salary of an assembler in this sector was 360 000 SEK per year [57]. The estimated total yearly cost for one employee, including employer’s social security contribution of 31,42 %, was 477 832 SEK according to the provided data by [58]. Considering the average working hours in Sweden, which is 40 hours per week, or 2080 hours per year, the actual worked time is 1444 hours per year after including holiday time and sick leave [59]. Therefore, the average hourly cost of an assembler was calculated to be 473 112 SEK divided by 1444 hours, which equals 324,64 SEK/hour. Based on the estimated data and the measured assembly time, it was calculated that the cost of assembling the existing solution was 24 SEK, while the total assembly cost for the prototype was 17 SEK, which is also presented in Table 9. This is because the prototype requires less time to assemble, as it only has 12 pieces compared to the existing solution's 21 pieces.

Total Cost

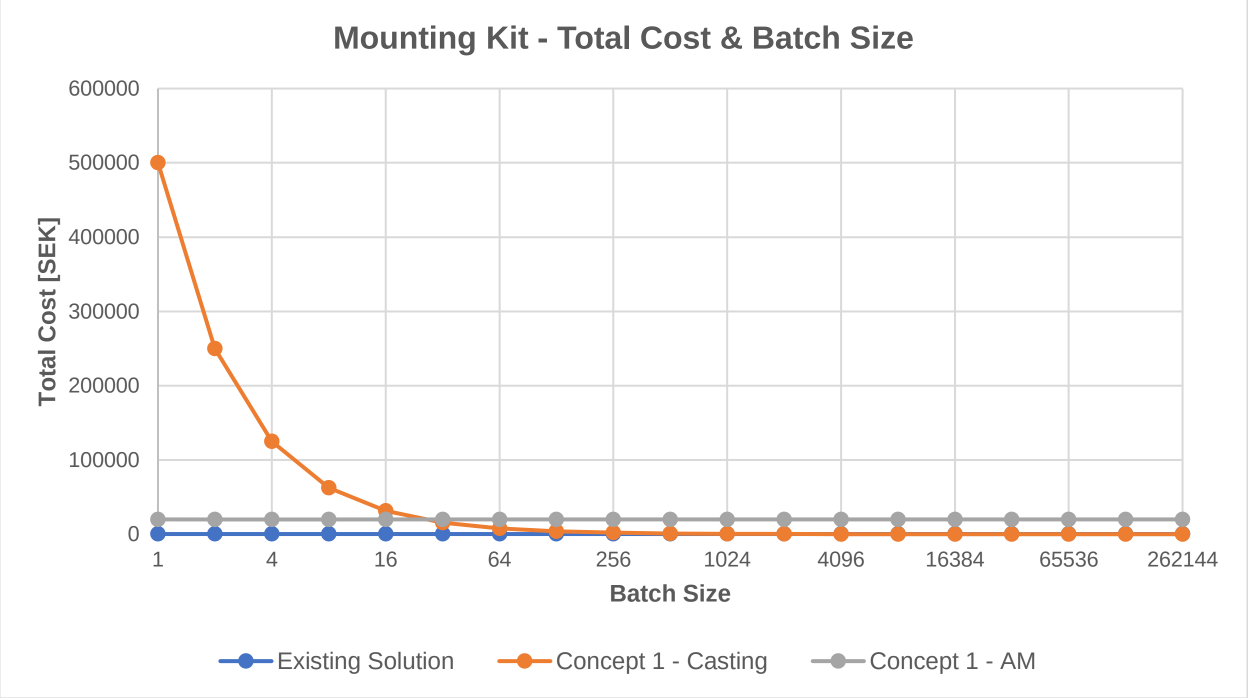
Table 9, as presented below, contains all the requisite data utilized in Equation 7. The data sources for this table are primarily derived from Granta, with the exception of the component masses, AM material cost, and production rate, as aforementioned. It is worth noting that the data obtained from Granta pertains specifically to the gravity die casting method and the SLM AM method, which is well-suited for metal 3D-printing.

Table 9 - Attributes and costs shown for the Existing Mounting Kit, and for the generated support arm and clamp (Casting and AM)

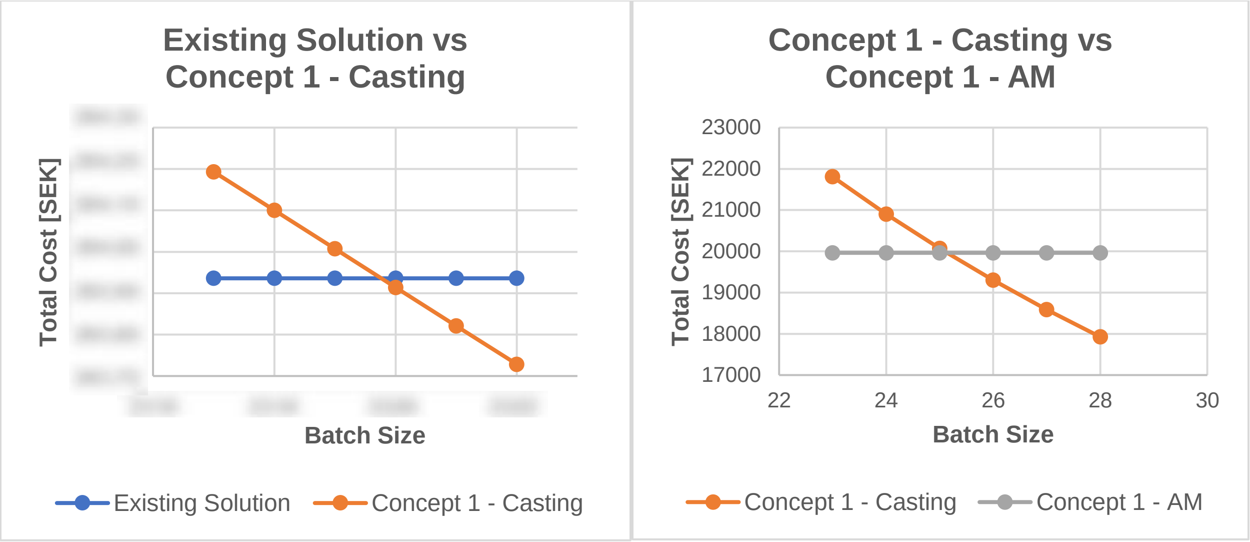
		Concept 1	
Attribute	**Existing Mounting Kit**	**Casting**	**AM**
$Cost_{material}\ [SEK/kg]$	N/A	18,8	586
$Cost_{tool}\ [SEK]$	N/A	500 000	0,44
$Cost_{overhead}\ [SEK/h]$	N/A	1308	1308
$Cost_{capital}\ [SEK]$	N/A	411 000	4 145 000
$Mass_{component}\ [kg]$	1,890	1,066	1,038
$Utilization_{material}\ [\%]$	N/A	70	80
$Batch\ Size\ [pcs]$	N/A	5000	5000
$Tool\ Life\ [pcs]$	N/A	550 000	550 000
$Production\ Rate\ [pcs/h]$	N/A	60	0,078
$Discount\ Rate\ [\%]$	N/A	5	5
$Capital\ Write-off\ Time\ [years]$	N/A	5	5
$Load\ Factor$	N/A	0,5	0,5

$Cost_{manufacturing}$ $[SEK/pcs]$	N/A	152	19 947
$Cost_{purchase}$ $[SEK/pcs]$	CONFIDENTIAL	N/A	N/A
$Cost_{assembly}$ $[SEK/pcs]$	24	17	17
$Cost_{total}$ $[SEK/pcs]$	CONFIDENTIAL	169	19 964

Figure 30 provides a graphical representation of the total cost associated with three different solutions. Graph a) visualizes the total cost of the existing solution, Concept 1 – Casting, and Concept 1 – AM, for various batch sizes ranging from 1 to 262 144, logarithmically scaled on the x-axis with a base of 2. Notably, Concept 1 – Casting exhibits a total cost of approximately 500 000 SEK for a batch size of 1, which can be attributed to its high initial cost incurred in the form of a casting mold that is the most significantly contributor to its $Cost_{tool}$ component. However, the total cost rapidly declines as the batch size increases and approaches approximately 68 SEK for batch sizes exceeding 250 000. In contrast, Concept 1 – AM displays a relatively constant total cost of around 20 000 SEK independent of the batch size. This can be attributed to the high $Cost_{capital}$ component, reflecting the purchase cost of the printer, and the low $Cost_{tool}$.



a) *Graph of the Total Cost for Concept 1 - Casting and Concept 1 - AM for batch sizes varying from 1 to 262 144*



b) *Graph of the intersection point between the Existing Solution and Concept 1 - Casting*

c) *Graph of the intersection point between Concept 1 - Casting and Concept 1 - AM*

Figure 30 - Graphs of the Total Cost and Batch Size for the Existing Solution, Concept 1 - Casting and Concept 1 - AM

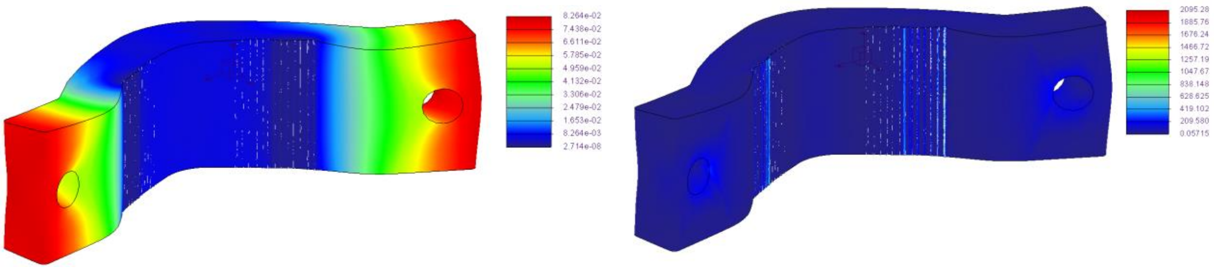
Graph b) and c), provide a comparative analysis regarding the economic viability of the different solutions of the mounting kit by better visualizing the intersection points of the solutions. Graph b) illustrates the total cost associated with the existing solution and Concept 1 – Casting, however, the axis of the graph has been blurred to keep the total cost of the existing solution confidential. The intersection point in the graph reveals that a batch size of approximately 2 000 pieces is required for Concept 1 – Casting to be considered economically advantageous. The precise intersection point has not been mentioned to ensure confidentiality regarding the purchase cost for the existing mounting kit. It is important to note that the decision to compare the existing solution with the casting alternative, rather than the AM alternative, was based on the significant economic viability of the former for what is considered as realistic batch sizes.

Graph c), depicts a comparison between the manufacturing methods of casting and AM for Concept 1. The total cost of the two alternatives is plotted for batch sizes ranging from 23 to 28. Employing the same logic as in the analysis of graph b), it can be concluded that the AM alternative is better suited for batch sizes equal to or below 25, as it exhibits a lower total cost in comparison to the casting alternative. Conversely, for batch sizes exceeding 25, Concept 1 – Casting is deemed more favorable in terms of economic viability. While it is expected that casting would be the superior manufacturing method for larger batch sizes, AM still holds utility in the realms of prototyping and proof of concept, especially in cases in which generative design has been used. Noteworthy is that the precision of the cost calculations lies within the ranges stemming from Granta, thus the breakeven of 25 pieces is merely an estimated magnitude of batch size.

