LAPIN AMK
Lapland University of Applied Sciences

TOPOLOGY OPTIMIZATION IN 3D PRINTING

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Abstract of Thesis

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Topology optimization is an optimization method to reduce material usage while also enhance the tension resistance of a part. This process creates complex, organic shapes and therefore, 3D printing is known to be able to print also complex structures without increasing manufacturing costs. The aim of this work was to carry out a topology optimization with suitable parts and to determine the mass reduction as well as the change in tensile stress.

The thesis was divided in two sections. The first part dealt with the theory behind the topology optimization and their components. For this purpose, literature research was carried out first. The second part dealt with the practical application of the topology optimization using the Solidworks simulation software. Therefore, 3D models have been created and first analyzed using the FEA to get an insight about the occurring tensile stress. Then the optimization was carried out and checked by a second FEA. Finally, the results of these analyses were discussed.

The results of these analyses showed, that the topology optimization is a strong software tool for material use optimization. However, Solidworks only removes material and is not able to enhance the tension resistance of a highly loaded area. Furthermore, the results have shown that not all material that is classified as removable by the software may be removed.

Key words topology optimization, 3D printing, stress analysis, Solidworks

CONTENTS

FOREWORD

I want to thank Ari Pikkarainen, Sanna Moisanen and the international office for enabling this double degree between the UAS Technikum Wien and the Lapland UAS. Also, a big thank you to the international tutors for the support and company over the last ten months. With you even the cold and dark winter in northern Finland was bearable. A special thanks to Ari not only for the support during the whole stay in Kemi, but also for the supervision of my bachelor thesis. Last but not least, I have to thank my three roommates and double degree colleagues Felix, Milijana and Johannes for the unforgettable memories we experienced together.

SYMBOLS AND ABBREVIATIONS

AM	Additive manufacturing
CAD	Computer- aided design
FEA	Finite element analysis
FDM	Fused deposition modeling
SLA	Stereolithography
SLS	Selective laser sintering
TO	Topology optimization
UAS	University of Applied Sciences

1 INTRODUCTION

3D printing or also known under the standardized term additive manufacturing (AM), is a process where mostly materials are bonded layer by layer to manufacture parts. For this process data from a 3D model needs to be provided. This type of manufacturing stands in contrast to traditional subtractive and formative manufacturing methods. (ISO/ASTM 52900:2021:3.1.2, 8.)

AM has its use case in individual or small series production with low production volumes and for parts with a high design complexity. It is known for its significantly reduced manufacturing times and costs of functional prototypes, compared to traditional manufacturing methods. (Abdulhameed, Al-Ahmari, Ameen & Mian 2019, 2.)

To reduce the material costs even more and to enhance the tension resistance of the parts, topology optimization can be applied. Software is used for this process. On one hand, the software removes material of locations which do not contribute to the tension strength of the part. On the other hand, it adds material to reinforce areas to improve the tensile stress resistance within given geometrical parameters. (Walzl & Buchmayr 2017, 110.) For this process many softwares are on the market e.g., Solidworks Simulation, Fusion 360, Autodesk Inventor and nTopology. This thesis will be carried out with the help of the Solidworks Simulation software.

The reduction of material costs due to topology optimization is also of great interest for the Lapland University of Applied Sciences (Lapland UAS) mechanical engineering degree. The university has a 3D printing laboratory with different technologies. These are also used for educational purpose by the students. Regardless of the printing technology the university wants not only to reduce the running and material costs of the printers, but also contribute to a more sustainable use of plastics.

1.1 Motivation

The topology optimization process is a method, where improved part properties are achieved while also the required material consumption is reduced. (Walzl & Buchmayr 2017, 110.) This means, that this process allows material savings without any negative impact on the product. Thus, in addition to the material cost reduction it is also a great way to get a more responsible use of the available resources. This side of consideration must already be taken into account in the designing and development process. The responsible approach of using resources only where they are really needed should also be implemented into the education of AM.

Therefore, this thesis deals with the process of topology optimization, but also includes the educational point of view for the Lapland UAS mechanical engineering degree. Thereby it enables an integration of the topology optimization process into the future education and imparting knowledge on the responsible use of resources.

1.2 Objectives

The first objective of this work is to lay the theoretical foundation of the part optimization tools especially for the topology optimization. Followed by the product and development process and the integration and connection of the topology optimization in these processes.

For the practical goals it is important to first familiarize with the use of Solidworks simulation topology optimization tool. This software is used, because it includes the CAD and the topology optimization software in one program. Later on, practical test will be carried out to optimize different 3D models. After that, the calculations of the material savings and the tensile strength improvements between the optimized and non-optimized parts are done.

1.3 Methodology

The thesis is divided in two sections. The first part deals with the theory of the product and development process as well as the topology optimization and their implementation. This includes also the finite element analysis (FEA). Therefore, literature research will be carried out to lay the foundation for the subsequent investigations.

The second part deals with the practical application of the topology optimization. Thus, research of the usage of the topology optimization tools in Solidworks Simulation is carried out with the Solidworks Web Help. Subsequently 3D models which are suitable for the optimization, 3D printing and strength testing are created. For each model requirements like areas which have to keep their shape are set. These requirements are put into the software and the program determines the resulting 3D models. The resulting models are strength tested also using the Solidworks Simulation software.

To ensure that the resulting parts are printable the new parts are printed out with an FDM printer. This technology enables a high printing speed with sufficient printing quality for this application.

To calculate the tensile strength improvements by this process, the FEA is used. In the FEA the optimized and non-optimized parts are loaded with the same parameters. The resulting tension strength of each part is compared.

2 PRODUCT DESIGN AND DEVELOPMENT PROCESS

There is no single correct product design and development process, but the different variants are very similar. In this case the process to develop a new product goes through six main stages. These are also accompanied by six evaluation gates. During the various gates, the product managers evaluate the efficiency and effectiveness of the stages by pre-specified performance criteria. These function as guidelines and make adjustments to the development process possible. (Tsokas, Hultink & Hart 2004, 620; Ulrich, Eppinger & Yang 2020, 9.)

2.1 Overview

As can be seen in Figure 1, the design and development process of a new product is not a straightforward process. In each evaluation gate the product manager decides whether the process can proceed to the next stage, has to repeat the last stage or the development is discontinued. (Tsokas, Hultink & Hart 2004, 619.)

The actual product designing is only one of the six stages for a successful product development. The whole new product development process also includes the idea generation, the creation of a product concept and the creation of a business case before the real product is developed. The process also includes stages after the actual product development, like the market testing and the market launch. (Tsokas, Hultink & Hart 2004, 620; Ulrich, Eppinger & Yang 2020, 9.)

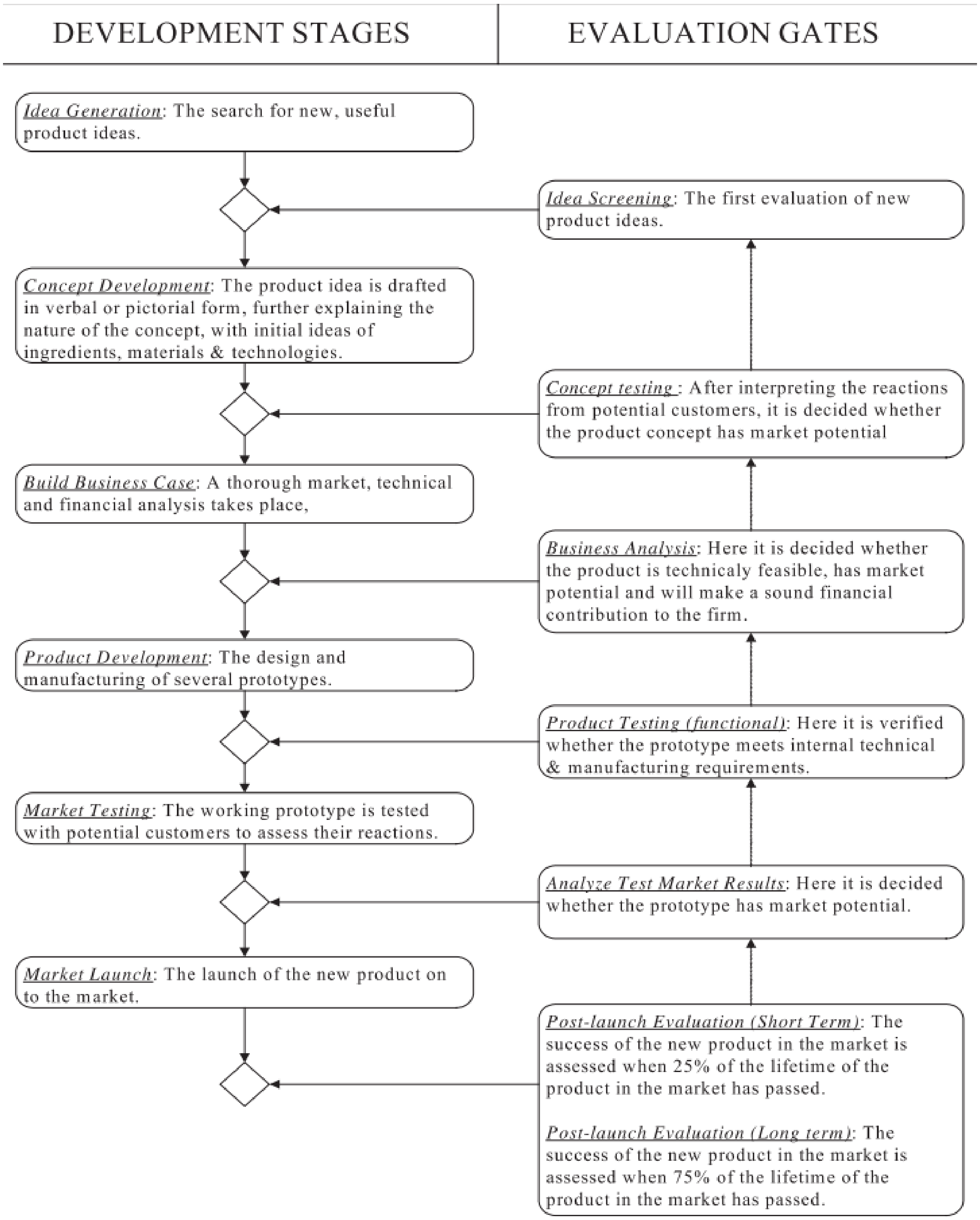


Figure 1. Product design and development process (Tsokas, Hultink & Hart 2004, 620)

2.2 Idea Generation

The idea generation is a creative process. Although creativity is difficult to measure, it is considered as an important component in research. Over the years many creativity techniques have been developed. The most common used in the area of product development is brainstorming. But there are also other strategies like free association, mind-mapping, divergent thinking and sketching. (Herring, Jones & Bailey 2009, 2.)

Brainstorming is a process, to generate ideas in groups while following a few rules. The rules include not to criticize any ideas, to create a large number of ideas and to also contribute unusual ideas. These rules contribute to an improved performance compared to a group which does not follows these rules. (Putman & Paulus 2008, 1.)

2.3 Concept Development

This phase requires a lot of specialist knowledge and is therefore carried out by engineers. The concept development of a new product mainly involves the identification of customer requirements, identification of product specification, concept generation and concept selection. However, the customer requirements and preferences are changing over time. This means the process needs to be repeated over time. (Wang, Zheng, Lee & Chen 2018, 478-479.)

The use of the topology optimization needs to be included already into this phase. For the optimization the desired constrains need to be determined. These include the material properties, component’s essential geometric features and loading conditions. This also means, that the whole part does not need to be accurate developed. The engineers can focus only on areas of the part which contribute to the functionality of it. The software will create structures for the rest of the part within the given parameters. (Rezaie, Badrossamay, Ghaie & Moosavi 2013, 521.)

2.4 Business case

The business case has the purpose to present an overview of the costs, benefits and risks of a project idea. In this phase, calculations are carried out to determine whether the implementation of the product is economically viable for the company. (Lind 2015.) The six steps of this evaluation process are shown in Figure 2.

Figure 2. Business case process (Lind 2015)

During the **purpose** phase, the objectives and the urgency of the objectives are elaborated. The result is a hierarchy with respective criteria to measure the progress and success of the objectives. In the **cost and benefit** stage estimated cost and their benefits are elaborated. This not only includes possible problems but also opportunities for the project. During the **effects** stage the previous elaborated benefits are broken down to smaller units. This must be done until it is known how to archive and how to measure every small piece of the effects. The **conditions** are set by merging the broken-down effects with the corresponding costs. In the **choice of the model** phase, is determined what is included in the calculation model. Only data which is highly quantifiable and traceable should be included into the actual business case. The **business case** includes the output of the previous stages. The calculations should not be high detailed, this increases the complexity of the business case strongly. Often a business case with a medium level of complexity is the preferred solution. (Lind 2015.)

2.5 Product development

In this phase, the actual product is finally developed. The findings from the conceptual design and any necessary changes based on the findings during the creation of the business case are incorporated into the development. The resulting product has to fulfil the customer requirements. However, the product designer has also to keep in mind about the manufacturing process of the product. The envisaged manufacturing process and the chosen material should not exceed the intended production cost. Subsequently the first prototypes are manufactured and tested for their functionality. (Wang, Zheng, Lee & Chen 2018, 478-479.)