5.3.11. Product Comparison

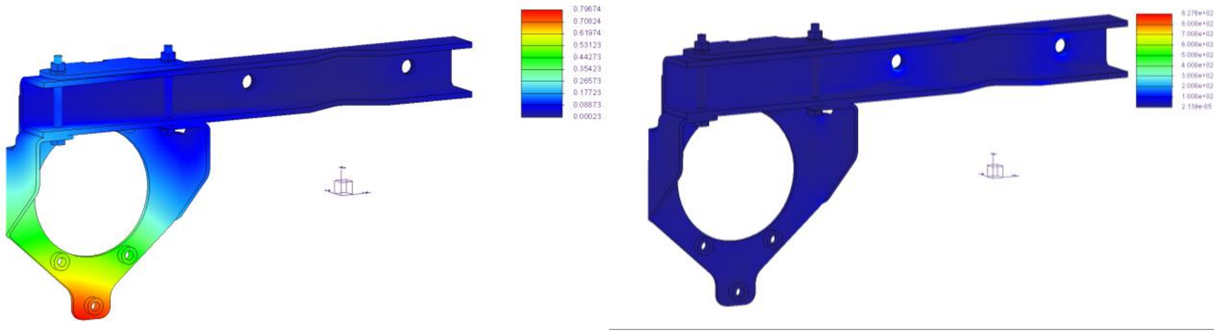
To further analyze how the generated concept stands against the existing solution a product comparison was conducted.

The product comparison undertook an analysis of the existing support arm and clamp design utilizing the von Mises stress and displacement criterion. As presented in 5.3.7, the generated design was analyzed in Creo. In the interest of consistency, it was decided appropriate to subject the clamp and support arm to similar scrutiny through the utilization of Creo Simulate as well. To ensure comparability with the generated design, it was deemed necessary to employ a reduced screw force of 3 000 N during the simulation of the existing mounting kit. This adjustment was made to obtain results that align with the values derived from the generative design process. The resulting findings are graphically presented in Figure 31, depicting the maximum and minimum stress and displacement values of the support arm and clamp respectively. This analytical methodology facilitated a systematic evaluation of the two product designs.



a) Displacement plot for the existing clamp

b) von Mises stress plot for the existing clamp



c) Displacement plot for the existing support arm *d) von Mises stress plot for the existing support arm*

Figure 31 - Displacement and von Mises stress plots for the existing solution

In addition to von Mises stress and displacement, the two products underwent a comprehensive evaluation in various aspects including mass, manufacturing cost, assembly cost, purchase cost, and total number of components. A comparative analysis of the evaluation results for the existing mounting kit and Concept 1 - Casting is presented in Table 10. Based on the findings, Concept 1 - Casting outperforms the existing solution in terms of mass, maximum displacement, total cost, and total number of components. The generated clamp exhibits a larger maximum displacement than the existing clamp, even though the difference is negligible in terms of its ability to withstand the applied screw force. Unfortunately, it was not possible to compare the maximum stress of the existing support arm or clamp since they exhibited stress concentrations and failed to converge. Consequently, it is concluded that Concept 1 - Casting is a more cost-effective and time-efficient solution than the existing one, based on the evaluated criteria. The cost of manufacturing for the existing solution is not applicable since the mounting kit is purchased from a supplier. Likewise, the purchase cost of Concept 1 – Casting is not applicable since the part will be manufactured and not purchased.

Table 10 - Product comparison of existing solution and Concept 1 - Casting

Criteria	**Existing mounting kit**	**Concept 1 – Casting**
Mass (support arm)	1581 g	760 g
Mass (clamp)	309 g	306 g

Max von Mises stress (support arm)	did not converge	28,8 MPa
Max von Mises stress (clamp)	did not converge	181,0 MPa
Max displacement (support arm)	0,7967 mm	0,0339 mm
Max displacement (clamp)	0,0826 mm	0,0878 mm
Cost of manufacturing (5000 batch size)	N/A	152 SEK/unit
Cost of assembly	24 SEK/unit	17 SEK/unit
Cost of purchase	CONFIDENTIAL	N/A
Total cost	CONFIDENTIAL	169 SEK/unit
Total amount of components	21 pcs	12 pcs

5.4. Generative Design Workflow Integration

Section 5.1.1 provides a comprehensive mapping and explanation of the existing product development workflow employed at Ericsson. Within this section, a novel proposal for a future workflow is presented, incorporating the integration of generative design. The enhanced workflow is illustrated in Figure 32 below. Notable deviations from the existing workflow commence immediately after the initial stage of the process, where the *Requirement Analysis* phase has been relocated and now includes a comprehensive load case investigation of the component. The output of this activity remains consistent with the past workflow, resulting in a requirement specification that now includes the load case to which the component will be subjected.

The subsequent phase entails the design of starting, preserved, and excluded geometries. When designing the preserved geometries, it is essential to minimize the volume retained, allowing the generative design module the freedom to allocate material as required. Conversely, when designing the excluded geometries, careful consideration must be given to the component's assembly process and its interactions with other components. This is crucial to prevent material placement that hinders the tightening of screws or causes clashes with other components, for example. With the load case and geometries established, the designer can start initial low-fidelity generations, incorporating various design objectives (maximizing stiffness or minimizing mass), target masses, materials, design constraints (e.g., symmetry, minimum radius), and/or manufacturing methods. The outcomes of these preliminary generations serve as replacements for the *Pre-Study* activity in the existing workflow, which involved generating different concepts.

Following this activity, the decision point *Start Implementation?* mirrors the existing workflow. If the decision is made to proceed with the project, another decision must be taken regarding any necessary modifications to the designed geometries or adjustments to the load case. If redesigning is required, it becomes the focus of the subsequent activity. Conversely, if no redesigning is necessary, high-fidelity generations can proceed immediately. Once different designs have been generated, they undergo evaluation and screening in the *Concept Evaluation* activity. By the conclusion of this activity, a final concept is selected, which may or may not require manual modeling. If manual modeling is required, it is conducted in the subsequent activity. In some cases, the concept may undergo a complete manual redesign, only drawing inspiration from the results of the generative design process. If so, an additional *Concept Evaluation* activity proceeds. If no manual modeling is necessary, the subsequent activity is *Design and Design Verification Preparation*, mirroring the existing workflow. All subsequent activities remain unchanged from the existing workflow.

The advantages associated with the implementation of an improved workflow includes multiple aspects. Foremost, generative design offers a notable benefit in the form of delivering designs characterized by a high stiffness-to-weight ratio. This attribute allows for the utilization of lesser quantities of materials while achieving comparable or superior stiffness in the model. As a result, not only are material and transportation costs reduced, but also an environmentally friendly approach is fostered.

Additionally, the integration of generative design within a workflow is likely to reduce lead times in the design process. By swiftly capitalizing on optimized designs with minimal input, the efficiency of the process is enhanced, leading to a reduction in costs in terms of labor hours. Furthermore, an advantage that may not be immediately apparent is that generative design facilitates a rapid evaluation of the component’s ability to withstand specified load cases. In contrast to traditional design approaches, where designers typically need to first develop a complete concept and subsequently validate it using FEM software, generative design allows for a prompt assessment of the component’s structural integrity. This capability enables designers to ascertain whether the design holds or not, avoiding unnecessary iterations or the need for overly conservative designs that result in excessive mass.

Moreover, during the course of product development, it is common for requirement specifications to undergo modifications or evolve. In such instances, generative design offers adaptability by enabling designers to easily update load values, alter geometries, and adjust design constraints. Consequently, designers can rerun the generative design process to obtain updated designs that align with the revised specifications. In contrast, in manually modeled designs, designers would need to reevaluate numerous phases of the process and potentially repeat multiple activities that have already been conducted.

In regards to an integration of generative design into a workflow, more specifically designers adopting a new such technology, as outlined in the study presented in 2.4, there are several challenges one can expect when designers first start using and co-creating with AI despite having support resources [21]. In light of the proposed workflow, it is imperative to develop support strategies that can aid designers in effectively utilizing generative design tools. These strategies may include encouraging designers to engage in reflective thinking and suggesting alternate design objectives that are compatible with the capabilities of the AI system as well as providing comprehensive guidance throughout the adoption phase. The guidance could for instance include workshops, instructions, and allocated time for training.

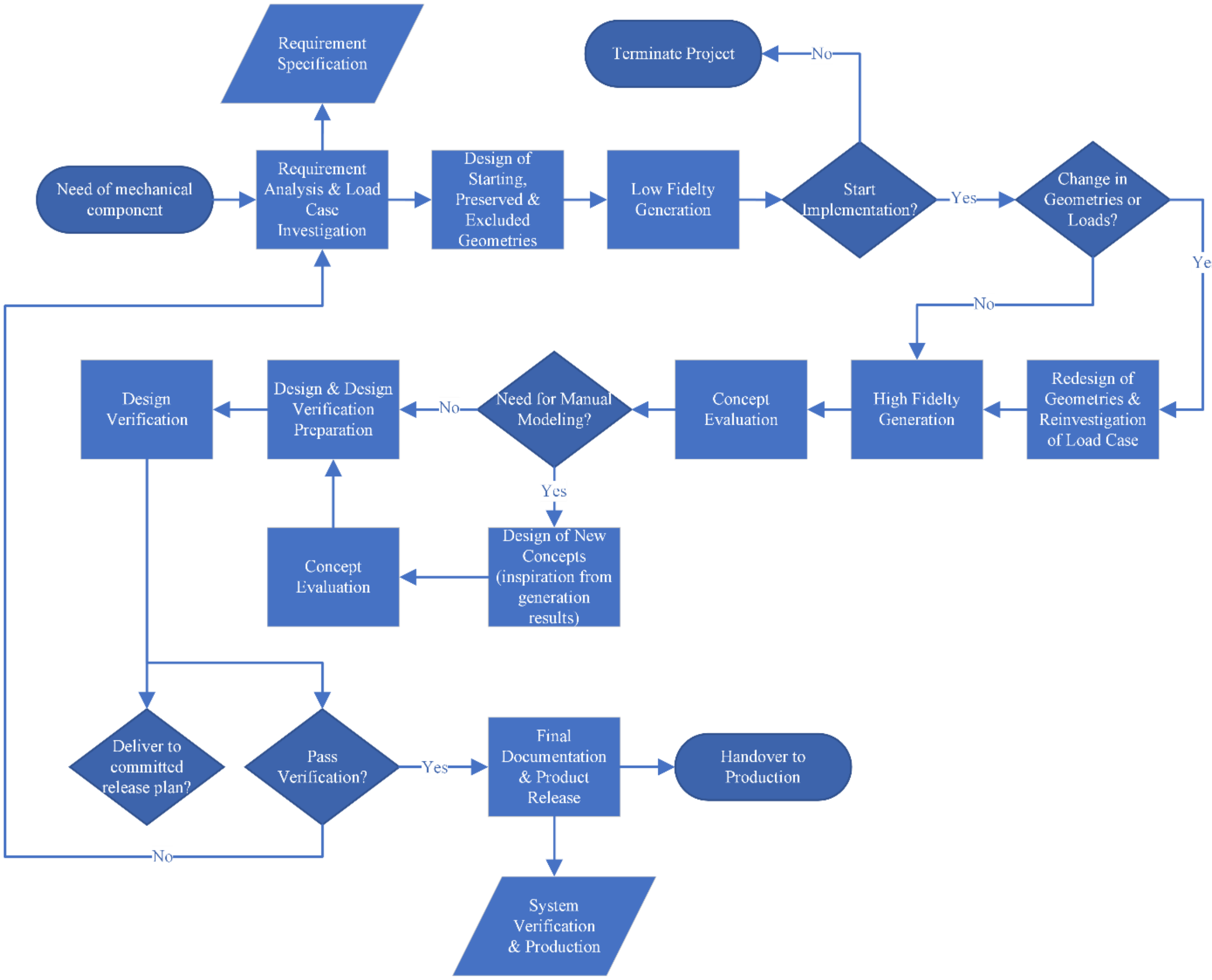


Figure 32 - New proposal for generative design integrated workflow

5.5. Utilization of AI and Deep Learning in Generative Design

As described in section 2.4, during recent years there has been an increased utilization of AI and deep learning in CAD tools. In terms of incorporating AI and deep learning into generative design, Creo is one software provider who claims benefits with such an integration [3] [22]. Although extensive research, no data was found in regard to which specific type of AI methodology Creo utilizes to generate their design in their generative design module. However, after utilizing the module during this thesis, it is assumed that Creo utilizes a similar method as the one called DzAIℕ, which is elaborated in 2.4. The method employs pre-trained deep networks to establish correlations between topologies of reduced order models and optimal topologies of large-scale models [20]. Similarly, to the DzAIℕ method, the generative design module in Creo can generate efficient designs with respect to set user-defined constraints. However, it must be emphasized that this only is an assumption in regards to the specific AI methodology employed by Creo, and further investigation is necessary to confirm this hypothesis. Additionally, there may be other AI techniques or combinations of techniques utilized by Creo or other software providers in their generative design modules, which may also warrant exploration. Therefore, it is crucial to conduct further research and analysis to fully understand the AI methodologies utilized in generative design modules, and their potential impact on the design process.

6. DISCUSSION

The discussion chapter involves reflection on the limitations, chosen methodologies as well as decisions made throughout the thesis and analyzing the results obtained. Further, the research questions are answered and discussed. The last section focuses on discussing potential areas for future research and providing recommendations based on the findings.

6.1. Discussion of Limitations

There are limitations to this thesis that had to be decided to consider the thesis as feasible within the scope of the allocated time. The first limitation *The benchmark will be limited to a selection of available software, and should not be considered as an exhaustive or complete benchmark* is chosen since there are other generative design software available than those in the benchmarking, yet these are not selected due to the absence of allocated capital for software licensing within the scope of this thesis. Software were acquired either with student licensing or internally. The consequence of this limitation is that there might be well performing software which are not selected and evaluated, thus the results of the benchmarking cannot be interpreted as fully comprehensive. The second limitation *The variety of geometric parts for the benchmark is limited in complexity and variation* was decided as feasible due to the fact that the thesis is restricted to a specific time scope of 20 weeks. As a result of not having complex and variation of several models used in the benchmarking, there might exist limitations and benefits of software that yet remain uncovered. This hypothesis is further fortified with the results of the redesign process of the mounting kit. Creo proved as a promising software in the benchmarking, yet as a more complex model was used in the redesign, its flaws proved to appear. The third limitation *The report will not cover any code-programming in the generative design modules* is chosen due to the fact that both students conducting the research acquires a limited amount of knowledge in regards to code-programming. The knowledge was not considered as sufficient enough to be used for programming the generative design modules or investigate its code, thus no attempts were made in this matter. A consequence of not utilizing any code programming might lead to a shallower investigation of the software, however, it is also considered to be a beneficial limitation as poor programming skills might have compromised the outcome. The fourth limitation *The benchmarking will only consider the design constraint of maximize stiffness* is chosen because considering more design constraints such as minimize mass would require more computational time and thus might jeopardize the time-schedule. By not examining all design constraints might lead to a lack of a comprehensive evaluation. Software that performs well regarding maximize stiffness as a design constraint might not perform as well regarding minimize mass and vice versa. The limitation *Only one existing Ericsson product will be redesigned using generative design* is decided upon since considering many designs would be too time consuming in terms of collecting information about several products. The consequence of this limitation is that there might prove to be products which are more suitable when utilizing generative design, for instance choosing a product which only is exposed to static loads might have been more suitable as the software currently is unable to handle both static and dynamic load cases. The sixth limitation *The benchmarking and redesign will only account for studies using a static load case* is chosen due to the fact that static and modal loads are not possible to combine in one study in any of the software evaluated. This leads to the generated design having a risk of being unrealistic in terms of eigenmode buckling, since these are not evaluated at all. The seventh limitation *Manufacturability of generated designs are restricted to the design criteria in the software* is chosen since manufacturing methods not being available in the software obviously cannot be explored. Consequently, there may be methods suitable for the design not being investigated. However, the most common manufacturing techniques as of today are often included in the generative design software, such as die casting, AM, extrusion, and milling. The eighth limitation *AM prototyping will only be conducted with an FDM printer available at Ericsson* is decided upon as no financial incentive exists for the allocation of capital towards prototyping beyond the current available materials and manufacturing methods at Ericsson. A realistic prototype manufactured with the intended method will therefore not be fabricated, which would uncover flaws and allow physical tests to a greater extent. The ninth and final limitation *The thesis does not intend to monitor the effects of generative design after it may have been implemented within the design process of the Ericsson team* is chosen because the thesis is limited to 20 weeks, thus there is no time to allocate within the 20 weeks scope to monitor the effect of such a possible implementation. As a result, no verification will be conducted regarding the feasibility of the new implementation recommendation, or analysis on expected advantages.

6.2. Discussion of Chosen Methodologies

The chosen methodologies employed in this report play an important role in terms of achieving the desired results. One important methodology utilized in this thesis is the integration of CAD-modelling and generative design. Through CAD-modelling, parts were created and modified to align with specific needs and requirements. Generative design further enhanced the process by optimizing the designed parts. Together, these methodologies facilitated efficient and effective exploration and optimization of components. In terms of data collection, the methodology incorporates several key elements: process mapping, interviews, user studies, and the evaluation of identified needs. Process mapping plays a significant role in identifying important aspects of the design process. By mapping out the various stages and activities involved, it becomes easier to identify areas for improvement and address specific needs within the proposed generative design workflow. Additionally, process mapping helps to gain a comprehensive understanding of the design process. Conducting interviews in a semi-structured format proves valuable in extracting essential information from design engineers. This approach ensures a comprehensive collection of data, providing depth and insights to the study. By engaging with the experts directly, valuable perspectives and insights are obtained. User studies serve as an effective means of collecting customer needs data. Allowing users to interact with the generative design tool provides valuable firsthand experiences, which can then be translated into expressed needs. This approach adds a practical and user-centric dimension to the study, moving beyond mere intuition. An important part of the data collection methodology is the evaluation of identified needs. This step involves structuring the needs effectively and transforming them into benchmarking criteria. By benchmarking different generative design or topology optimization software, a comparative analysis is conducted to assess their performance. This helps in identifying the most suitable software options for potential adoption within the workflow. The benchmarking criteria are derived from the communicated needs of the stakeholders, ensuring relevance and applicability in the decision-making process. Throughout the redesign process of the MINI-LINK mounting kit, several key methods were employed. The function-means-tree and requirement specification methods played a significant role in understanding the essential aspects of the existing mounting kit. This understanding proved invaluable in generating concepts and selecting the most suitable solution for the redesign.

6.3. Discussion of Results

This section intends to discuss the results and decisions made throughout each one of the phases during the project.

6.3.1. Customer Needs

In the process of identifying the customer needs for generative design within Ericsson, mechanical engineers were interviewed and included in a user study, as described in section 5.1.3. However, it is acknowledged that the inclusion of a larger sample size of engineers, who could potentially serve as users of generative design, would have been advantageous. By expanding the number of interviewees and participants in the user study, the risk of overlooking certain needs could have been mitigated. Furthermore, the interviewed mechanical engineers exhibited varying levels of knowledge and familiarity with generative design. It could have been beneficial to involve external engineers who possess greater practical experience and expertise in the field, in order to address this knowledge gap effectively.

In hindsight, upon reflecting on the knowledge acquired through benchmarking and the subsequent analysis of customer needs, it becomes evident that Ericsson encountered challenges in effectively articulating their requirements pertaining to generative design, particularly in formulating benchmarking criteria. Notably, the primary need expressed initially was the evaluation of the generative design module and the subsequent redesign of the mounting kit. However, it is important to highlight that Ericsson’s main objective was to assess the capabilities of the generative design tool. Nevertheless, had their needs been clearly expressed and thoroughly investigated at an earlier stage of the process, the benchmarking criteria and subsequent outcomes might have differed.

6.3.2. Software Benchmarking

During the benchmarking process, selection of software for evaluation was based on ABI Research’s investigation outlined in section 3.2. Specifically, software options were chosen from the pool of highest-performing solutions that either had student licenses or were available at

Ericsson. This decision was influenced by budgetary constraints, as there was no dedicated allocation for acquiring licenses solely for benchmarking purposes. It is worth noting that the inclusion of additional software, such as Siemens NX, would have been of interest if a budget had been available. This would have ensured an even more comprehensive evaluation, further minimizing the risk of overlooking potentially suitable software for Ericsson.

To mitigate complications stemming from complex geometries, a part with simple geometries was designed for the benchmarking exercise. By opting for simplicity, potential issues associated with complex geometries were preventatively avoided. Similarly, the load case employed in the generative design iterations was intentionally kept basic. This decision aimed to mitigate challenges that may arise with complex load cases, thereby facilitating a smoother benchmarking process even though we had not experienced generative design previously.

A concerted effort was made to maintain consistency across all evaluated software by establishing an identical study setup in all the software. Special attention was given to ensuring uniformity in mesh size, as variations in mesh configuration can significantly impact the generated results. By minimizing the risk of encountering problems related to complex geometries and load cases, potential time-consuming troubleshooting was anticipated and effectively mitigated, preserving the integrity of the predetermined timeline.

Upon reflecting on the results obtained from the benchmarking process, notable differences emerge. However, it is crucial to acknowledge that these results only reflect the software capabilities based on the identified criteria and needs of Ericsson, rather than encompassing the full range of capabilities each software offers. There may be additional features and functionalities that have not been fully explored or uncovered.

As evidenced in section 5.2.3, Creo is concluded to be the most suitable software in accordance with the identified needs. This finding holds particular significance for Ericsson, as it eliminates the need for extensive adaptation to a new software, considering that Creo is already extensively utilized within the mechanical design department. Conversely, Ansys Workbench showcases a wealth of features and impressive potential for parameter adjustment. For example, the ability to customize the topology optimization method, be it density-based or level-set, offers the opportunity to achieve diverse desired outcomes. However, it should be noted that utilizing Ansys Workbench requires both proficiency in the tool and the allocation of sufficient time and resources for the more labor-intensive optimization procedures. Therefore, Ansys Workbench may be considered the most appropriate solution for mechanical design engineers with a strong inclination and a broader knowledge base in regard to optimization. Furthermore, it is important to highlight the varying levels of technical support provided by each software provider. While the specific level of support was not explicitly evaluated in this study, it is worth speculating that different levels of support could potentially lead to different outcomes. Therefore, the support aspect should be considered alongside the software capabilities when making decisions regarding software adoption and implementation.

It is noteworthy to acknowledge that the benchmarking results only reflect the current state in regard to software capabilities evaluated. Consequently, with the release of a new version of any software, these results become outdated due to the potential implementation of new features. In such circumstances, it becomes necessary to conduct a fresh benchmarking exercise to obtain an updated and equitable comparison.

6.3.3. Redesign of the Mounting Kit

In light of the benchmarking results outlined in Section 5.2.3, the selection of Creo for the redesign of the mounting kit was deemed appropriate. Among all the evaluated software options, Creo demonstrated particular performance, emerging as the frontrunner with the highest number of points awarded. It was also noted that neither Creo nor any of the other evaluated software possessed the capability to effectively combine static and modal loads. Consequently, this limitation led to the decision to exclude modal load cases from the scope of the redesign.