2.6 Market testing

In this phase the product is not yet available for the whole market. It is tested on a small group of customers. Depending on the product this can mean, that the product is only sold in a small area or the potential customers need to be contacted and asked to test the product. It is important to get feedback from the customers, whether the product fulfils their requirements or what needs to be improved. This stage is vital, it is the first real test if the previous identified potential customers are willing to buy the new product. (Entrepreneur Media 2022.)

2.7 Market launch

This is the phase where the largest commitment in time, money and management resources are needed. The success of a new product launch depends on a number of factors. These can be categorized into strategic launch decisions and tactical launch decisions. The strategic launch decisions involve the overall firm, product, market and competitive strategy. These are long term decisions and can’t be adapted for a single product launch. This includes for example, whether the company is in the premium or low-cost segment or the development if the entire product portfolio. Tactical launch decisions are set only for the new product. These are the short-term decisions and contain the price, promotion and distribution strategy. This includes if the product is sold in a store or on a website and trough which channels the product is advertised. (Hultink, Griffin, Hart & Robben 1998, 244.)

3 TOPOLOGY OPTIMIZATION

The topology optimization (TO) is one of several optimization methods to enhance component properties while also reducing the material consumption of manufactured parts. TO is a three-dimensional optimization method, therefore the output of this method are complex, organic structures. To manufacture the optimized parts with conventional manufacturing methods e.g., milling or drilling, would be either very costly or even not possible at all. Therefore, the AM technology comes into play. Even the most complex structures can be manufactured by this process without increasing manufacturing costs. (Walzl & Buchmayr 2017, 111.) On the part shown in Figure 3 TO is applied. Only 50% of the material is left and thus necessary for the required stiffness (Jensen 2019).

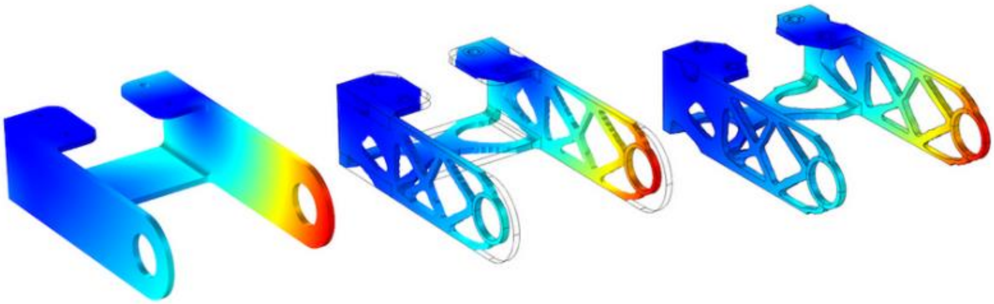


Figure 3. Topology optimization (Jensen 2019)

The main goal of TO is to find the optimal material distribution in a defined volume, for the best achievable structural performance. In doing so, also predefined loads boundary conditions and constraints are considered. Therefore, computer-aided design (CAD) software is used. The software generates design suggestions that show how the component can be designed in a material reduced but also load oriented way. Especially with the combination of AM this tool has a huge impact on the final geometry of the part. With conventional manufacturing methods, the optimization is limited due to geometric manufacturing possibilities. AM allows to fabricate also parts with a high complexity as long as the part sticks to the respective designing rules of the AM method. (Tyflopoulos, Flem, Steinert & Olsen 2018, 2.)

3.1 Implementation process

TO is a tool to optimize three dimensional parts. Therefore, the 3D model for the optimization needs to be designed. Before the actual optimization process can start, environmental and part properties have to be defined shown in Figure 4. These are e.g., the acting forces and torques, part dimensions or max. internal tensions. (Tyflopoulos, Flem, Steinert & Olsen 2018, 2.)

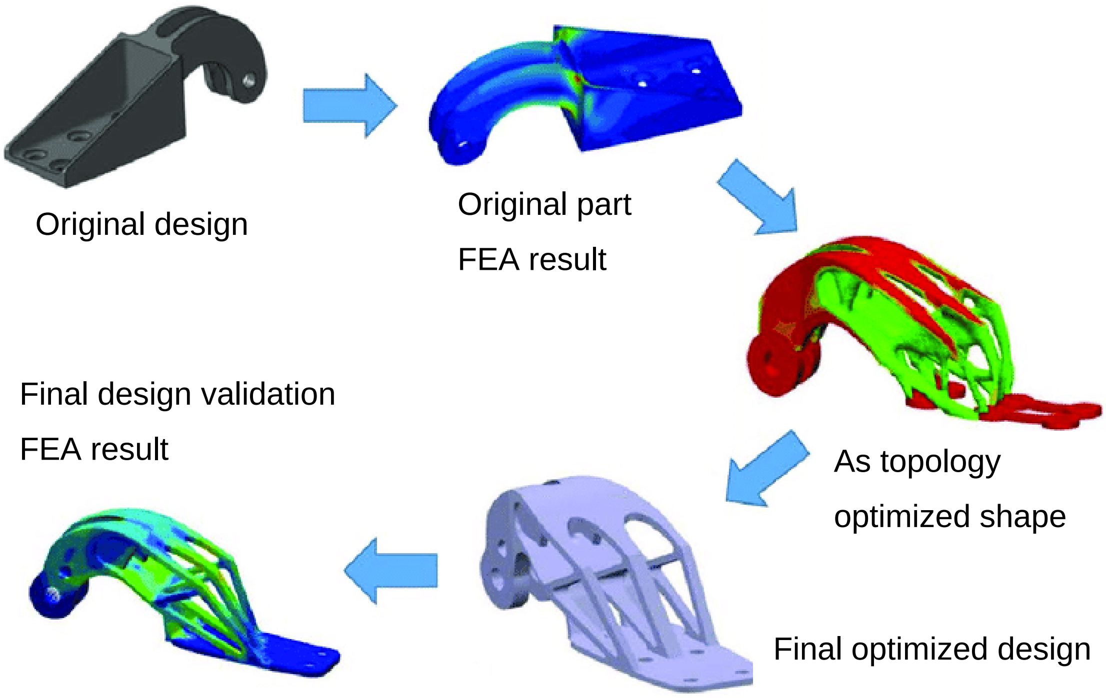


Figure 4. Topology optimization implementation process (Gebisa & Lemu 2017)

During the optimization, the software locates heavily loaded areas of the part. The algorithm goes through multiple iterations to generate ideal support structures for these areas. In addition, also less loaded areas are located. In these locations, the algorithm reduces the material used to generate a uniformly loaded structure. If desired or even necessary, more optimization parameters can be added to change geometry of the resulting structures. This is depending on the intended manufacturing method. (Walzl & Buchmayr 2017, 112.)

A problem which can occur during the optimization process is a too low mesh resolution. The higher the resolution, the better the mesh can represent the structure and the better is the reachable optimum topology. The mesh must contain a certain number of datapoints per surface to make an accurate calculation possible. (Brackett, Ashcroft & Hague 2011, 349.)

The output of the optimization program needs to be reviewed, if the new shape is manufacturable with the chosen method. If it is feasible, the FEA with the firstly defined environmental properties is carried out. Thereby it is checked, whether the optimizations worked as planned or it has failed and needs to be repeated. (Brackett, Ashcroft & Hague 2011, 349.)

3.2 Other Techniques

TO is not the only optimization method to enhance component properties. Apart from that, there are three other optimization methods. These are the topography optimization, the size and shape optimization and the optimization via grid structures. (Walzl & Buchmayr 2017, 112.)

3.2.1 Topography optimization

The difference between the TO and the topography optimization is, that the topography optimization only applies on two-dimensional parts like sheet metals. In this process beads and similar stiffeners are applied to the sheet metal to maximize the strength against a predefined load. (Walzl & Buchmayr 2017, 112.) These stiffeners are applied on the sheet metal part in Figure 5.

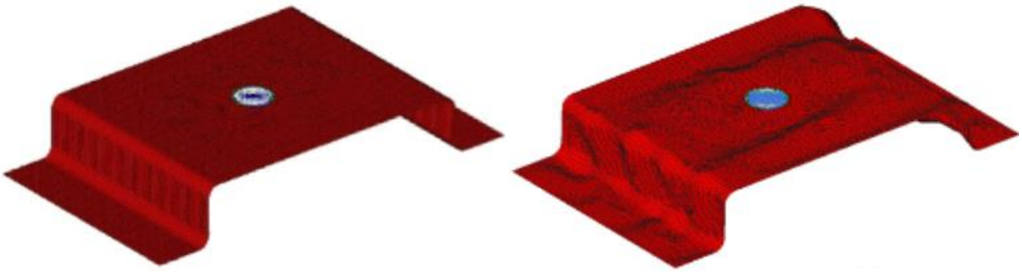


Figure 5. Topography optimization (Choi, Kim & Park 2016)

3.2.2 Size and shape optimization

The size and shape optimization is often applied after the topology optimization. Here, critical areas with high internal tension are adapted with thickness or shape changes. However, it does not change the number of support structures. (Walzl & Buchmayr 2017, 112.)

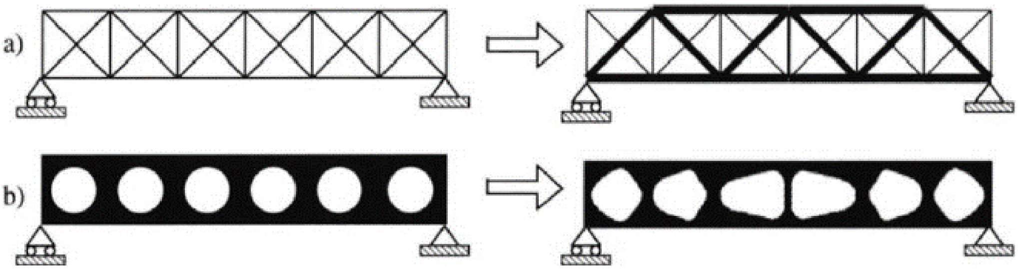


Figure 6. Size and shape optimization (Tyflopoulos, Flem, Steinert & Olsen 2018)

As shown in Figure 6, illustration a) shows the size optimization. The shape of the beams nor the amount of them has been changed. Only the size of certain beams has been adjusted to reduce tension in certain areas. Illustration b) shows the shape optimization. Here, the amount of the holes did not change either. Only the shape of them has been adjusted.

3.2.3 Grid structure optimization

This optimization method is often used combined with the previous mentioned methods. It generates automatically a grid structure with an optimal geometry to replace a filled surface or volume. In Figure 3 is the grid structure already integrated into the TO. It replaced the filled-out surface with a grid structure. (Walzl & Buchmayr 2017, 112.)

4 FINITE ELEMENT ANALYSIS

The finite element analysis (FEA) is an analysis method where the whole complexity of a problem, e.g., boundary conditions and loads, is preserved. However, the obtained results of the analysis are only approximations. This numerical technique is carried out with the help of computers and is often already integrated into CAD programs. The FEA originated as a stress analysis tool but today it is also used in fluid flow, heat transfer and electric and magnetic fields. Furthermore, it can not only be used for static but also for dynamic problems. (Bhavikatti 2021.)

4.1 Description of the method

When the behavior of complex structures is calculated for certain conditions, small deviations to the actual behavior of the part occur. This happens due to unknown variables which are encountered in engineering problems. If an infinitely accurate result is desired, an infinite number of these variables will occur. The FEA reduces these unknown variables to a finite number. Therefore, the solution region is split up into smaller parts. In these so-called elements the unknown variables are assumed by approximating functions. (Bhavikatti 2021; TWI 2022.)

4.2 Difference between FEA and classical methods

With both, the FEA and classical methods, the formed equations for the calculations are exact. However, the obtained results differ in accuracy. While the solutions of classical methods are also exact, the solutions from the FEA are approximations. The calculation by classical methods is only suitable for standard cases. For the FEA it is not a problem to also calculate structures with not isotropic material properties and when there is more than one material. (Bhavikatti 2021.)

4.3 Tensile strength

As the name indicates, tensile strength is the capability of a material to withstand a pulling force. It is specific for every material, even for different variants of the same material (steel). The deformation of a material under load is separated in two different kinds of deformation, elastic and plastic. The tensile strength indicates the amount of stress the material can handle before it stretches. It is measured in N/m². (Mansur 2016, 17.) The tensile strength can be presented in a stress-strain diagram in Figure 7.