During the redesign process of the mounting kit, three significant flaws in the generative design module of Creo were identified, which had not been encountered during the benchmarking phase. The first flaw was discovered when it became necessary to reduce the screw force from 13 128 N to 3 000 N, as described in section 5.3.6. This adjustment was required to ensure the proper connection of all preserved geometries. It was observed that, during the setup of the load case, it was sometimes necessary to introduce false loads to obtain realistic results. This flaw rendered the stress and displacement values obtained after the generation process invalid, as they were influenced by the incorrect load case. It would have been beneficial to have a feature that could force the software to connect all preserved geometries, irrespective of the load magnitude. Notably, this flaw raises doubt regarding the claimed AI and deep learning integrated in the software. As the same faulty design is generated repeatedly it must be discussed whether or not the software actually learns and improves from its mistakes. Further, the previously mentioned flaw highlights concern regarding the software dependence and, more importantly, underscores the important role of the engineer making decisions. Consequently, it becomes necessary for the engineer to possess the requisite knowledge and expertise. As of now, there exists a potential for errors to occur, thereby undermining the reliability of the final outcome, despite the software providers' claims of dependability.

The second implication arose from the observation that generated designs occasionally intersected with thin excluded geometries, as seen in Appendix 10. Although no material actually clashed with the excluded geometry, the software generated branches on both sides, assuming a connection. Consequently, the resulting designs were highly unrealistic. This issue was reported to PTC R&D, who acknowledged it as a bug within the software and indicated that it would be rectified in the forthcoming version. As a temporary solution, additional excluded geometries were designed to create a foolproof setup.

The third and final flaw identified in Creo during the redesign process pertained to its inability to generate a solid model of the design due to the complex geometry involved. This limitation hindered the export of a solid model for further manual development. Instead, a tessellated model, essentially a facet model, was generated, restricting the scope of manual adjustments. While this sufficed for the assembly, renderings, and exporting the model in .STL file format for 3D printing, it posed a challenge for conducting modal analysis.

These three implications were specific to the redesign of the mounting kit and were not encountered during the benchmarking phase. The complex nature of the redesign's geometry contributed to the emergence of these issues. Therefore, it can be inferred that similar problems may arise in other evaluated software as well, or that the results obtained from the benchmarking process may not be entirely accurate.

Additionally, during the analysis of the existing solution, no maximum value for von Mises stress was identified, primarily due to the presence of stress concentrations. However, it is plausible that maximum values for principal stresses could have been determined.

By examining the results in Table 6 and Table 7 respectively presented in 5.3.5 and 5.3.7 the maximum values for displacement appear to be almost unrealistically low. Therefore, it would be recommended to evaluate the displacement using a dedicated FEM software and also conducting a convergence analysis similarly as done in the benchmarking presented in 5.2.3. As a final note, it is important to acknowledge that the resulting redesign may not fully reflect the optimal design, as modal loads were not taken into consideration. Ideally, a comprehensive design would incorporate both static and modal loads, allowing for appropriate weighting and prioritization of the two factors. The importance of a modal analysis increases with optimized designs as they typically are more lightweight and slenderer opposed to non-optimized designs, being more exposed to failure modes with lower eigenfrequencies.

6.3.4. Product Cost Calculations

When reflecting on the results from the cost calculations, it is important to recognize that the analysis relied on a calculation model provided by Granta. As presented in section 5.3.10, certain attributes in the model employed average values from a predetermined scale in Granta for each attribute. Consequently, it is crucial to approach the results with caution and acknowledge that they may not accurately represent fully reliable cost calculations. Nonetheless, the calculations offer valuable insights into the relative economic feasibility of different manufacturing methods for each concept, particularly in relation to a specific batch size when compared to the existing solution. To enhance the reliability of the attributes used in the calculation, a more thorough investigation of the selected attribute values could have been conducted, rather than solely relying on the scale provided by Granta. Another important limitation of Granta is its lack of accounting for the shape and design of the geometry used in the cost calculation. Very complex and odd geometries might increase manufacturing cost. Lastly, an additional aspect which is not regarded in the total cost calculations is the cost for shipping of components. Generative design might produce bulkier models that require more freight space and thus might increase cost for packaging.

6.3.5. Proposed Workflow

The presented workflow proposal aims to illustrate an ideal approach for incorporating generative design within Ericsson's existing workflow. It is important to note that immediate adoption by the mechanical design department may not be recommended, considering the continuous approaches of integrating AI and deep learning. In the interim, it is speculated that a collaborative utilization of generative design is beneficial. This holds the potential to empower design engineers with faster decision-making capabilities and effective utilization of generative design and possibly leading to an improved workflow characterized by reduced lead times in the design process.

6.3.6. Utilization of AI and Deep Learning in Generative Design

Throughout the study, efforts have been dedicated to comprehending the utilization of AI and deep learning within the generative modules of the software under investigation. As outlined in section 5.5, it yet remains unsure of what specific method of AI and deep learning the software might be using. However, when comparing the software functionalities to the framework of the DzAIℕ method presented in 2.4 it is observed that the generative design module in Creo demonstrates the ability to generate efficient designs while adhering to user-defined constraints, which points some similarities with the DzAIℕ method. However, it is important to note that this observation is purely speculative in terms of what AI methods are possibly used by Creo. Subsequent investigation is nevertheless necessary to support this hypothesis. During both the benchmarking and redesign, with the same input the software generates the same outcome even though the generation is repeated, this might signify a lack of learning and adoption by the software. Further, it is important to highlight that, without casting doubt on the credibility of statements made by software providers regarding the integration of deep learning and AI, such assertions may serve as a means to attract customers towards utilizing their software solutions. Consequently, extensive investigation and verification is required to validate the extent to which these claims hold true.

6.4. Answering the Research Questions

RQ1: What are the advantages and limitations of generative design?

Through the redesign of the mounting kit, it has been demonstrated that generative design offers notable advantages over traditional modeling approaches. As presented in 5.3.11, specifically in Concept 1 - Casting, the generated design achieved a reduced total mass while simultaneously maintaining a better total displacement compared to the existing design. Although the cost comparison was based on a few estimated attributes, it can be inferred that generative design has the potential to yield cost-effective designs. Notably, the redesign showcased the capability of generative design to integrate components within the design itself, resulting in a reduction of total parts from 21 in the existing solution to 12 in the generatively designed proposal. Consequently, this report underscores the numerous advantages of generative design when appropriately employed, notably expediting the design process, and enhancing time efficiency. Moreover, data-driven decision-making ensures that the software generates the most optimal outcome given a comprehensive study of load cases and properly set up boundary conditions. Additionally, generative design facilitates customization to specific manufacturing methods, thereby enhancing its utility. Nevertheless, it should be acknowledged that the optimization process overlooks the consideration of multiple potential production processes which are often required during post-processing. Therefore, the design criteria for manufacturability only applies to the specific manufacturing method that the generative design software is designed to optimize for. Another significant benefit lies in the adaptability of generative design, as the iterative development process and evolving requirements can be easily accommodated by adjusting load cases and design criteria accordingly.

Conversely, certain limitations of generative design software and its FEM calculations must be acknowledged. As evident from the benchmarking analysis in section 5.2.4, the FEM tools in several evaluated software exhibited inconsistencies, highlighting their unreliability in von Mises stress and displacement compared to Ansys Workbench, in which a convergence analysis was carried out to gain accurate results. Another limitation of generative design is the challenge of accurately capturing fully realistic load cases in complex dynamic systems, necessitating the utilization of assumptions and simplifications. Consequently, a thorough load case investigation assumes critical importance in the design process. The limitations could however be mitigated by integrating modal load cases with static load cases, thus reducing reliance on assumptions and simplifications. Moreover, the algorithmic and parameter-based nature of generative design may result in a deficiency of human artistic expression and creativity, which stands in contrast to traditional design approaches. This limitation might impede the aesthetic appeal of a design in certain contexts or its ability to harmonize with a specific theme. Conversely, achieving these outcomes is possible through intuitive, human-based design.

RQ2: Is generative design feasible to implement within the existing design procedure of the mechanical design department at Ericsson?

The benefits of implementing generative design into the design procedure are detailed in section 5.4. One notable advantage of this implementation is the reduction in lead time, leading to increased efficiency and decreased labor costs. Additionally, the utilization of generative design in the workflow enables seamless adaptation to changing requirements, eliminating the need for extensive product redesign. Modifying boundary conditions within the generative design module and iterating designs quickly provides benefits resulting in significant time savings. Furthermore, with future advancements and enhanced software capabilities, generative design might have the potential to serve as a collaborative tool across departments, facilitating cross-functional work centered around the generative design tool. However, as highlighted in the research presented in section 2.4, integrating such technologies requires designers to embrace new practices, which can be challenging. Such practices include more emphasize on load case investigation, knowledge about how to set up a generative or topology optimization study in an appropriate manner and analyzing the outcomes. It is also worth mentioning that the requirements for a concept are not always as easy to define as in the case of the mounting kit. Furthermore, the initial governing design requirements may be such that the generative design tool cannot take them into account, for instance, cooling and electrical shielding which might be relevant for Ericsson. Lastly, proper support, training, and ongoing efforts are necessary to ensure a successful adoption of generative design in the workflow.

RQ3: How does the functional capabilities of generative design in different software vary?

The functional capabilities of the software are comprehensively assessed in the benchmarking chapter 5.2. The results indicate that Creo performs the best among the evaluated software packages, aligning with the identified customer needs to a great extent and proving a high level of user friendliness which is showcased in its total amount of clicks and total accumulated time to set up the study, as presented in section 5.2.3. 3DExperience and Fusion 360 closely follow Creo in terms of the assessed functional capabilities. On the other hand, Ansys Workbench, although not performing as well as the other software, is acknowledged as a powerful tool with extensive parameter adaptation and optimization possibilities to achieve desired outcomes. It is concluded that Creo is most suitable tool for concept generation and for users who seek to utilize generative optimization tools without investing significant time in learning complex capabilities. Conversely, Ansys Workbench is a more appropriate tool for users who prioritize generating results based on finely defined parameters and optimization methods as a result requiring them to allocate more time to study setup and post-processing. The findings emphasize the importance of investigating customer needs to select the most suitable software. In this particular case, when comparing the functional capabilities of each other, Creo is deemed suitable for the mechanical design department at Ericsson as it fulfills their needs effectively.

RQ4: What are the potential savings in cost when utilizing generative design instead of traditional modeling?

This research question is addressed through an investigation of the redesign process of the MINI-LINK mounting kit, serving as a case study. A comprehensive examination was conducted to assess manufacturing costs, assembly costs, and purchase costs associated with both the existing solution and the generated solutions for casting and AM. The related cost data utilized in the calculation are presented in Table 9. The analysis reveals that Concept 1 – Casting is economical favorable for batch sizes exceeding 2 000.

The calculations presented herein do not incorporate potential cost savings resulting from reduced lead times in the design phase, as reliable data, or estimations regarding the design time for the existing solution were unavailable. Nevertheless, it is noteworthy to acknowledge that further cost and time savings could potentially arise from the implementation of generative design.

RQ5: What are the critical factors to redesign on the MINI-LINK mounting kit?

The existing mounting kit exhibited a singular weakness concerning the geometries associated with the screws that fastened it to the mast. Under the influence of the prescribed tightening torque, the existing solution showed excessive stresses, thereby posing a risk of permanent deformation. This difficulty formed the basis for the decision to initiate a redesign process, initially focusing on the clamp to ascertain whether an improved design could be attained by employing the appropriate screw force. Subsequent to the successful redesign of the clamp, incorporating the correct screw force in its generation, attention shifted towards the redesign of the support arm. It was found that generating the support arm with the desired screw force was impractical, leading to the need for its reduction.

The redesign efforts centered on optimizing the design with regard to mass and stiffness, the two primary pillars of generative design. As indicated in Table 10, Concept 1 - Casting surpassed the existing solution in both of these aspects. The total mass experienced a reduction of 44%, while the total displacement of the support arm was diminished by 96%, signifying a significantly enhanced stiffness. Furthermore, all other requirements for the mounting kit were duly satisfied, as exemplified in Table 8, except for the passage of the vibration test, which was deliberately disregarded.