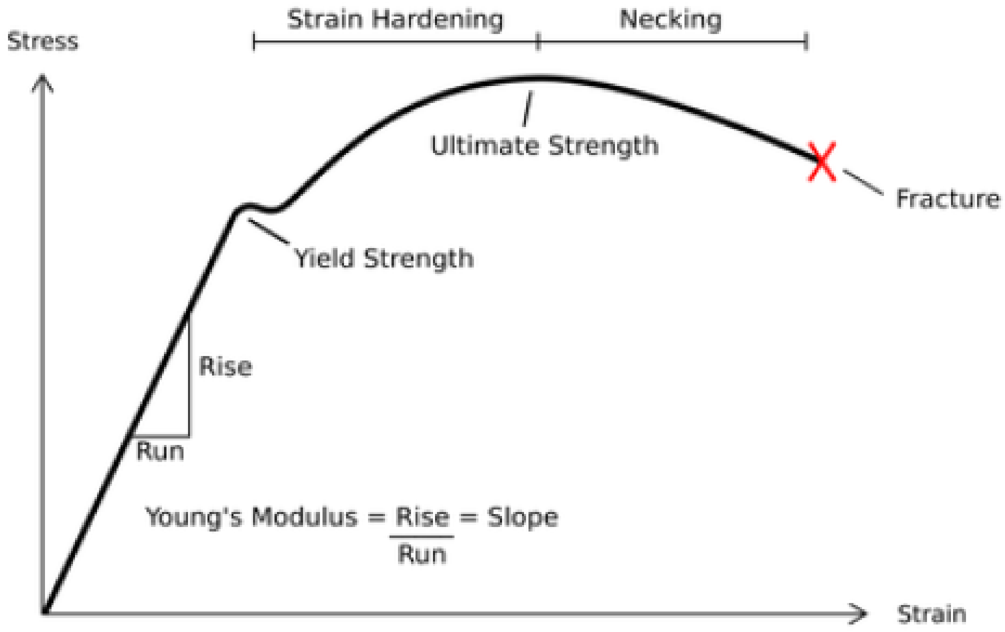


Figure 7. Stress-strain diagram (Mansur 2016)

The straight part in the diagram indicates the elastic deformation of the material. The maximum stress load within this range is the yield strength. Till this point the material will form back to its initial position. The curve in the diagram indicates the plastic deformation and the failure of the material. The straight to the top of the curve is the plastic deformation located. From then on, the material starts to necking till it fails at the end. The top of the curve is called ultimate strength or tensile strength. This value is even given in the name of some materials like steel. (Mansur 2016, 5-7.)

5 APPLICATION OF THE TOPOLOGY OPTIMIZATION

To demonstrate the functionality of the TO, two parts are optimized in the following. These are subjected to a permanent load during use. Usually, the original part would be manufactured out of structural steel. However, this kind of steel is not suitable for AM. Furthermore, the material of the 3D-printed part would not be isotropic. To enable a comparison between the optimized and original parts some simplifications have been made. Therefore, and for a suitable comparison between the parts, the same material for all parts was chosen.

5.1 Material

The selected material for the simulations is the structural steel S355JR. S stands for structural steel, 355 stands for the yield strength and JR means that the material can withstand an impact energy of 27J at 20°C (Weltstahl 2022). The properties of this material are taken from the Solidworks database and shown in Table 1.

Table 1. Material properties (Solidworks Simulation)

Property	Value	Unit
Elastic Modulus	210000	N/mm^2
Poisson's Ratio	0,28	---
Shear Modulus	79000	N/mm^2
Mass Density	7800	Kg/m^3
Tensile Strength	450	N/mm^2

5.2 3D models

The chosen parts for the TO process are the arm of a workshop crane and the tine of a forklift. These are both good examples of parts which are under load during use. That implies an occurring tensile stress within the parts. The workshop crane is shown in Figure 8.

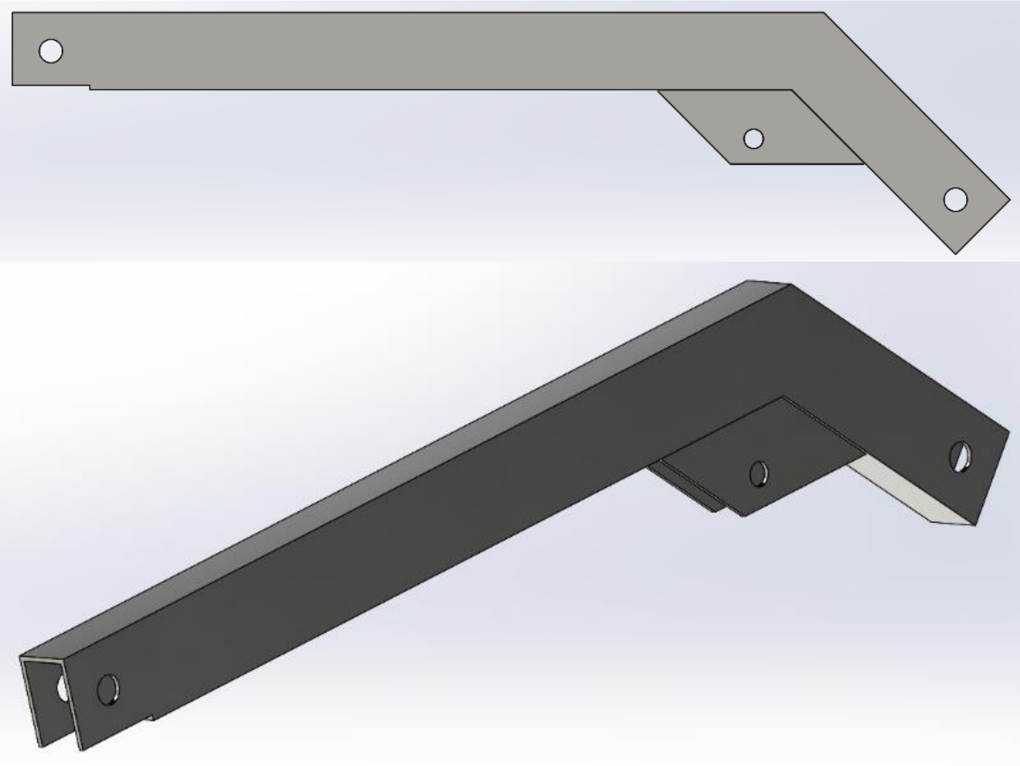


Figure 8. 3D model of the workshop crane

The workshop crane is made of a 5mm thick square steel, it is not filled out. The hole on the right is the pivot point of the part. On the hole in the middle is the hydraulic cylinder to push the load upwards is attached. The load of 4000N is attached to the hole on the left and pulls downwards. The exact measurements can be taken out the drawings in the appendix.

The forklift fork tine has a cross section of 60mm x 120mm. The tine is designed to carry a standardized euro pallet. They have the size of 1200mm x 80mm and a working load of approximately 2000kg (European Pallet Association 2022). Therefore, with the weight of the pallet and a bit of a tolerance, one tine has to withstand 1000kg. The tine is shown in Figure 9.

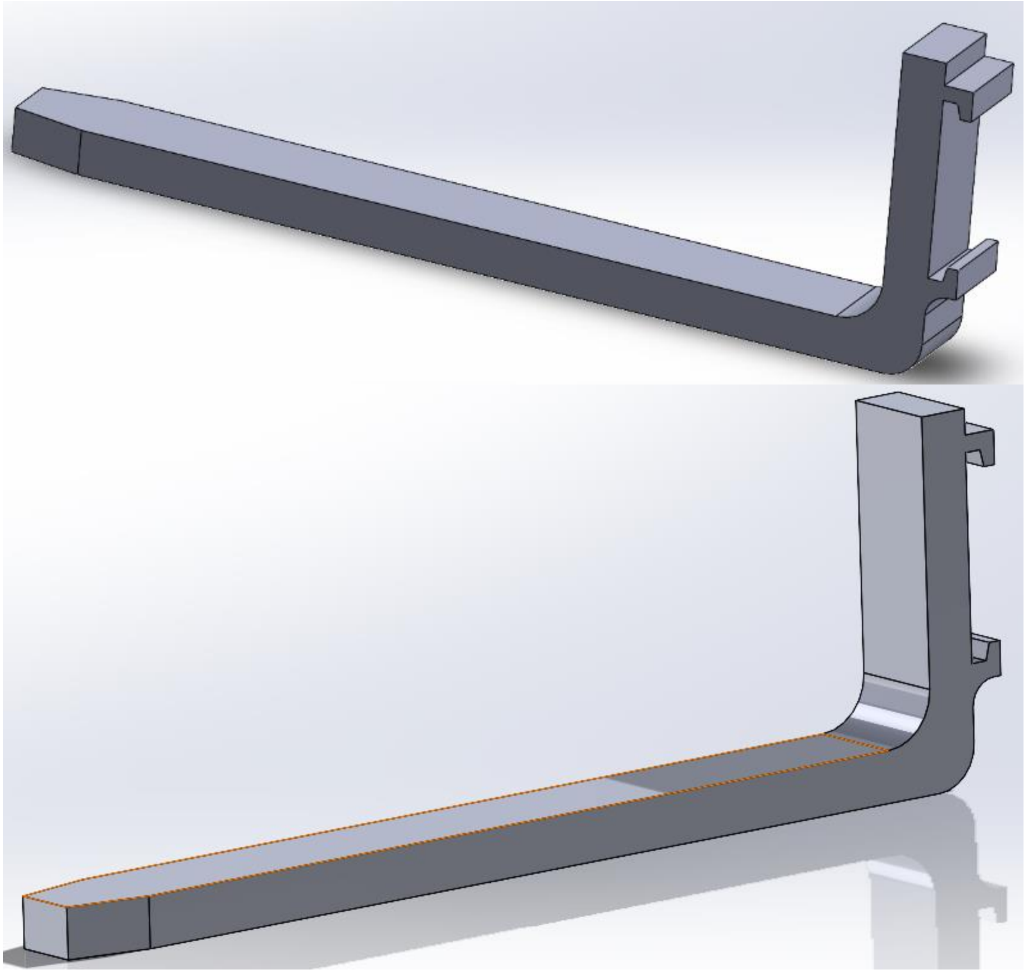


Figure 9. 3D model of the forklift fork tine

To be able to carry the euro pallet it has a length of 1200mm. The brackets on the back of the tine are there to mount it onto the forklift. A drawing of the fork tine is shown in the appendix.

5.3 FEA framework conditions

The analyses carried out are static. They do not include the movement of the load. The specific conditions for the workshop crane are shown in Figure 10.

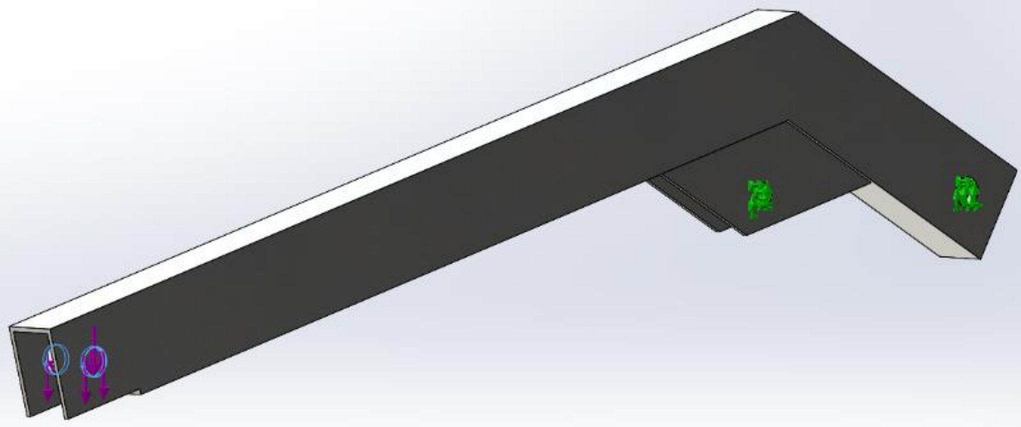


Figure 10. Workshop crane framework conditions

The green marked areas are the fixtures of the model. When the load is lifted up, the hydraulic cylinder fixes with the pivot point the arm in position. The crane arm is not located horizontal. It has an angle of 30°, however the load pulls straight to the ground indicated by the purple arrows.

The framework conditions of the fork tine are shown in Figure 11.

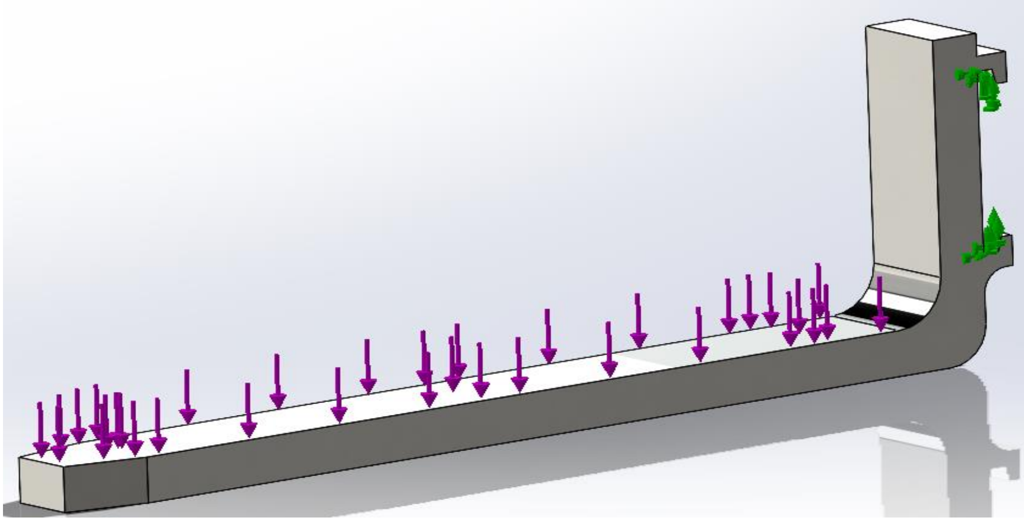


Figure 11. Fork tine framework conditions

The fork tine is fixed to the forklift, therefore the areas which are in contact with the forklift are fixed, indicated in green. The load of the pallet, indicated again with purple arrows, is distributed over the whole length of the tine pushing it down.

Before the FEA can start, a mesh needs to be created. The software calculates every single node of this mesh. The denser the mesh is, the more accurate are the results. The parts with the mesh are shown in Figure 12.

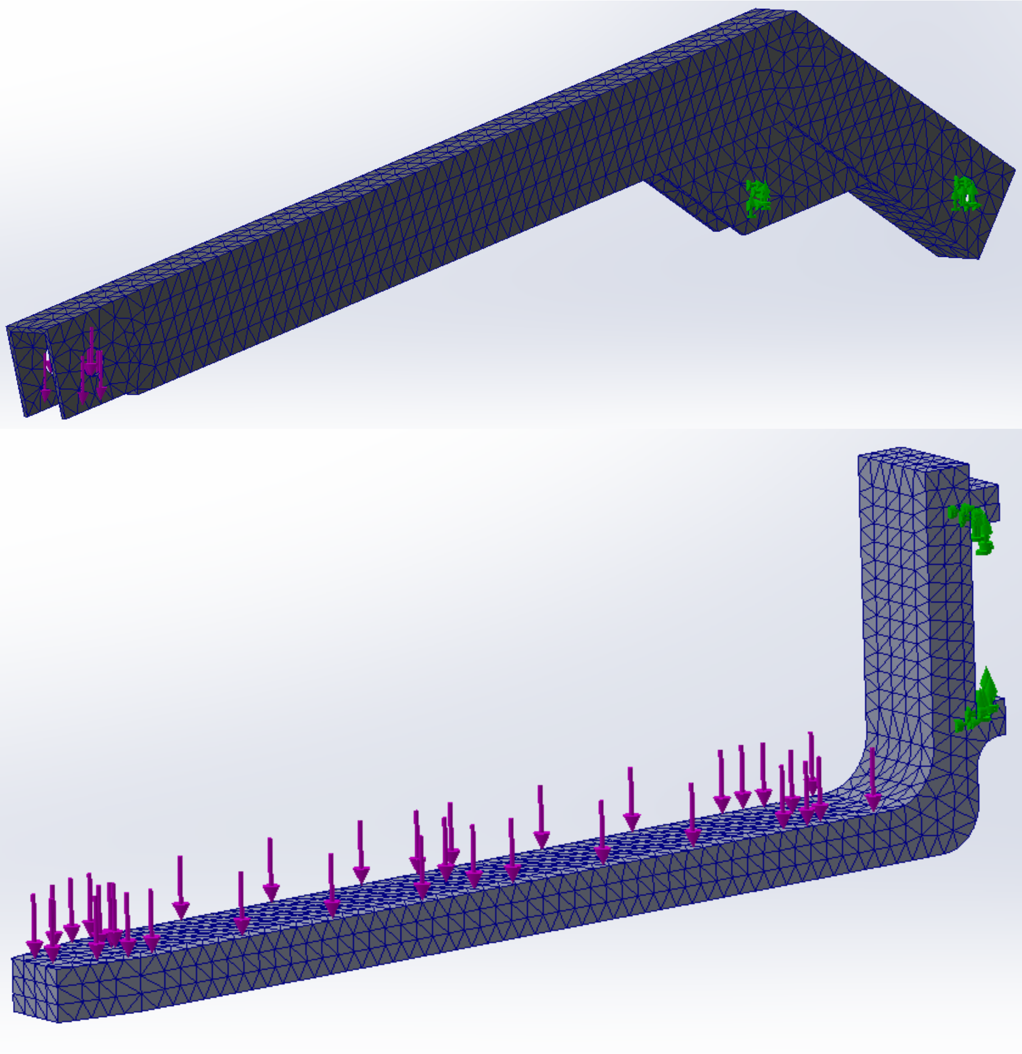


Figure 12. Mesh for the FEA

5.4 FEA Results

The result from the FEA which is important for the next steps is the stress analysis. The FEA calculates the stress which occurs in the part when it is under load. The software also displays the levels of stress with different colors. The stress analysis of the workshop crane is shown in Figure 13.

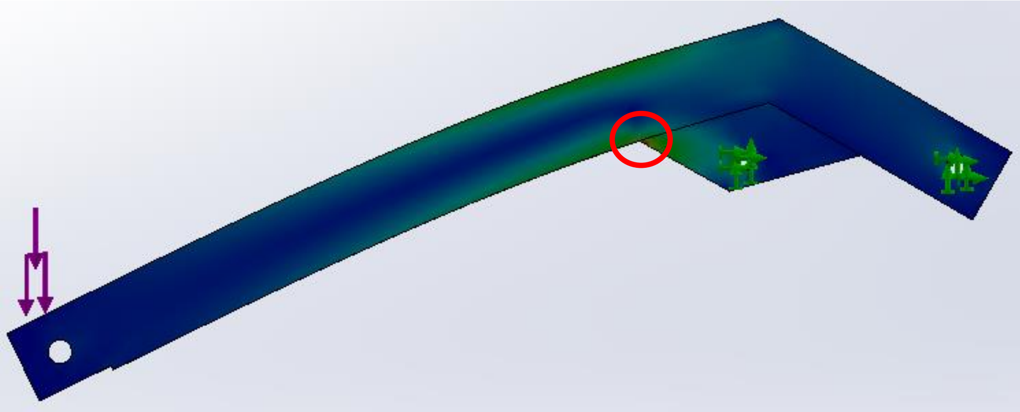


Figure 13. FEA of the workshop crane

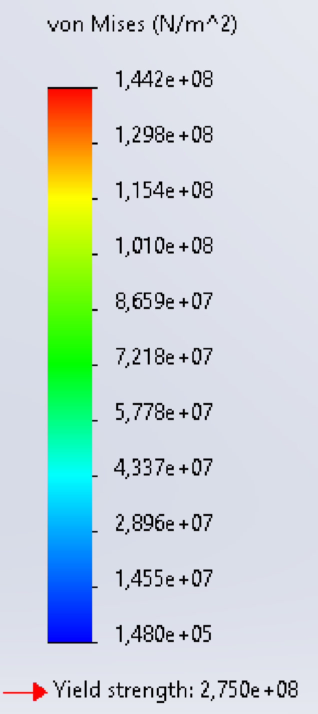


Figure 14. Scale of the stress analysis of the workshop crane

The greatest stress occurs within the red circle indicated with red color. The red color only indicates where the most stress occurs and not if it is problematic or not. The scale in Figure 14 shows that the yield strength is much higher than the maximum occurring stress within the part. That means, the load causes no permanent deformation of the part and is not a problem.

The analysis also shows the elastic deformation of the part under load. However, the shown deformation does not correspond with the real one. It is amplified for a better visualization.

In Figure 15 the stress analysis of the fork tine is shown. As indicated in red, the most stress occurs at the filet at the front and the back of the tine within the red circle.

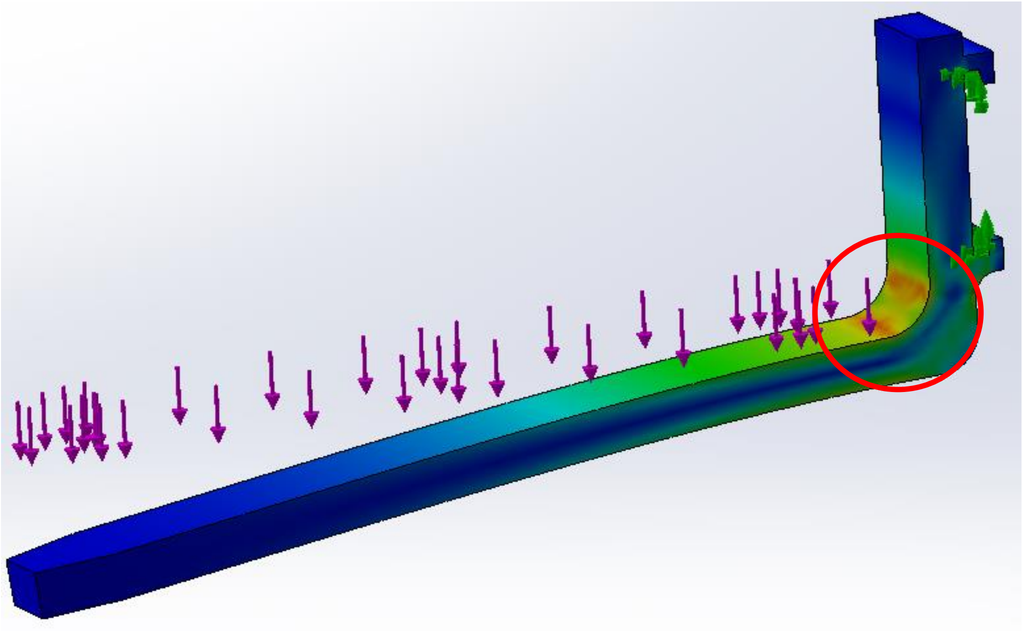


Figure 15. FEA of the fork tine

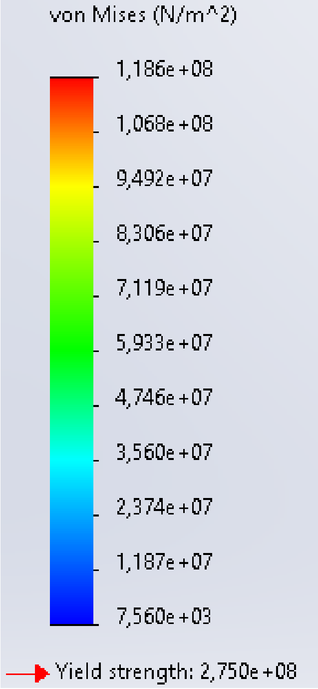


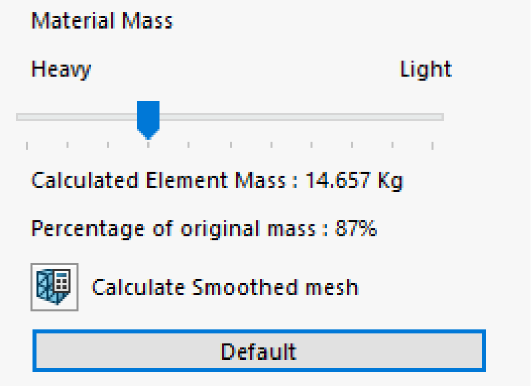
Figure 16. Scale of the stress analysis of the fork tine

Also in this case, Figure 16 indicates that the yield strength of the material is higher than the occurring stress. The fork tine is, like the workshop crane, elastically deforming under load.

Therefore, it is possible to remove material in areas which do not or only in few amounts contribute to the overall stress resistance of the parts. To calculate which material can be removed, the TO is carried out in the next step.

5.5 TO of the workshop crane

The framework conditions of the FEA are taken over for the TO. Additionally, more constrains have to be set. The main goal is to achieve the best stiffness to weight ratio. Therefore, the targeted mass reduction needs to be set. This value only has a small impact on the simulation, it only defines the size of the steps for the controller. The controller for the workshop crane is shown in Figure 17 .



Calculated Element Mass : 14.657 Kg

Percentage of original mass : 87%

Figure 17. TO controller for the workshop crane

The originally set mass reduction was 15%. However, the TO resulted in a mass reduction of 13%. That resulted from another constrain. The maximum stress should not exceed 80% of the materials yield strength. When the sliding controller gets moved, the model in Figure 18 and Figure 19 changes. The different colors indicate how important the area is to fulfill the set requirements. The meaning of them is explained in Figure 20.