6.5. Future Research & Recommendations

At the inception of this thesis at Ericsson, the mechanical design department at Lindholmen had limited to negligible familiarity with generative design. Considering the aforementioned assertions regarding the rapid advancements in AI and deep learning integration within CAD systems, it is imperative to maintain a prominent position in the ongoing progression of this field. This report has successfully identified and presented several significant elements that hold substantial value for Ericsson. However, there remains a wealth of untapped potential within generative design and topology optimization methods that demands further exploration. Thus, this section puts forth recommendations for future research endeavors.

It is recommended to continue evaluating generative design and topology optimization, given the rapid development of such software. Industry projections indicate that the market size in this domain is expected to more than triple from 2022 to 2030, as discussed in section 3.1. Therefore, it is crucial to remain updated on the advancements in order to sustain competitiveness as a company. Additionally, this thesis proves that limitations may be discovered by utilizing the generative design tool with a varied product complexity. There is a lot of uncovered knowledge to be exposed, both in terms of software capabilities and lateral needs on behalf of the organization, design department or the user itself. Thus, it is recommended to establish the utilization of the generative design tool in various subjects as it may yield even mo knowledge and information than from the actual software provider.

It is further advisable to investigate the feasibility and potential implementation of generative design in a cross-functional manner, including various departments in a pilot project. For instance, exploring the incorporation of thermal aspects through collaborative efforts could provide insights into the synergistic benefits and challenges associated with such integration. However, it must be emphasized that the predictability of when such an integration on behalf of the software capability is mature enough yet remains unknown.

As a final recommendation, it would be beneficial for Ericsson to pilot the proposed workflow in a product development project to evaluate its advantages. Following the completion of the project, a careful evaluation of the workflow's results should be conducted to determine whether it should be standardized for all future projects or if adjustments to the implementation strategy are necessary.

7. CONCLUSION

In conclusion, the thesis conducted by the authors successfully achieves its aim of studying the possibility of implementing generative design into the workflow of the mechanical design department at Ericsson. Outlined in this report is an extensive user needs study comprised of interviews, a user study, and a workflow mapping. The outcome of the user need identification and analysis proves user-friendliness and ease of adoption is highly prioritized.

By benchmarking available software that provide generative design or topology optimization it is found that PTC Creo parametric is considered as the most suitable generative design tool for Ericsson. This is due to the fact that Creo fulfills the identified needs and requirements of Ericsson to a greater extent than any other of the evaluated software. Further, it is also found that Ansys Workbench is superior to Creo and other evaluated software in terms of optimizations studies with specific requirements due to its extensive library of editable parameters and the possibility of choosing optimization method.

Considering the potential shown by Creo in the benchmarking, it was decided to be applied in the redesign case of a mounting kit used to install Ericsson MINI-LINK radios in telecom towers. The redesign process generated two concepts, namely, Concept 1 and Concept 2, each with two significant manufacturing methods, casting and AM. When evaluated, Concept 1 - Casting and Concept 1 - AM designs exhibit favorable performance, although the AM-based design proves to be more costly. Both Concept 1 - Casting and Concept 1 - AM was prototyped using a FDM printer which proved beneficial in terms of assessing their functionality. Overall, the generated designs meet the specified requirements, except for two instances. Concept 1 - AM does not meet the cost requirement due to the high expenses associated with AM as a manufacturing method. Additionally, time limitations and limitations of resources to manufacture both concepts prevent vibration tests for both concepts, resulting in the requirement not being fulfilled. In conclusion, the redesign showcases enhanced performance compared to the existing mounting kit, notably in terms of reduced mass, higher stiffness, and a reduced number of components. Further, the redesign process uncovers flaws of the generative design software that were not found during the benchmarking. The redesign demonstrates the software inability of generating realistic designs when having multiple loads with large differences. Further, it is unveiled that the generated design often intersects thin excluded geometries. Finally, one crucial flaw noted is the impossibility to convert a solid model of the generated design in cases where the shape of the model is complex.

Based on the findings, it is recommended continuing to evaluate generative design and topology optimization as it is rapidly developing, and projections indicate it to triple in market size the coming decade. It is further recommended to pilot a project using generative design to evaluate its ability of integration regarding the current workflow and possible cross-functional work.

DECLARATION OF COMPETING INTEREST

The authors of this report declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this thesis.

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APPENDICIES

	Software Evaluation (scale 1-5)			
	1. Design Spaces			
Software	**1.1 Is there an automated creation of starting geometry?**	**3**	**1.2 Are you able to select an offset for the excluded geometry?**	**4**
PTC Creo Parametric	Yes.	5	No.	0
Autodesk Fusion 360	Yes, this is the smallest possible volume that connects all preserved geometries.	5	Yes.	5
Inspire by Altair	No, you do it yourself.	0	No, it is not possible to select an excluded geometry at all.	0
3D Experience Functional Generative Design	No, the part itself is the starting geometry.	0	No.	0
ANSYS Discovery 2023 R1	No, the part itself is the starting geometry.	0	No.	0
ANSYS 2022 R2 WB	No, the part itself is the starting geometry.	0	No.	0

	Software Evaluation (scale 1-5)									
	2. Physics									
Software	**2.1 Is it possible to define several load cases in one study?**	**4**	**2.2 What are the possible load selections?**	**4**	**2.3 What are the possible constraints?**	**4**	**2.4 Is is possible to define contact?**	**4**	**2.5 Does the software suggest gravitational load?**	**3**
PTC Creo Parametric	Yes.	5	**Force** **Moment** **Pressure** **Centrifugal** **Linear Acceleration**	3	**Fixed** **Displacement** **Planar** **Cylindrical** **Ball**	4	Yes, between two surfaces.	4	No.	0
Autodesk Fusion 360	Yes.	5	**Force** **Moment** **Pressure** **Bearing Load** **Remote Force** **Remote Moment**	3	**Fixed** **Pin** **Frictionless** **Remote**	4	No, loads can only be applied to preserved geometries.	1	Yes.	5
Inspire by Altair	Yes.	5	**Force** (as regular, distrubutited bearing or traction) **Pressure** **Moment** (torque) **g-loads** **Angular velocity and acceleration**	4	**User defined constraints, named support** (Tx, Ty, Tz, Rx, Ry, Rz)	4	Yes, it is done automatically/manually.	5	Yes.	5
3D Experience Functional Generative Design	Yes.	5	**Force** **Torque** **Gravity** **Pressure** **Bearing Load** **Remote Force** **Remote Torque** **Centrifugal Force**	5	**Fixed Displacement** **Clamp** **Applied Translation** **Ball Joint** **Slider** **Hinge**	5	Yes, it is done manually.	4	It exists, not suggested.	5
ANSYS Discovery 2023 R1	Yes.	5	**Force** **Pressure** **Moment** **Mass** **Velocity** **Acceleration** **Bearing Load** **Bolt Preload**	5	**Fixed** **Sliding** **Hinged** **Ball** **Displaced**	5	Yes, it is done automatically/manually.	5	Yes.	5
ANSYS 2022 R2 WB	Yes, but only if you supress the other ones.	4	**Pressure** **Hydrostatic Pressure** **Force** **Remote Force** **Bearing Load** **Bolt Pretension** **Moment** **Line Pressure** **Thermal Condition** **Joint Load**	5	**Fixed Support** **Displacement** **Remote Displacement** **Frictionless Support** **Compression Only Support** **Cylindrical Support** **Elastic Support**	5	Yes, it is done automatically/manually.	5	It exists, not suggested.	5

	Software Evaluation (scale 1-5)					
	3. Design Criteria					
Software	**3.1 What are the possible design objectives?**	**5**	**3.2 What are the possible manufacturing constraints?**	**5**	**3.3 What are the possible geometry constraints for the generated design?**	**5**
PTC Creo Parametric	**Minimize mass** (Set safety factor) **Maximize stiffness** (Limit mass to number of set mass unit or limit mass to percentage of starting geometry)	3	**Unrestricted** **Build Direction** (Reduces the number of supports for additive manufacturing) **Parting Line** (Creates an angle between the pull direction and the resulting drafted surfaces) **Linear Extrude** (Creates a linear pull direction extrude)	4	**Planar Symmetry** (Builds and mirrors individual halves of geometry) **Material Spreading** (Controls the spreading of the material) **Minimum Crease Radius** (Creates geometry with a minimum radius of specified value)	4
Autodesk Fusion 360	**Minimize mass** (Set safety factor) **Maximize stiffness** (Set safety factor & limit mass to x *kg)* **Displacement** (globally or locally, can be combined with the two above)	4	**Unrestricted** **Additive** (set orientation, overhang and minimum thickness) **Milling** (2,5- 3- & 5-axis and tool settings) 2-axis Cutting (svarvning?) **Die casting** (set ejection direction, mimum draft angle and maximum/minimum thickness) It is possible to choose multiple so multiple versions are generated at once.	5	None, models are not symmetrical.	0
Inspire by Altair	**Maximise stiffness** **Minimize mass** **Maximize frequency**	4	**Parting line single draw** (used when the molds parting line lies outside of the design space) **Parting line split draw** (used when the molds parting line lies within the design space) **Radial draw** (used when a machine tool needs to enter in a radial direction toward the center of the plane) **Extrusion** (used when the profile of the resulting shape maintains a constant cross-section) **Overhang** (used to eliminate overhang and minimze use of support)	4	**Symmetric** (applies a symmetry plane to a design space) **Cyclic** (applies cyclic repetation to a design space) **Cyclic symmetric** (applies both cyclic repetition and symmetry to a design space) **Thickness constraint** (minimum & maximum)	4
3D Experience Functional Generative Design	**Maximise stiffness** **Minimize mass** **Maximize lowest frequency**	4	**Casting** (Applies a casting controll to the simulation) **Milling** (Applies a milling controll to the simulation) **Extrusion** (Applies a extrusion controll to the simulation) **Overhang** (Applies a overhang controll to the simulation) **Rib** (Applies a rib controll to the simulation)	4	**Symmetry** **Cyclic Symmetry** (Applies a cyclic symmetry to the simulation) **Thickness Control**	3
ANSYS Discovery 2023 R1	**Maximize Stiffness** (not able to select target mass, only specify reduction of volume in % or other units) **Maximize Natural Frequency** **Balance Stiffness and Frequency** **Target Natural Frequency** **Remove Excess Matieral**	5	**Min Thickness** **Max Thickness** **Pull Direction** (molding) **Table Direction** (3-axis milling) **Overhang Prevention** (AM)	4	**Symmetry** (planar, does not work on constructed planes)	1
ANSYS 2022 R2 WB	**Minimize Compliance** **Minimize Mass** **Minimize Volume** **Minimize Stress**	4	**Pull Out Direction** (Specify the direction to remove the model from the mold) **Member Size** (Specify the minimum thickness of the supporting structures and maximum thickness of connected parts in the final design) **Extrusion** (Ensures cross section is kept constant along a selected plane) **AM Overhang Constraint**	4	**Symmetry** **Cyclic Repetition** (Circular sectors are repeated along the specified axis) **Uniform** (Density is kept constant at specified sections)	3

	Software Evaluation (scale 1-5)							
	4. Validation							
Software	**4.1 What simulation criterias are possible to display in plots after the generation?**	**4**	**4.2 Is it possible to compare the different generated alternatives?**	**4**	**4.3 How can you filter design outcomes?**	**4**	**4.4 Are you able to go back in the number of iterations of each generation and export one particular design?**	**2**
PTC Creo Parametric	Displacement Von Mises Stress Safety Factor	3	Yes, you can compare alternatives side by side through Generative Design Extension (GDX). However, there is no such license currently at Ericsson.	5	Not possible to evaluate. It does exist	3	No.	1
Autodesk Fusion 360	Stress reference (only possible to display stress results from low to high)	2	Yes, you can compare alternatives side by side.	5	Study x Manufacturing method Materials Volume Mass Max von mises stress Min safety factor Max global displacement Piece part cost Fully burdened cost	5	Yes.	5
Inspire by Altair	Displacement Factor of safety Percent of yield Tension/compression Max shear stress Von mises stress Principal stress Principal strain	4	Yes, but they need to be generated separetly and manually.	3	Load case Max Displacement Mass total Displacement Factor of safety Percent of yield Tension/compression Max shear stress Von mises stress Principal stress Principal strain Element density Compliance	4	Possible to view, not export.	2
3D Experience Functional Generative Design	Stress (Various) Deformation Displacement (Various) Strain (Various) Reaction force Safety Factor	4	Yes, but they need to be generated separetly and manually.	3	Not possible to evaluate. It does exist	3	Possible to view, not export.	2
ANSYS Discovery 2023 R1	Displacement Von Mises Stress Principal Stress Strain (elastic) Principal Strain (elastic) Reaction Force Reaction Resultant Contact Stress	5	Only one alternative is generated.	1	N/A	1	You are able to pause the simulation anytime and export that design.	3
ANSYS 2022 R2 WB	Stress (Various) Deformation Strain (Various) Energy Safety Factor	5	Only one alternative is generated.	1	N/A	1	Possible to view, not export.	2

Software Evaluation (scale 1-5)

5. Miscellaneous

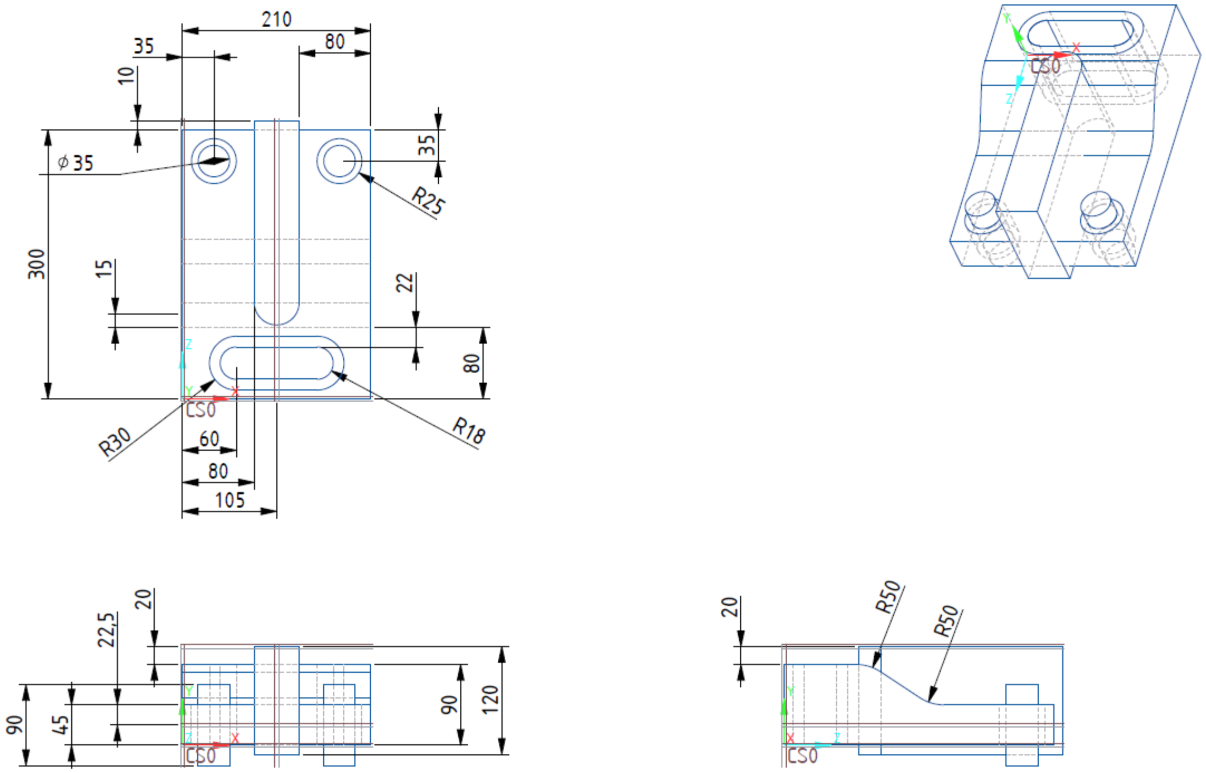
Software	5.1 Are there several generated design alternatives?	4	5.2 Is there a cost estimation for manufacturing?	4	5.3 What are the options for setting the accuracy of the generation?	5	5.4 Is it possible to update the generation when the geometries are out of date?	4
PTC Creo Parametric	Yes, through Generative Design Extension (GDX). However, there is no such license currently at Ericsson.	5	Yes, through Generative Design Extension (GDX).	5	Slider for *Fidelity*, or select *Min. element size* & *Max. iterations.*	3	Yes, you just open the GD module and re-run the optimisation.	5
Autodesk Fusion 360	Yes, by default.	5	Yes, by default.	5	Only a slider from *coarse* to *fine.*	1	Yes, you just open the GD module and re-run the optimisation.	5
Inspire by Altair	No.	1	No.	1	*Faster* & *More accurate.*	1	Yes, you can replace the geometry and update.	5
3D Experience Functional Generative Design	No,	1	No.	1	Mesh Size Max cycles	2	Yes, you need to locally update	5
ANSYS Discovery 2023 R1	No.	1	No.	1	Slider for Fidelity	1	Yes, you can replace the geometry and update.	5
ANSYS 2022 R2 WB	No.	1	No.	1	Maximum Number of Iterations Minimum Normalized Density Convergence Accuracy Mesh Size Mesh Type Top. Op. Method	5	Yes, you can replace the geometry and update.	5

	Software Evaluation (scale 1-5)							
	6. Results from AM generations (times, clicks, stress & displacement)							
Software	**6.1 How long time did it take to set up the study? (hh:mm)** **≤ 00:05 = 5p** **≤ 00:07 = 4p** **≤ 00:09 = 3p** **≤ 00:11 = 2p** **> 00:11 = 1p**	**10**	**6.2 How many clicks did it take to set up the study?** **≤ 102 = 5p** **≤ 122 = 4p** **≤ 142 = 3p** **≤ 162 = 2p** **> 162 = 1p**	**10**	**6.3 How long time did the AM generation require? (+computer specifications)** **(hh:mm)** **≤ 00:01 = 5p** **≤ 00:10 = 4p** **≤ 00:19 = 3p** **≤ 00:28 = 2p** **> 00:28 = 1p**	**10**	**6.4 How long time did it take to perform the post-processing & verification?** **(hh:mm)** **≤ 00:01 = 5p** **≤ 00:03 = 4p** **≤ 00:05 = 3p** **≤ 00:07 = 2p** **> 00:07 = 1p**	**10**
PTC Creo Parametric	00:05	5	82	5	00:01 128GB RAM, Intel® Xeon® Gold 6246 CPU @ 3.30GHz (2 processors)	5	00:01	5
Autodesk Fusion 360	00:07	4	105	4	00:26 Cloud based	2	00:01	5
Inspire by Altair	00:08	3	157	2	01:43 8GB RAM, AMD Ryzen 5 5500U with Radeon Graphics 2.10 GHz	1	00:07	2
3D Experience Functional Generative Design	00:09	3	117	4	00:53 Cloud based	1	00:07	2
ANSYS Discovery 2023 R1	00:07	4	119	4	00:06:00 GPU-driven	4	00:07	2
ANSYS 2022 R2 WB	00:10	2	255	1	01:25 384GB RAM, Intel® Xeon® Gold 6246 CPU @ 3.30GHz (2 processors)	1	00:08	1

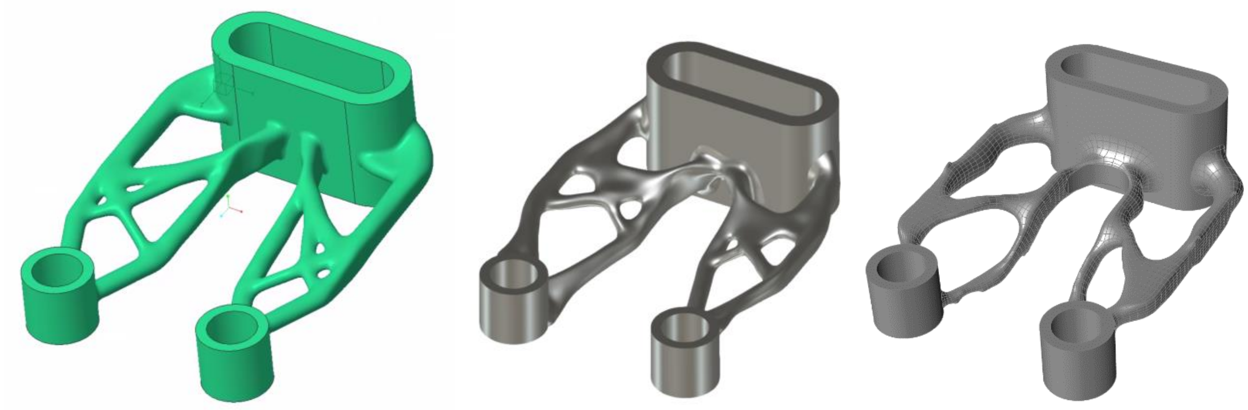
	Software Evaluation (scale 1-5)					
	6. Results from AM generations (times, clicks, stress & displacement)					
Software	**6.5 How many clicks did it take to perform the post-processing & verification?** **≤ 8 = 5p** **≤ 28 = 4p** **≤ 48 = 3p** **≤ 68 = 2p** **> 68 = 1p**	**10**	**6.6 What was the maximum stress? Software based** **(MPa)**	**6.7 What was the maximum displacement? Software based** **(mm)**	**6.8 What was the maximum stress?** **Ansys - convergence analysis** **(MPa)** **≤ 30 = 5p** **≤ 50 = 4p** **≤ 70 = 3p** **≤ 90 = 2p** **> 90 = 1p** **> yield limit = -5p**	**10**
PTC Creo Parametric	8	5	19,84	0,155	29,35	5
Autodesk Fusion 360	21	4	19,95	0,291	50,28	3
Inspire by Altair	58	2	did not converge (stress concentration)	16,53	did not converge (stress concentration)	-5
3D Experience Functional Generative Design	18	4	51,10	0,345	47,25	4
ANSYS Discovery 2023 R1	273	1	62,90	0,493	76,51	2
ANSYS 2022 R2 WB	287	1	65,40	0,328	65,40	3