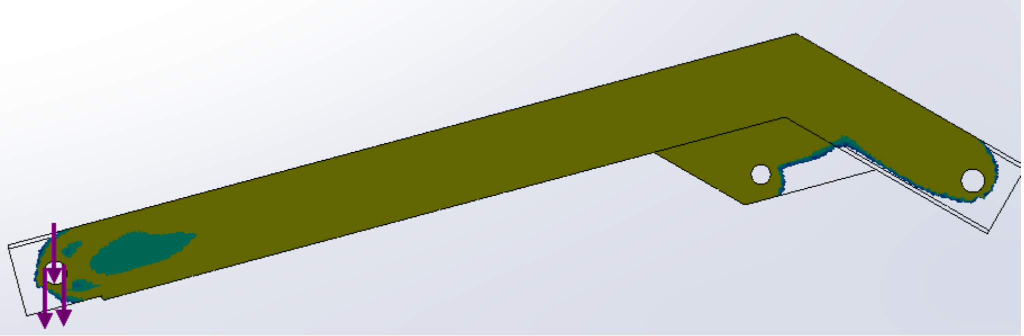


Figure 18. TO of the workshop crane 1

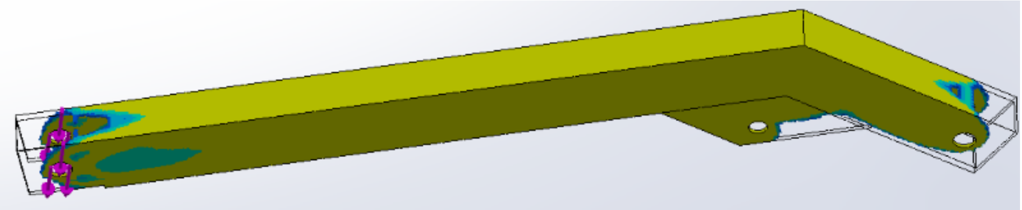


Figure 19. TO of the workshop crane 2

The third and last constrain for the TO is the preservation of certain areas. To ensure that the crane arm can be mounted to the rest of the machine the contact surfaces need to be preserved. In this case all six holes are preserved with a set depth of 5mm.

Figure 20. Meaning of the colors

To achieve the final form of the optimized part, the smooth mesh needs to be calculated. In this step, the software calculates a uniform surface from the edges of the modified regions. The smoothed surface is shown in Figure 21. The outlines show the original part dimensions.

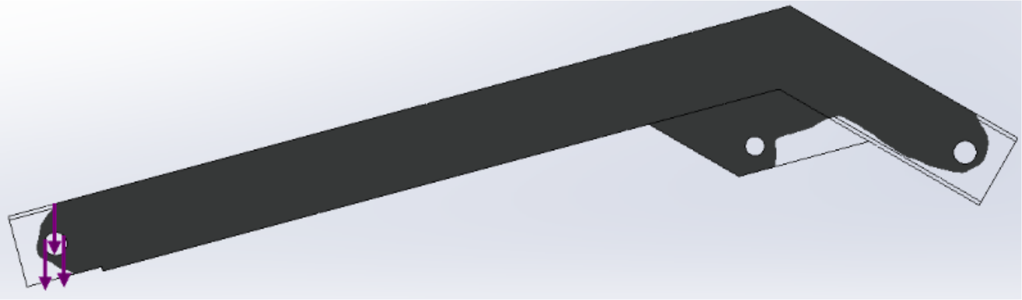


Figure 21. Smoothed surface of the workshop crane

To check if the TO was successful a second FEA needs to be carried out. The second FEA has the same framework conditions than the first FEA. While carrying out the FEA with the optimized part, Solidworks does not visualize it. Even though it looks like the original model, the software calculates with the optimized and smoothed model in the background as shown in Figure 22.

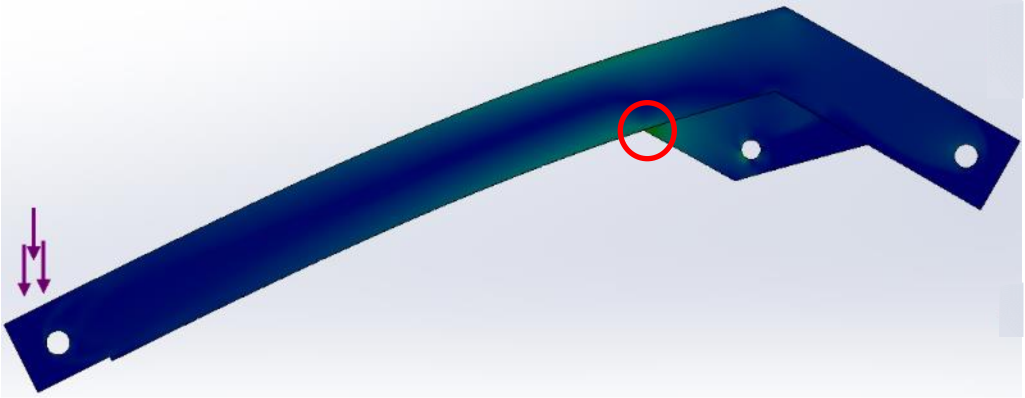


Figure 22. FEA of the optimized workshop crane

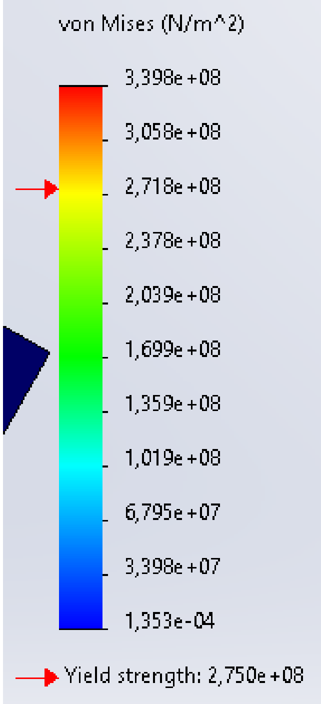
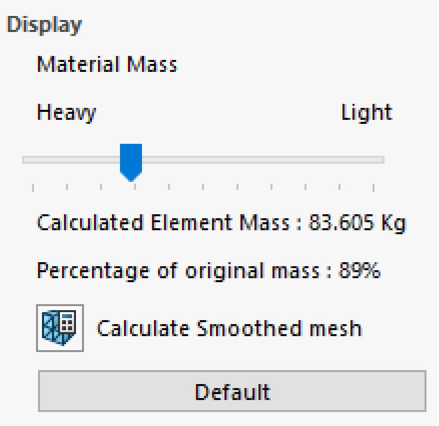


Figure 23. Scale of the second stress analysis of the workshop crane

The most stress occurs again within the red circle. However, as shown in Figure 23 the maximum stress is much higher than the yield strength of the material, indicated by the small red arrow. Solidworks calculates for this area an amount of stress higher than the yield strength even if the slide controller is on the far left. That means with 100% of the original mass the stress level is too high. This error occurs in areas which are under high stress already before the TO.

5.6 TO of the fork tine

The targeted mass reduction goal for the fork tine was also about 15%. In this analysis resulted in a reduction of 11% of the original mass. The slide controller for this TO is shown in Figure 24.



Calculated Element Mass : 83.605 Kg

Percentage of original mass : 89%

Figure 24. TO controller for the fork tine

Like at the optimization of the workshop crane, the goal for the maximum stress for the fork tine is 80% of the yield strength. The preserved areas of the fork tine are also the areas where it is connected to the rest of the machine. The fixed areas of the brackets and the contact area with the pallet are preserved. This time no depth for the preservation has been selected. The TO model is shown in Figure 25.

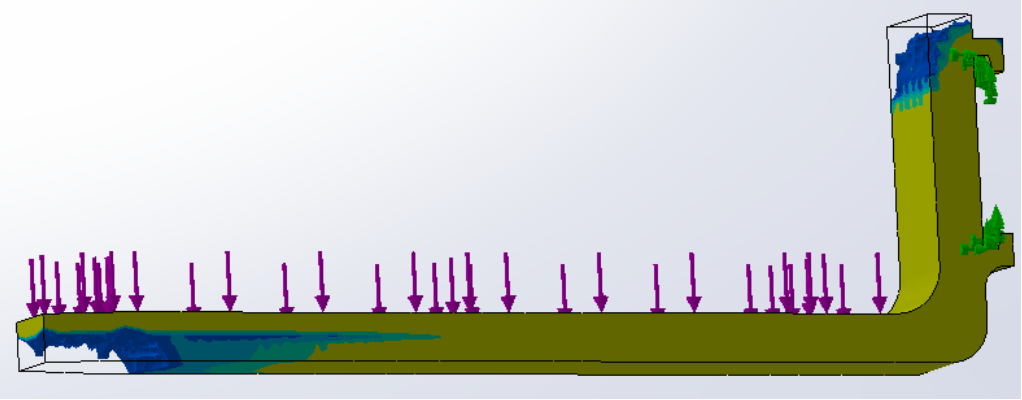


Figure 25. TO of the fork tine

An additional constraint was added to this TO. A symmetrical constraint was added along the tine. Therefore, the model resulted symmetrical along this axis.

When the edges are smoothed where material has been removed the model looks like in Figure 26. The optimized areas are the bottom of the tip of the tine and the top edge on the right side. This is indicated by the outlines of the original part.

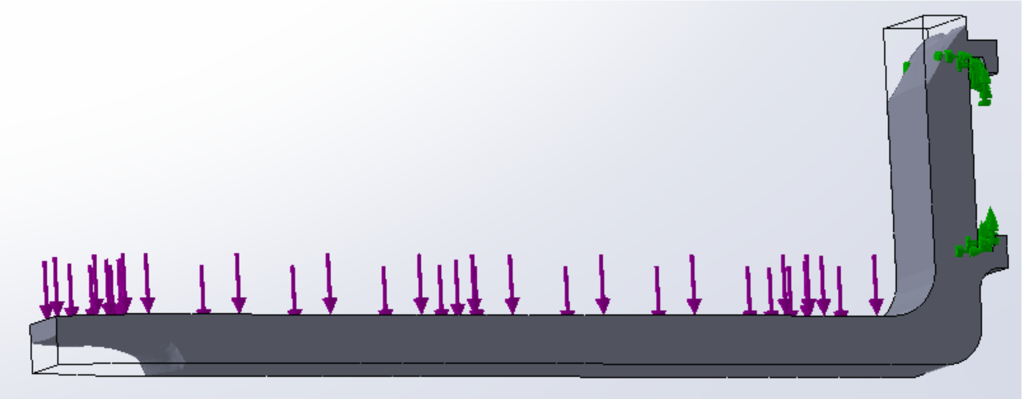


Figure 26. Smoothed surface of the fork tine

The subsequent analysis was also carried out with the same framework conditions as the FEA. The optimized shape is again only calculated in the background and not visualized. The highest stress occurs this time at the back of the tine under the lower bracket marked with a red circle in Figure 27.

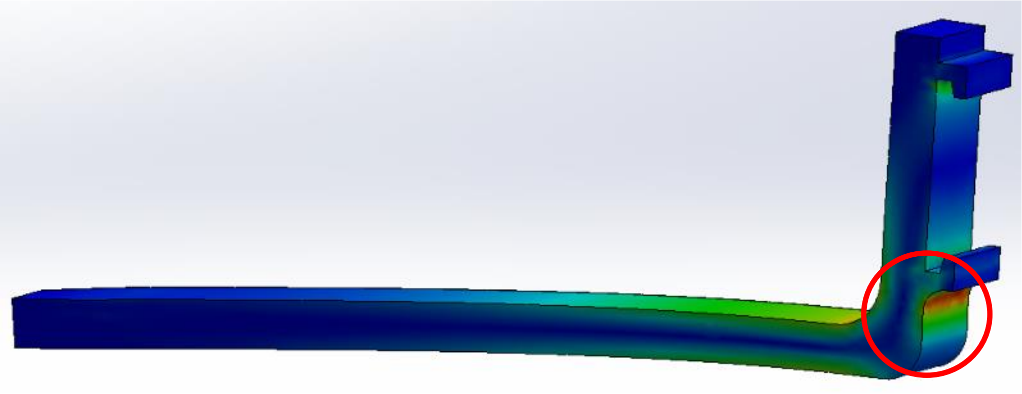


Figure 27. FEA of the optimized fork tine

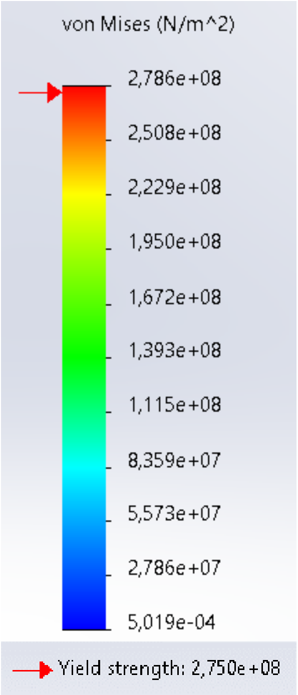


Figure 28. Scale of the second stress analysis of the fork tine

In this analysis the same error occurs than at the workshop crane optimized stress analysis. As shown in Figure 28 the stress level is higher than the yield strength of the material. This is also the case when the reduced mass is set to 0%.

It seems, that this error occurs when an area is already under a high stress level before the analysis. Solidworks only removes material but it does not add material in highly stressed areas. The chosen models look like to be already so specifically designed to be optimized by the Solidworks TO software. To solve this problem a second TO process was carried out with adapted models.

5.7 Adapted 3D models

To give the TO software more room to work with the models are adapted. The new models consist of more material, especially in the highly stressed areas. In Figure 29 the adapted workshop crane is shown.

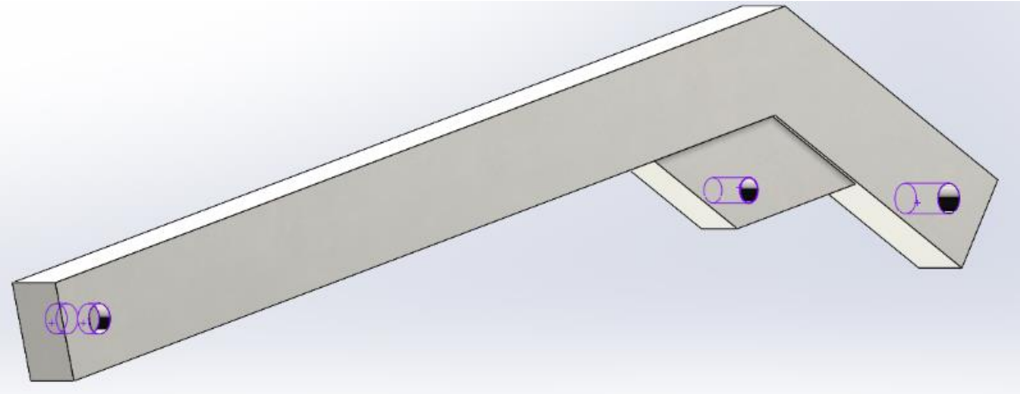


Figure 29. Adapted workshop crane 3D model

The new model is not built with a hollow square steel. It is completely solid. The two reinforcement plates where the hydraulic cylinder is connected are merged to one solid element. The holes are still on the same positions and the overall dimensions of the model did not change.

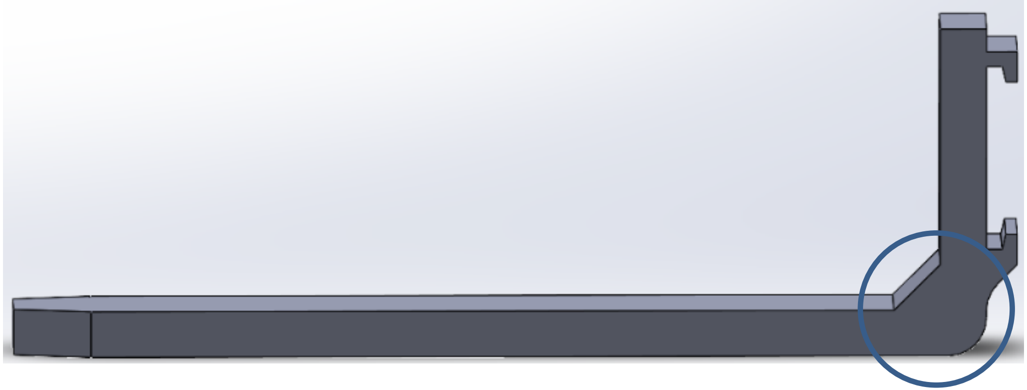


Figure 30. Adapted fork tine 3D model

The model of the tine shown in Figure 30 only changed within the blue circle. The filet was changed to a chamfer and a chamfer with a small filet was added to the lower bracket to enhance this week spot.

As can be seen in Figure 31 and Figure 32 the simplified workshop crane and the reinforced fork tine are analyzed under the same framework conditions as the original models.

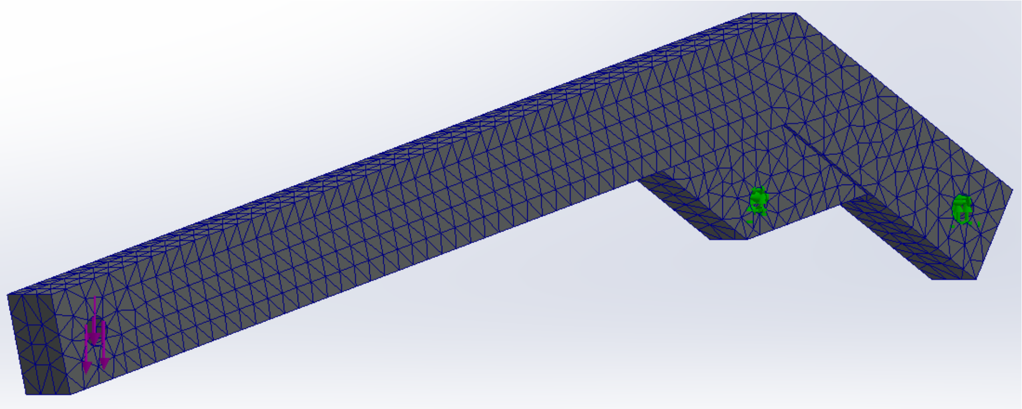


Figure 31. Adapted crane framework conditions

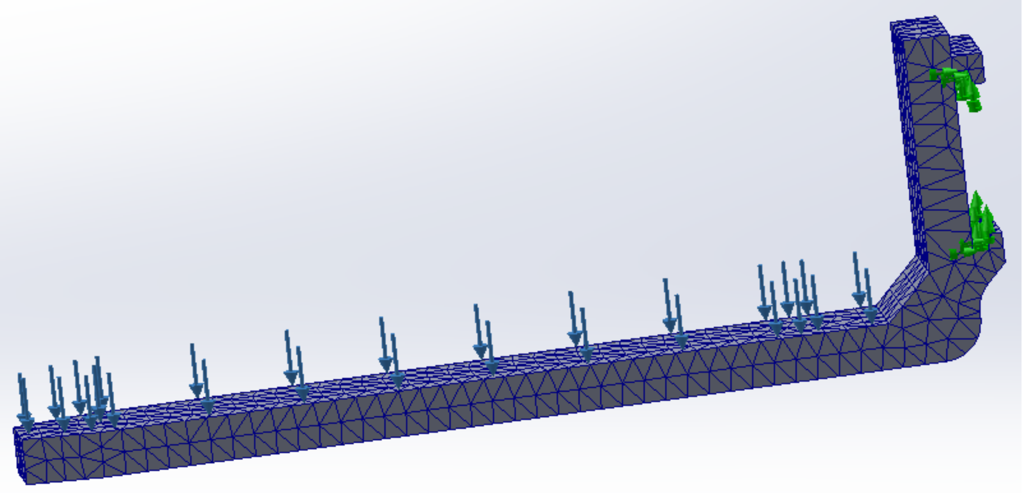


Figure 32. Adapted fork tine framework conditions

The only parameter that changed for the FEA is the new created mesh. That needed to be calculated again due to the changed geometry in both parts. The following FEA resulted, on basis of the changes, in lower maximum stress compared to the original parts.

5.8 TO of the adapted workshop crane

The framework conditions for the TO also did not change. The only parameter that got tweaked is the targeted mass reduction. Due to solidifying the part it had more mass, so the reduction could increase to 58% for the workshop crane shown in Figure 33.

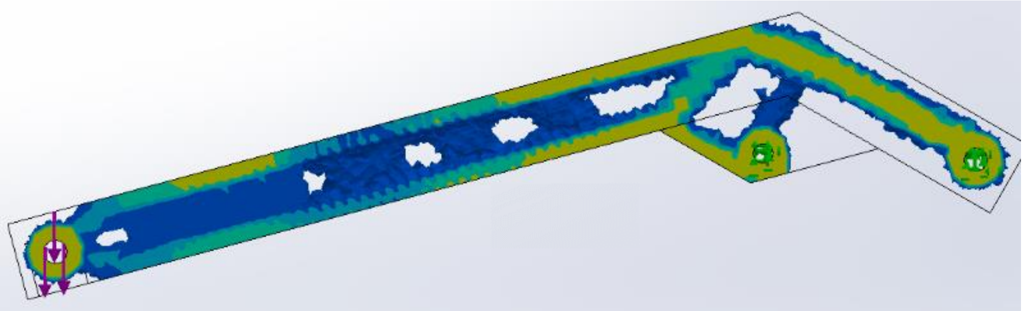


Figure 33. TO of the adapted workshop crane

The resulting shape is a much more organic one than the TO of the original part. Furthermore, the preservation of the holes is much more visible than before. Also, the optimization work of the software in the background is due to the new holes within the part more visible. It is even better shown in Figure 34 and Figure 35 with the smoothed mesh.

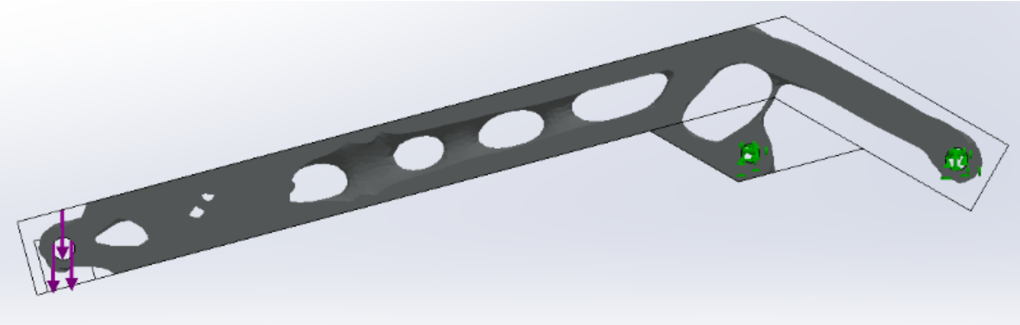


Figure 34. Smoothed surface of the adapted workshop crane 1

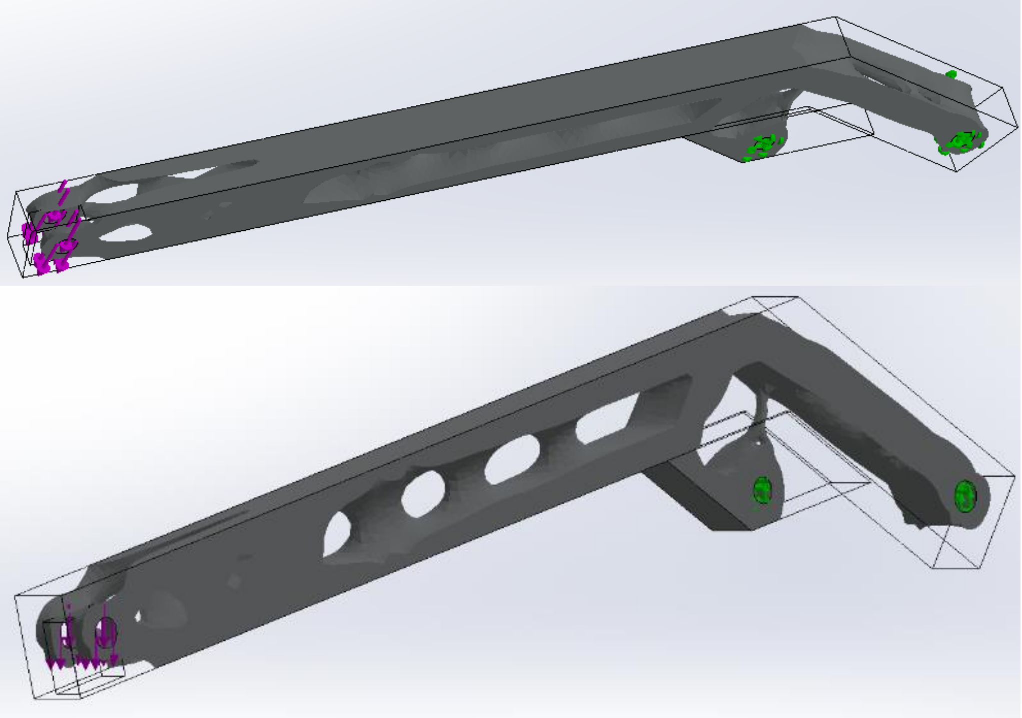


Figure 35. Smoothed surface of the adapted workshop crane 2

After the TO a FEA is carried out again to check if the TO worked and the new part can handle the occurring stress levels. The area with the highest stress levels stood the same like before. However, with this design it distributes over a larger area and the stress peak is much lower than before. The spot with the high stress level is highlighted in Figure 36.

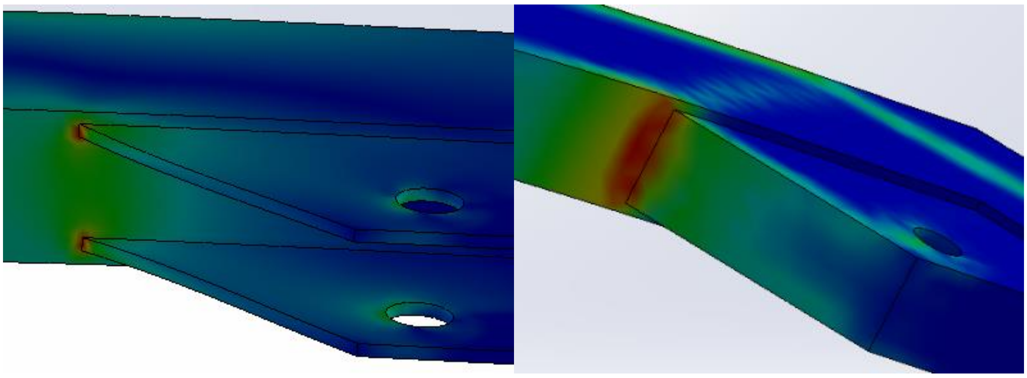


Figure 36. Comparison of the week spot of the workshop crane

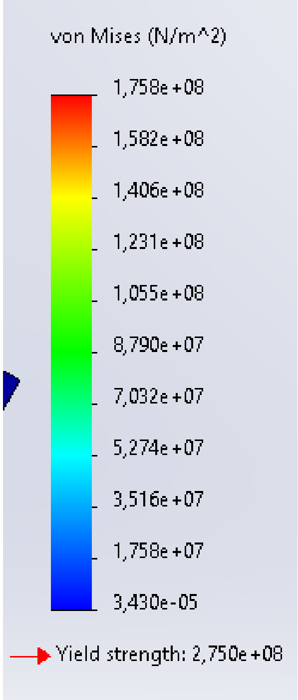


Figure 37. Scale of the adapted and optimized workshop crane

As can be seen in Figure 37 the maximum stress level in this analysis does not exceed the yield strength of the material. Actually, it is much further away than the intended 80% of the yield strength. However, Solidworks again did not change the thickness in this area of the model. In Figure 33 can be seen, that the area around the stress peak is colored yellow and must not change even if the targeted mass reduction would be risen.