	Software Evaluation (scale 1-5)								
	6. Results from AM generations (times, clicks, stress & displacement)								
Software	**6.9 What was the maximum displacement? Ansys - convergence analysis (mm)** $\le 0{,}172 = 5p$ $\le 0{,}222 = 4p$ $\le 0{,}272 = 3p$ $\le 0{,}372 = 2p$ $> 0{,}372 = 1p$ $> 5 = -5p$	**10**	**6.10 What is the factor of change in maximum stress in the software and maximum stress in Ansys Workbench? (%)** $-1 \le x \le 1 = 5p$ $-21 \le x \le 21 = 4p$ $-41 \le x \le 41 = 3p$ $-61 \le x \le 61 = 2p$ $\lvert x\rvert > 61 = 1p$	**10**	**6.11 What is the factor of change in maximum displacement in the software and maximum displacement in Ansys Workbench? (%)** $-12 \le x \le 12 = 5p$ $-32 \le x \le 32 = 4p$ $-52 \le x \le 52 = 3p$ $-72 \le x \le 72 = 2p$ $\lvert x\rvert > 72 = 1p$	**10**	**6.12 What is the mass of the support material? (%)** $\le 19 = 5p$ $\le 23 = 4p$ $\le 27 = 3p$ $\le 31 = 2p$ $> 31 = 1p$	**10**	**Total score:**
PTC Creo Parametric	0,189	4	48%	2	22%	4	28%	2	675
Autodesk Fusion 360	0,909	1	152%	1	212%	1	23%	4	560
Inspire by Altair	16,592	-5	N/A	0	0,4%	5	30%	2	298
3D Experience Functional Generative Design	0,350	2	-8%	4	1%	5	19%	5	568
ANSYS Discovery 2023 R1	0,862	1	22%	3	75%	1	22%	4	472
ANSYS 2022 R2 WB	0,328	2	0%	5	0%	5	24%	3	471

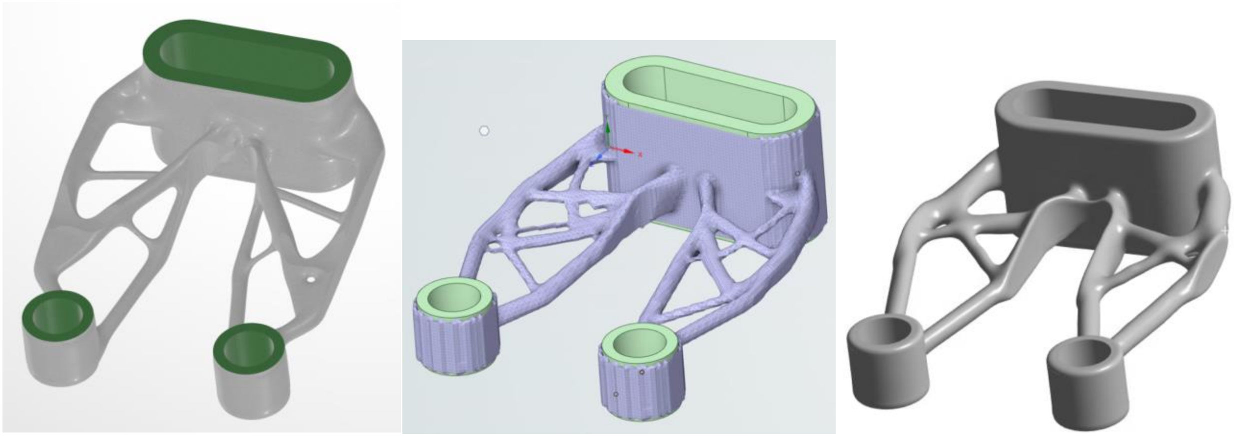
Appendix 1 - Benchmarking criteria and all software performance with rankings



Appendix 2 – Drawing of the part used in the benchmarking

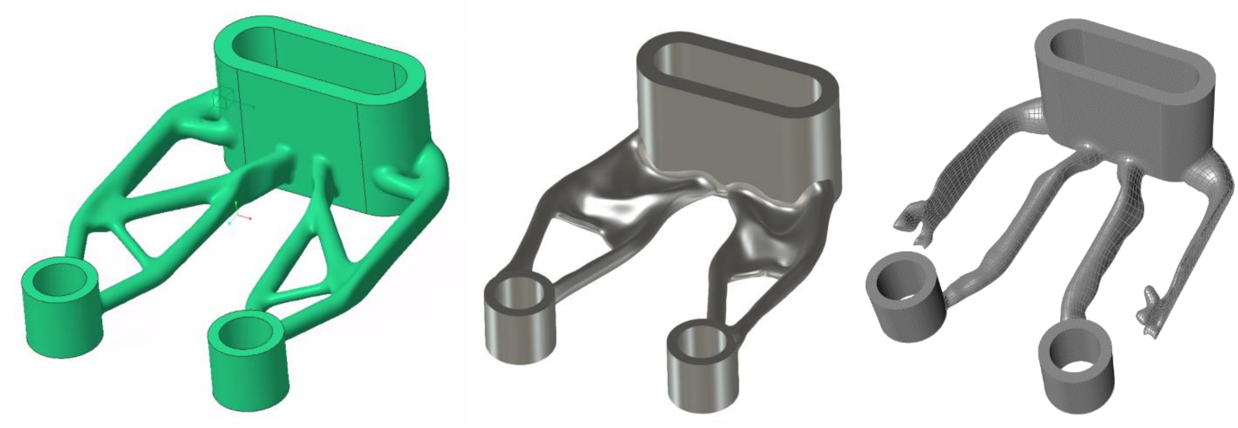


a) *from Creo* *b) from Fusion 360* *c) from Inspire by Altair*



d) *from 3DExperience* *e) from Ansys Discovery* *f) from Ansys Workbench*

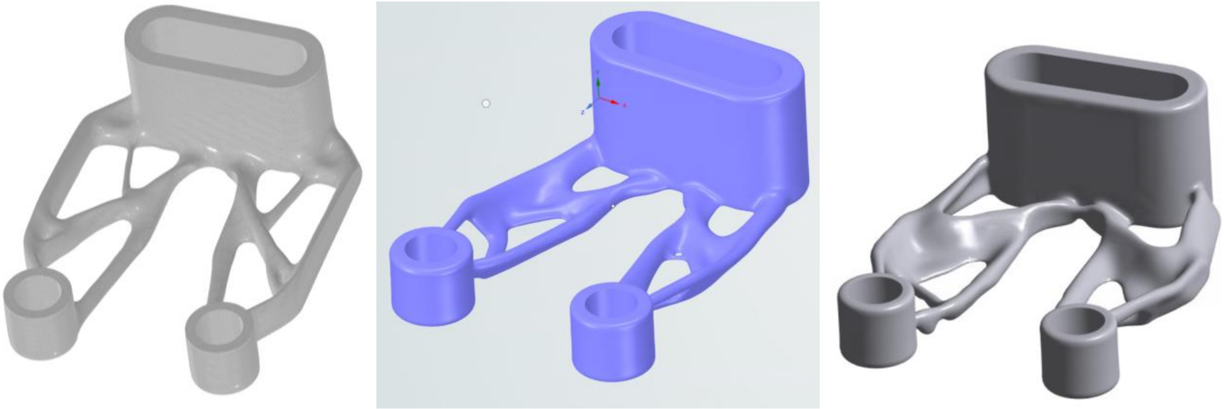
Appendix 3 - Generated Designs using no manufacturing constraint



a) *from Creo*

b) from Fusion 360

c) from Inspire by Altair

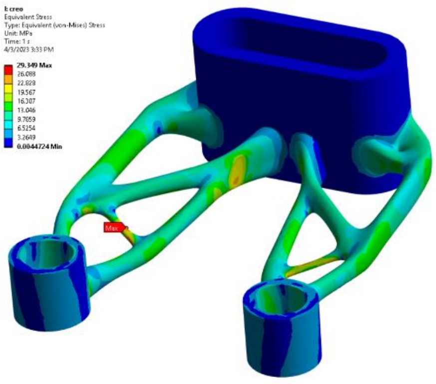


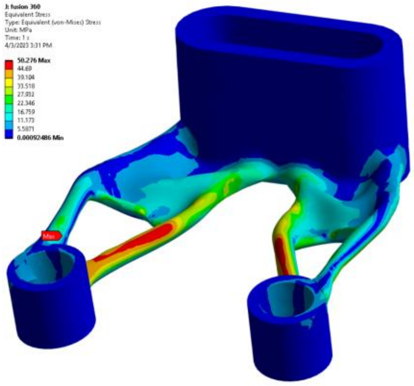
d) *from 3DExperience*

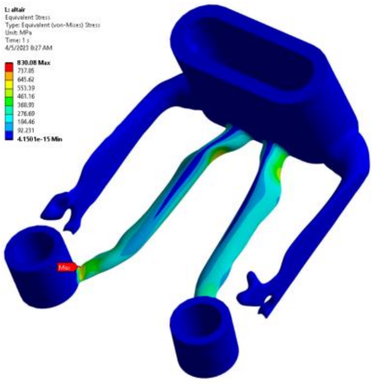
e) from Ansys Discovery

f) from Ansys Workbench

Appendix 4 - Generated Designs using the AM-constraint



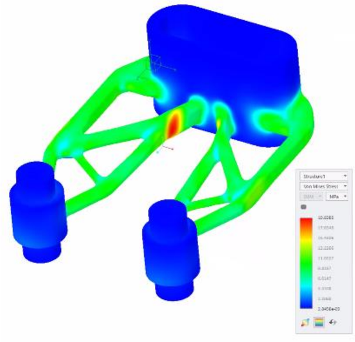


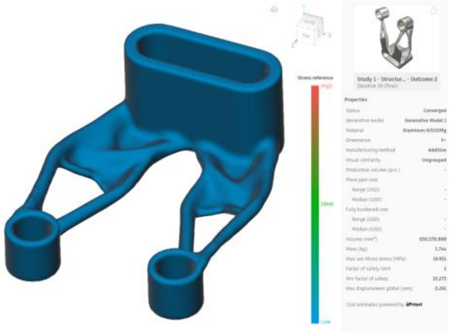


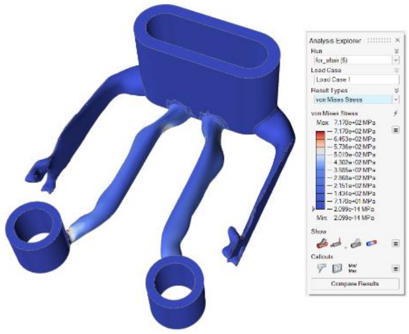
a) *Creo design evaluated in Ansys*

b) Fusion 360 design evaluated in Ansys

c) Inspire design evaluated in Ansys



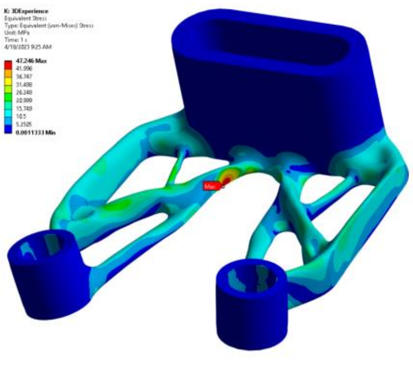


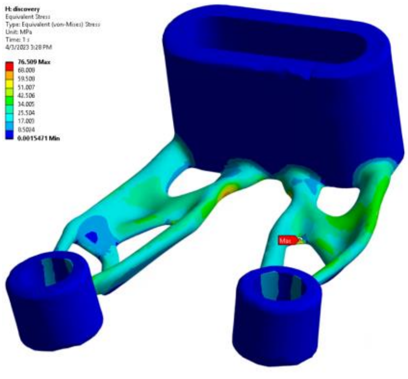


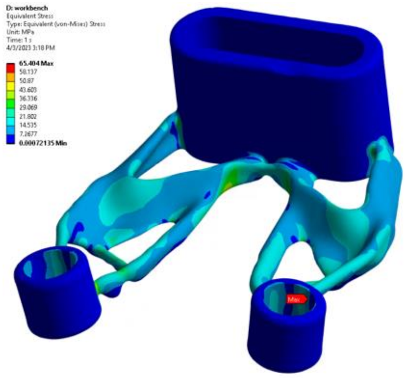
d) *Creo design evaluated in Creo*

e) Fusion 360 design evaluated in Fusion 360

f) Inspire design evaluated in Inspire



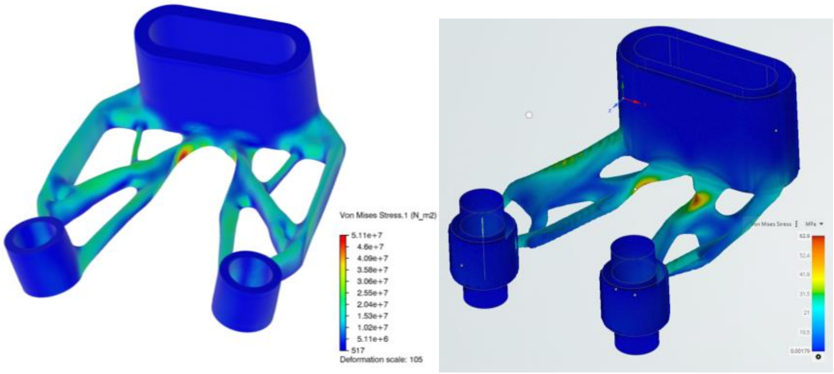




g) *3DExperience design evaluated in Ansys*

h) *Ansys Discovery design evaluated in Ansys*

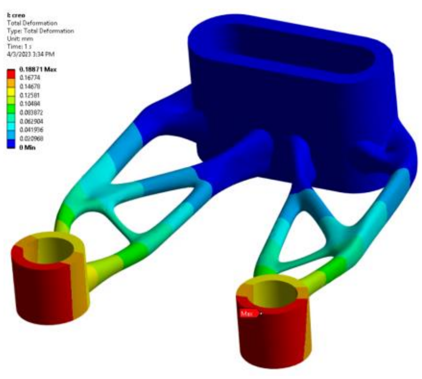
i) *Ansys workbench design evaluated in Ansys*