5.9 TO of the adapted fork tine

Due to reinforcing the area with the most amount of stress the adapted part has a higher mass and therefore a higher potential mass reduction. The simulation software calculated a mass reduction of 23%.

Figure 38. TO of the adapted fork tine

As shown in Figure 38, the reinforced areas in the blue circle must not be changed. However, due to the higher capability of stress resistance in this area, the mass at the tip of the fork tine can be reduced further.

The smoothed mesh of the fork tine in Figure 39 shows that the area where the mass has been removed at the tip is significantly larger than at the original part. Additionally, a third small area appears where the model has been optimized. Between the two mounting brackets is a small optimized area.

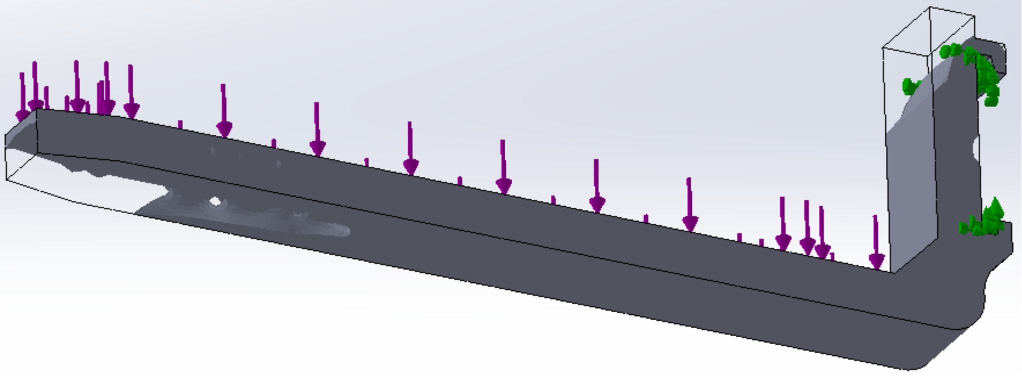


Figure 39. Smoothed surface of the adapted fork tine

The geometry changes led to a shift of the maximum stress level location. It moved from the back of the tine to the end of the added chamfer on the tines top surface in Figure 40.

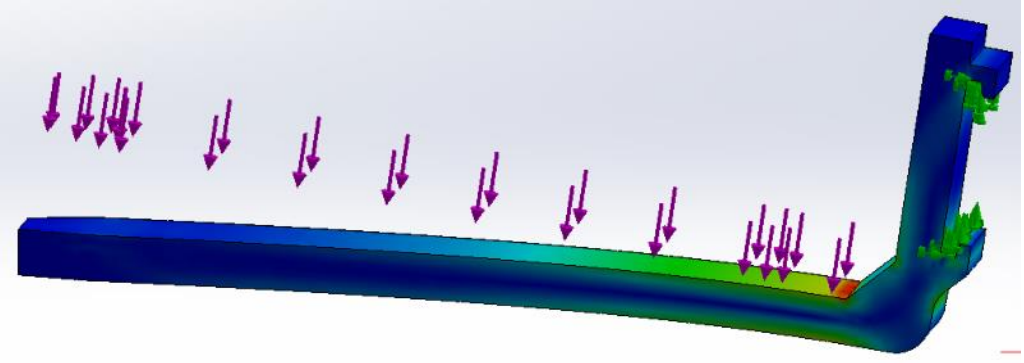


Figure 40. FEA of the adapted and optimized fork tine

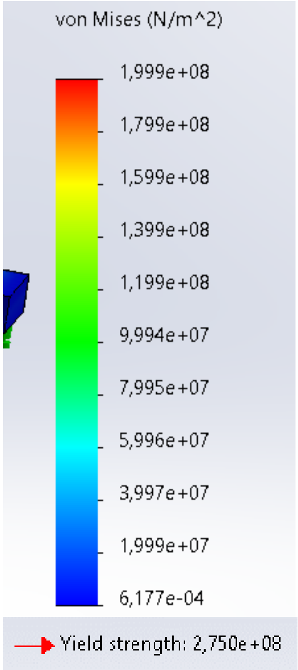


Figure 41. Scale of the stress analysis of the adapted fork tine

The result in Figure 41 is similar to the one from the workshop crane. The maximum stress level is now within the material limits. However, it is not at the intended 80% of the yield strength.

6 CONCLUSION

In this chapter the results of the TO are presented and interpreted. Furthermore, it is shown that the output of the optimizations should always be reviewed and how it should be integrated into the design and development process.

6.1 Mass reduction

Due to the adaption of the 3D models, there are four models to compare. With the set material Solidworks can calculate the mass of the 3D models. The different masses are presented in Table 2.

Table 2. Mass comparison

3D model	Mass before TO [kg]	Mass after TO [kg]	Mass reduction [%]
Workshop crane	16,7	14,6	13
Adapted workshop crane	68,1	28,6	58
Forklift fork tine	93,9	83,6	11
Adapted forklift fork tine	94,8	73	23

The adapted 3D models have a higher initial mass, but therefore a higher mass reduction compared to the original parts. The adapted forklift fork tine has after the TO a lower mass than the original part has after the TO. Furthermore, the maximum tensile strength of the adapted part is lower than the original one. It is not only lower, in fact it is lower than the yield strength of the material and the part does not deform plasticly under load.

On the other hand, the optimized adapted workshop crane is twice as heavy compared with the non-adapted one. The tensile strength of the adapted workshop crane is significantly lower than the yield strength. However, the removal of more material is not possible.

6.2 Excessive material removal

An occurring problem is, that at a certain point the software tries to remove material in locations where it is logically not possible. This can be seen in Figure 42.

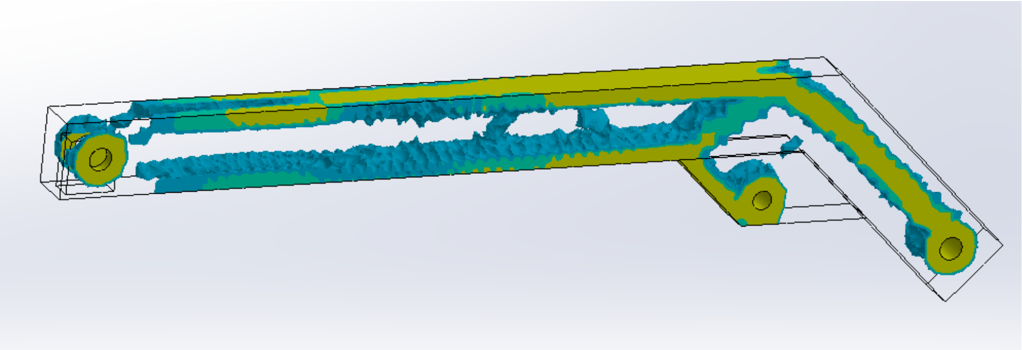


Figure 42. Excessive material removal

The end where the load is located is barely connected to the rest of the crane and even that small connection is not market yellow. This model would split up in many small parts and for sure not work when only the yellow areas remain.

6.3 Stress level comparison

The comparison of the occurring stress is due to the different results of the original models before the TO and after the TO with 100% of the mass not meaningful. The amount of stress in the adapted models is shown in Table 3.

Table 3. Comparison tensile stress (yield strength: 2,75*10^8 N/m²)

3D model	Stress before TO [N/m²]	Stress after TO [N/m²]	Stress increase [%]
Adapted workshop crane	4,815*10^7	1,758*10^8	365
Adapted forklift fork tine	1,013*10^8	1,999*10^8	197

The stress level increased on the basis of the TO in both models. Before the TO the stress level was way below the targeted yield strength. When the stress level is far below the yield strength, too much material is in use and an unnecessary amount of resources are used. Due to the removal of material, the stress in the remaining one rose.

6.4 The additive manufactured 3D models

To see if the output of the TO is manufacturable, the optimized 3D models are printed out with a FDM printer. To fit on the printing platform, the models have been scaled down approximately on a tenth of the original size. The models are shown in Figure 43.

Figure 43. AM 3D models

Due to the use of a FDM printer, supporters are necessary for a successful print. These have been partly removed from the print to give a better view on the actual shape of the parts. However, the supporters on the inside of the workshop crane are difficult to remove and show one of the constrains of FDM printing.

6.5 Integration to product design and development process

When considering the application of TO in the design and development process, it is important to know the external system constraints. The areas where the part is mounted to other parts have to be designed properly. These include holes for bolts, the contact surface for washers as well as flanges. Furthermore, it is important to set which areas of the part are necessary to have a certain shape to fulfil the function of the part. Of course, the rest of the part for which no specific function is intended needs also to be designed, but these areas do not need to be developed accurate. The optimization software will change them anyway significantly.

However, the part needs to be designed realistically. Even though, the topology optimization can redistribute the material and improve the strength of the part, it cannot work wonders. The engineer needs to have a feeling what is suitable for the demands on the part. The software can only help to optimize the already designed product and cannot design it without sufficient initial input.

When designing a part for AM the engineer has to keep the designing rules for the chosen AM method in mind. The technologies differ in some categories significantly. For example, there are more design restrictions when using a FDM printer than a SLS printer. (Hubs 2022.)

7 DISCUSSION

The topology optimization is a powerful tool to optimize parts under load. It not only reduces the amount of material used, but should also reinforce areas where high stress levels are present. The Solidworks TO only manages to remove material. Therefore, the models used for the TO need to be designed properly in critical areas and adapted manually when using this software. In order to take advantage of all the benefits of TO it is important to include it already in the design and development process. The designer needs to detect which areas are crucial for the performance and need proper design and which areas the software can handle.

With the small manual changes to the fork tine, the optimization worked well. The mass could be reduced by a few kilograms while staying within the stress limits. Due to the extremely high stress level in the workshop crane in the first place and the adaption of the whole model is a meaningful comparison to the original model not possible.

The weight reduction makes the topology optimization useful in application areas where a moving mass contributes significantly to the performance of the application. This is the case for the aerospace and automotive industries. In these industries every reduced gram of material contributes to a lower fuel consumption. Therefore, it not only lowers material manufacturing costs but also operating costs.

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LIST OF FIGURES

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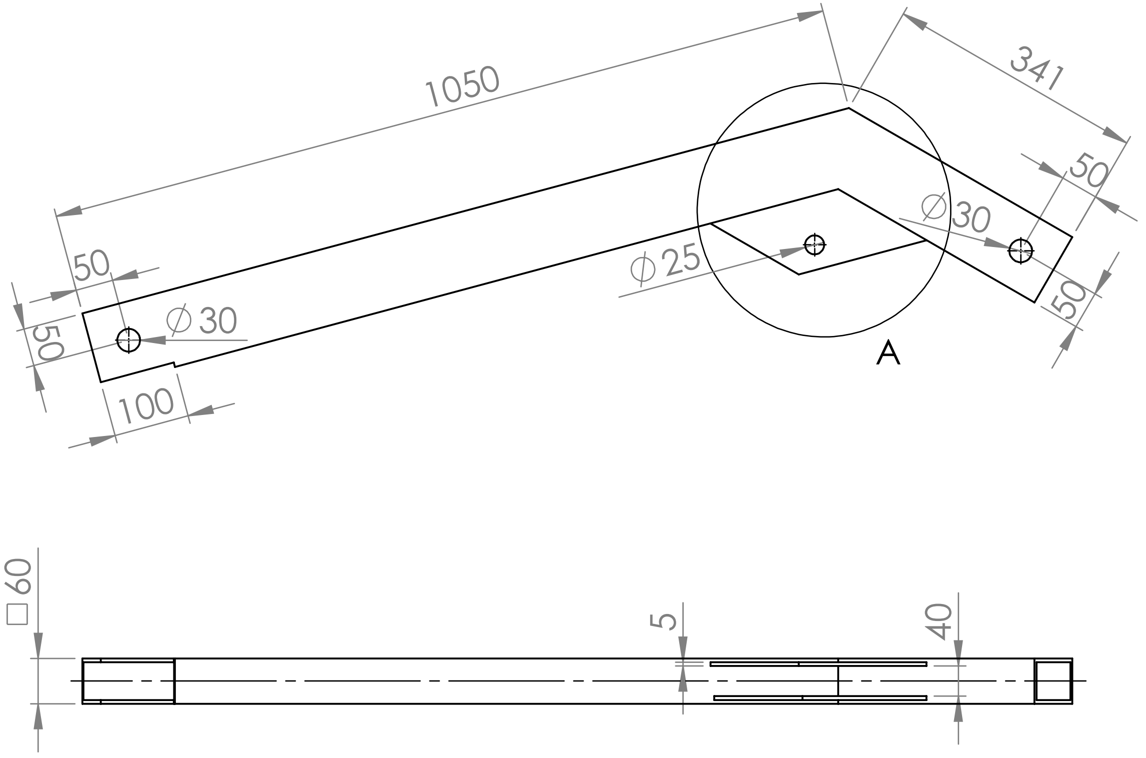
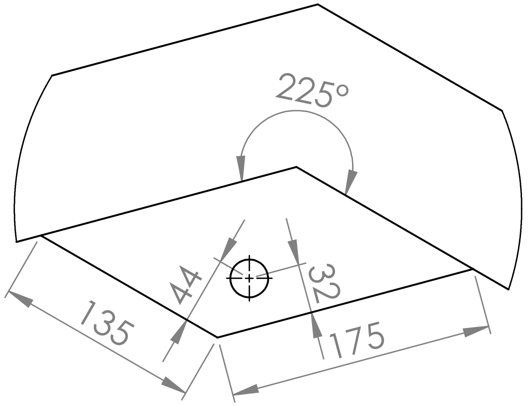
APPENDICES