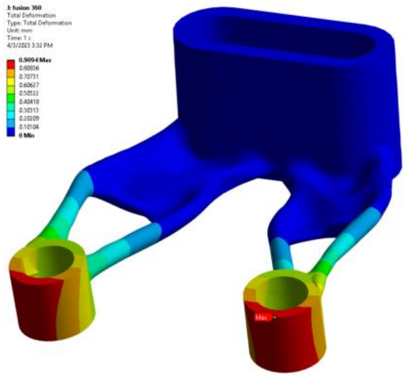
j) *3DExperience design evaluated in 3DExperience*

k) *Ansys Discovery design evaluated in Ansys Discovery*

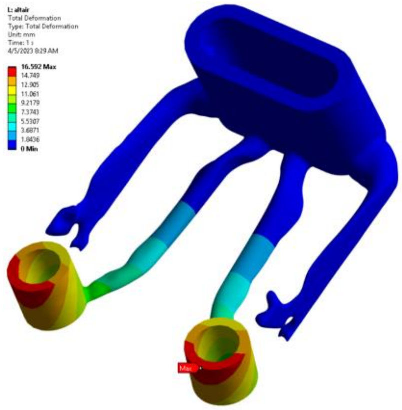
Appendix 5 - von Mises Stress plots from the evaluated software and Ansys Workbench



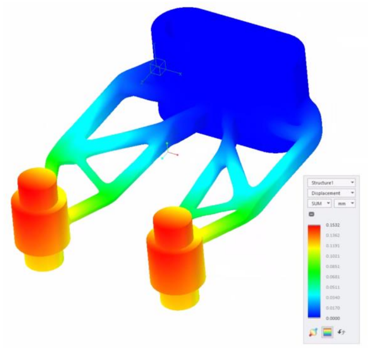
a) *Creo design evaluated in Ansys*



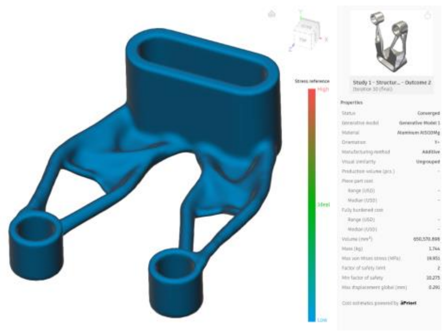
b) *Fusion 360 design evaluated in Ansys*



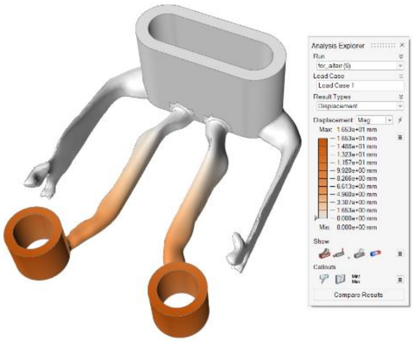
c) *Inspire design evaluated in Ansys*



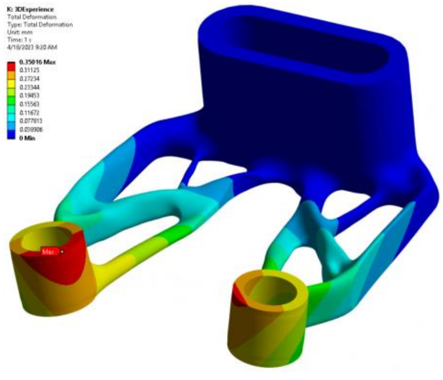
d) *Creo design evaluated in Creo*



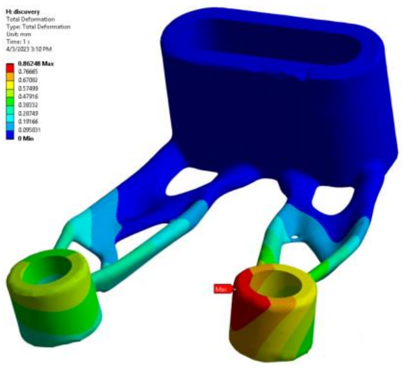
e) *Fusion 360 design evaluated in Fusion 360*



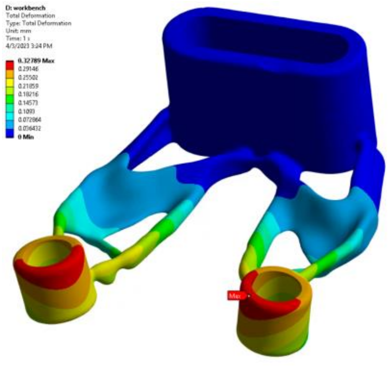
f) *Inspire design evaluated in Inspire*



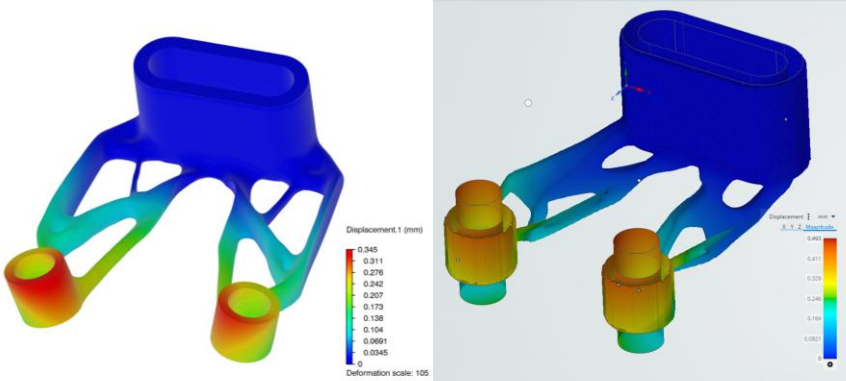
g) *3DExperience design evaluated in Ansys*



h) *Ansys Discovery design evaluated in Ansys*



i) *Ansys Workbench design evaluated in Ansys*



j) *3DExperience design evaluated in 3DExperience*

k) *Ansys Discovery design evaluated in Ansys Discovery*

Appendix 6 - Displacement plots from the evaluated software and Ansys Workbench

a) *from Creo*

b) from Fusion 360

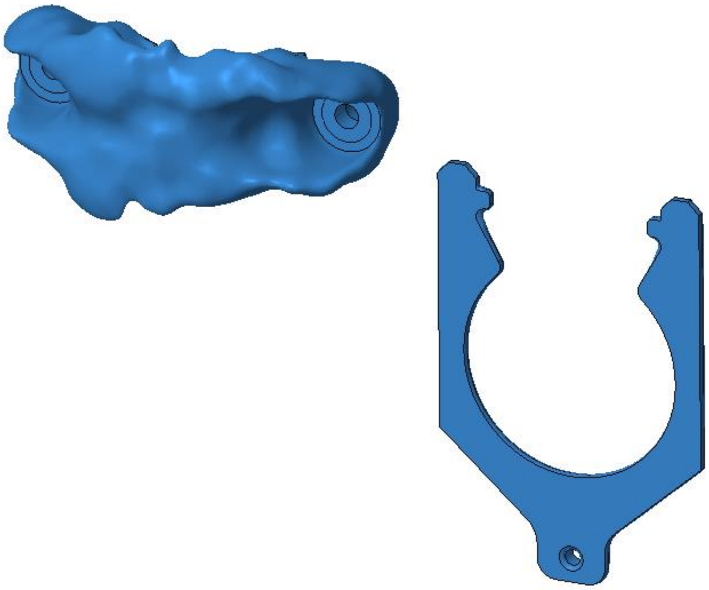
c) from Inspire by Altair

d) *from 3DExperience*

e) from Ansys Discovery

f) from Ansys Workbench

Appendix 7 - 3D-printed designs



Appendix 8 - Failed generation of concept 1 with correct screw force

a) Concept 1 – Casting from the front

b) Concept 1 – Casting from the rear

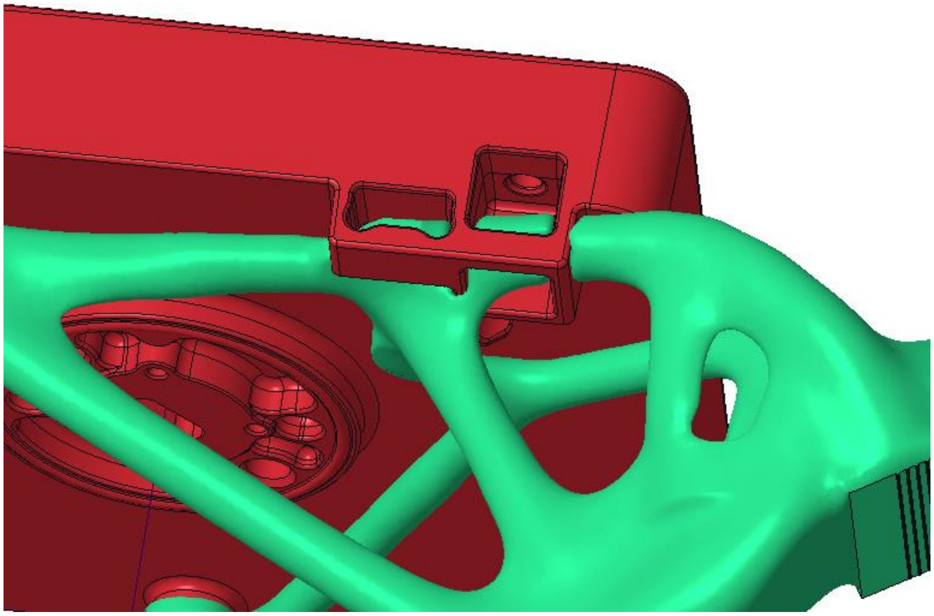
c) Concept 2 – AM from the front

d) Concept 2 – AM front the rear

e) Concept 2 – Casting from the front

f) Concept 2 – Casting from the rear

Appendix 9 - Rendered illustrations of casting and AM for Concept 1 & 2 in a realistic environment



Appendix 10 - Generated design intersects thin excluded geometries

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