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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1

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CHK'D			
APPV'D			
MFG			
Q.A			

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DWG NO.
CWe 1000

A4

WEIGHT:

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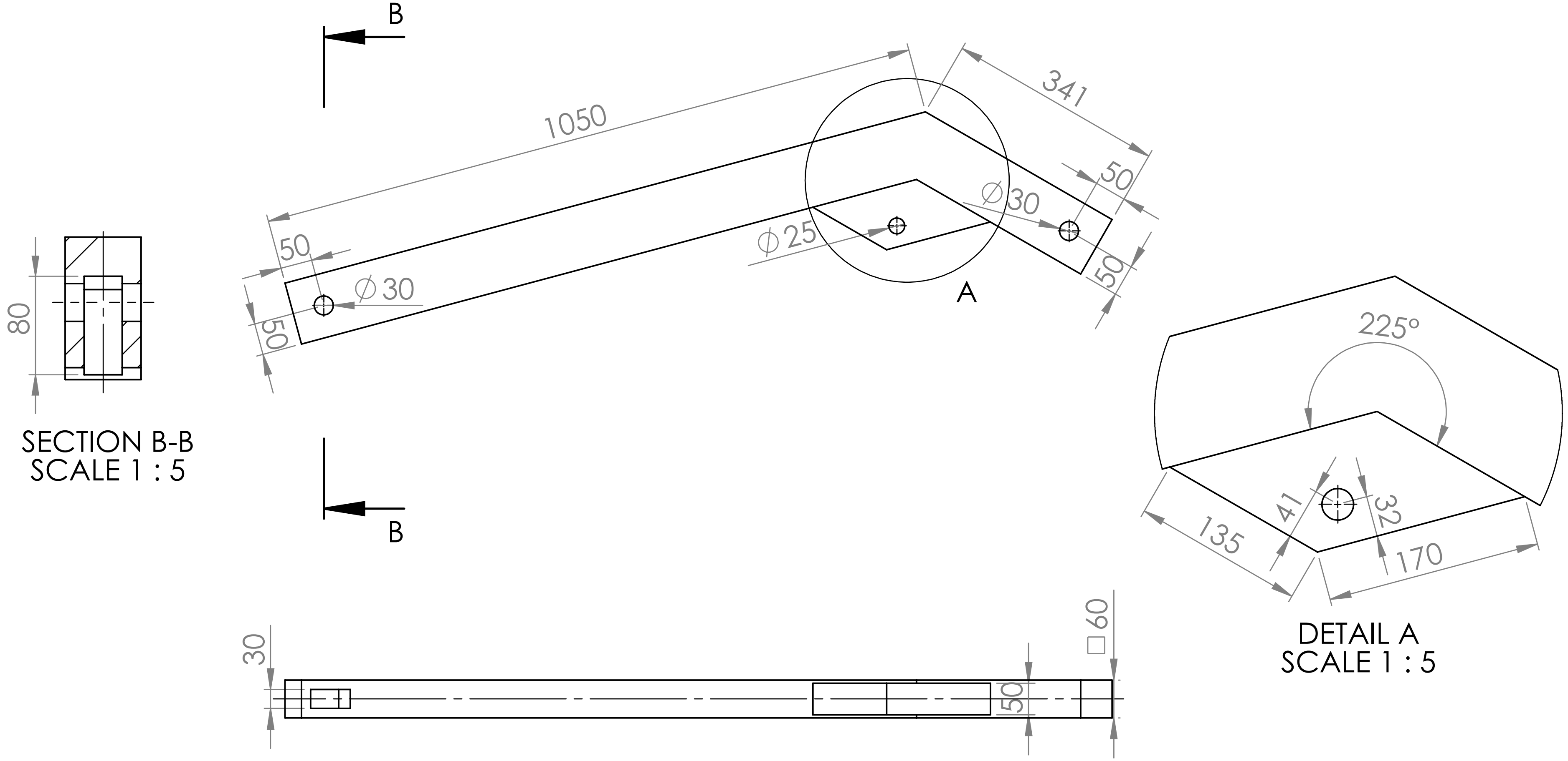
SHEET 1 OF 1



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DETAIL A
SCALE 1 : 5

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LINEAR:
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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION 1

	NAME	SIGNATURE	DATE
DRAWN	CWe		
CHK'D			
APPV'D			
MFG			
Q.A			

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Adapted
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CWe 1100

A4

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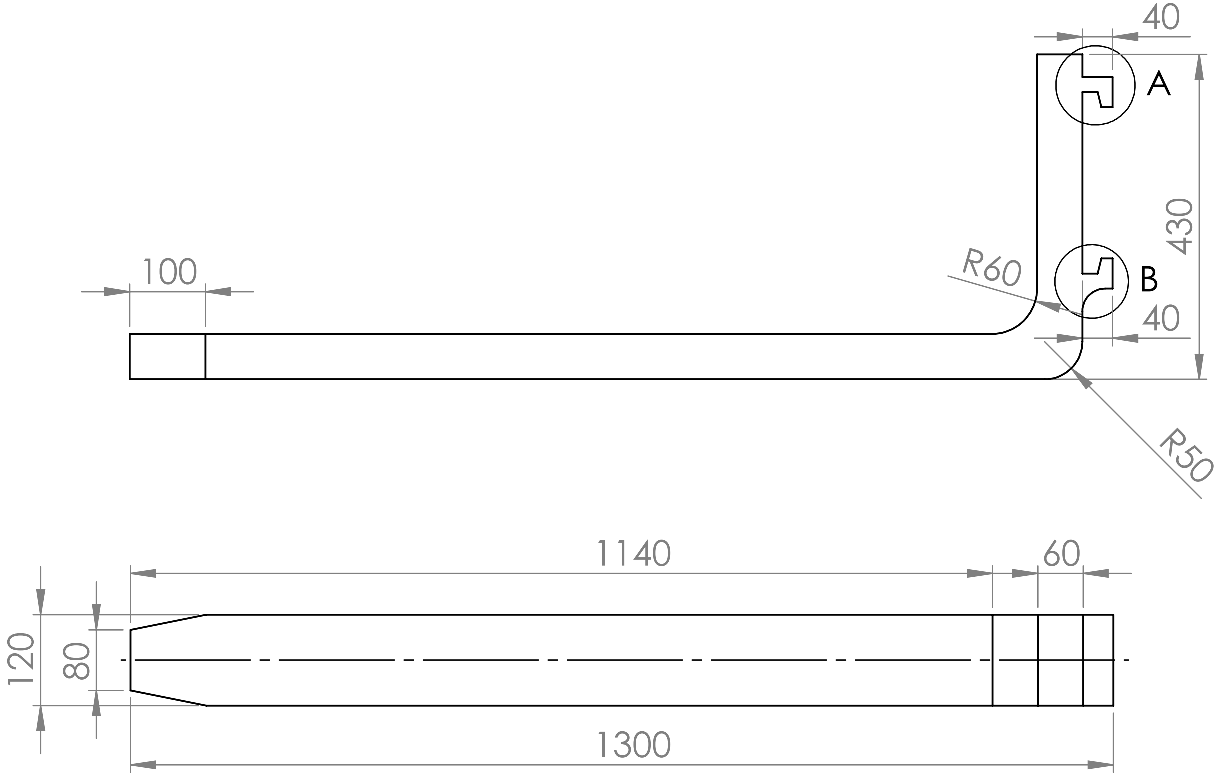

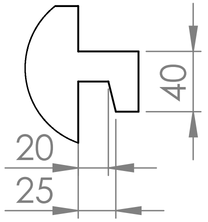

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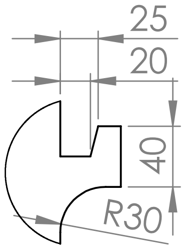

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TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1

	NAME	SIGNATURE	DATE
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CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Forklift tine

MATERIAL:

S355JR

DWG NO.

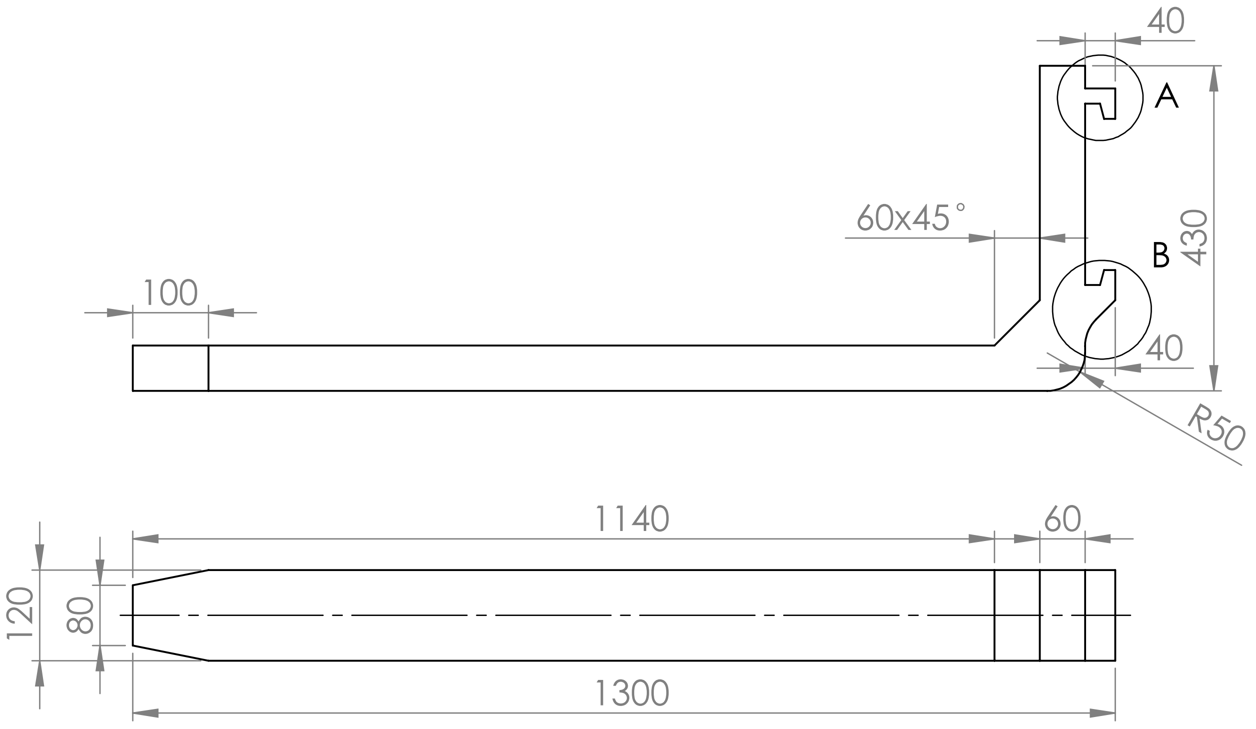
CWe 2000

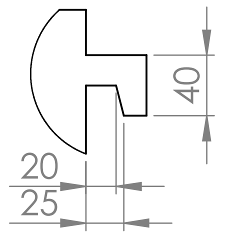
A4

WEIGHT:

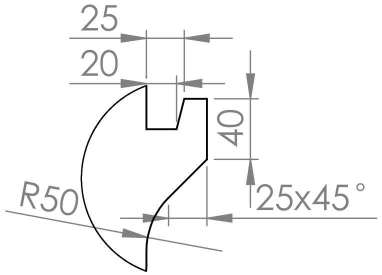
SCALE:1:10

SHEET 1 OF 1





DETAIL A
SCALE 1 : 5



DETAIL B
SCALE 1 : 5

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1	
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	CWe			Adapted forklift tine	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: S255JR	DWG NO. CWe 2100	A4
			WEIGHT:	SCALE:1:10	SHEET 1 OF 1