L.T.M. Gevers

A lightweight cart frame design created that makes use of topology optimization

TU Delft VANDERLANDE

A lightweight cart frame design created that makes use of topology optimization

By

L.T.M. Gevers

in partial fulfilment of the requirements for the degree of

Master of Science
in Mechanical Engineering

at the Delft University of Technology,
to be defended publicly on Monday November 28, 2016 at 10:00 AM.

Thesis committee:	Prof. dr. ir. J.L. Herder	TU Delft
	Ir. P.T.C. Vervoort	Vanderlande
	Prof. dr. ir. P. Breedveld	TU Delft

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface

Six years ago, I came to Delft to start my academic career. I started at Industrial Design Engineering, but unfortunately I did not find the technical challenge I was looking for. Therefore, after completing my bachelor's degree, I changed directions and decided to do a master's degree in Mechanical Engineering, which fits my interests and me much better. Therefore, I am happy with the choice I have made.

This graduation project was in collaboration with Vanderlande. I want to thank them for the opportunity they have given me and for the freedom they gave me to make it my own project. In particular, I would like to thank Peter Vervoort, my supervisor from Vanderlande, for his experienced view.

Furthermore, I would like to thank two individuals from the TU Delft; Just Herder for his supervision and Matthijs Langelaar for helping me get started with topology optimization.

L.T.M. Gevers
Delft, November 2016

Introduction

Vanderlande started in 1949 as a company specialised in material handling and logistics. Nowadays the company focuses on three different sorts of systems, baggage handling systems for airports, sorting systems for parcel and postal services and warehouse automation systems. Vanderlande is global market leader in the first and second systems.

This graduation project is about a baggage handling system. Worldwide over 600 baggage handling systems of Vanderlande are active at airports including 17 of the world's top 25 largest airports. Vanderlande provides two different types of baggage systems, the Tubtrax system and the Bagtrax system. Both systems are developed to transport baggage individually (per unit) at high speed over long distance. The Tubtrax system transports baggage in a carrier, also called a Tub, over a conveyer. The advantage of this system is that it allows for compact baggage storage that is required for early check-ins or transfers with a long transfer time. The Bagtrax system transports baggage in a cart driving over rails, like a rollercoaster. The advantage of this system is that it allows for high-speed transport with speeds up to 50 km/h that is required for transfers with a short transfer time. Especially at large airport with multiple terminals.

Vanderlande has developed a new baggage system that combines the advantages of both, the Tubtrax system and the Bagtrax system. This new system allows for compact baggage storage and transporting at high-speeds.

For the new system the cart of the Bagtrax was adapted for the new functionality, this adaption resulted in a cart that would be too heavy according to the specified requirements. Therefore, a new cart needed to be created to find a way to reduce the mass. Vanderlande has already developed four new concept but these, unfortunately, were not completely satisfying.

Topology optimization is a technique to determine the optimal material distribution with a minimal amount of material. Most commercial companies do not yet use it, because it is still a relatively new technique and companies have not yet adapted to it. However, it can create new opportunities for companies to create lightweight designs. For this graduation project, a topology optimization will be performed on the cart frame. The resulting design, called the initial design, will be used as source of inspiration to create a new lightweight cart frame design for the new system of Vanderlande.

A LIGHTWEIGHT CART FRAME DESIGN CREATED THAT MAKES USE OF TOPOLOGY OPTIMIZATION

Lotte T.M. Gevers, 2016

Abstract

Topology optimization is a bio-inspired optimization method based on the growth of bones. With this method, the optimal material distribution with the minimal amount of material for a product can be defined. This could help engineers create innovative lightweight designs and get rid of benchmark and pervious design on which current designs are commonly based. The goal of this graduation project is to show that topology optimization is useful as a source of inspiration for commercial companies to create innovative lightweight designs. Therefore, a design assignment is performed for a baggage cart frame design. The new cart frame design is based on the topology optimization in 3D. In the end, the new design is compared with four concepts designed by the company to show that the use of topology optimization resulted in a lighter and more innovative design.

1. Introduction

Nowadays, new concept designs of commercial companies are often based on benchmark designs or previous designs (Schramm, 2006). In general, this approach does not result in new innovative designs and the mass saving will be minimal. Nevertheless, it is in the interest of companies to innovate lightweight designs, in order to be energy efficient and to stay competitive.

A relatively new optimization method that can assist the engineer to create an innovative lightweight design is topology optimization. Topology optimization is a bio-inspired optimization method based on the growth of bones (Mattheck, 1990). This makes it possible to find the optimal material distribution for a product (Sigmund, 2013). However, this optimization method is not yet widely used in commercial companies.

Commercial companies do not use topology optimization as a designing tool, probably since they are not familiar with this optimization method. Another reason is that topology optimization often results in complex structures that need to be produced with additive manufacturing techniques such as 3D printing (Langelaar, 2016). The introduction of manufacturing constraints in the topology optimization process makes it possible to develop a design that can be created with a different production method. This option makes the use of topology optimization more interesting for commercial companies. To be able to apply manufacturing constraints to the optimization process, the production process needs to be defined in advance. To find the optimal design in terms of mass and costs it is better to define the production method later in the design process.

However, the use of topology optimization could be a great design tool for commercial companies wanting to create lightweight designs. Using the initial design, the design outcome of topology optimization, as a source of inspiration will help to get a better understanding of where to place the material. This allows the engineer to think more out-of-the-box. A new design can be developed whereby the focus will be on the shape, afterwards the best suitable production method can be used for the design. Topology optimization as source of inspiration could help commercial companies to break down their barriers and create new innovative lightweight designs.

The goal of this work is to show that topology optimization is useful as a source of inspiration for commercial companies to create innovative lightweight designs. Topology optimization looks very useful for this approach. To validate this statement, a design assignment is carried out, in which a new design will be created that makes use of topology optimization.

2. Method

To test whether topology optimization is useful for commercial companies, a design case will be carried out. The company for which the design case will be performed should have some concept designs to compare with the design created with topology optimization in terms of performance, shape and mass. In the design case, the goal will be to create an innovative lightweight design.

The following steps will be performed in the design case:

- Perform a topology optimization.
- Use the initial design as inspiration to create a new design.
- Translate the new design into a manufacture design.
- Compare the new design with the existing concepts.

This paper is organized as follows. In Section 3, the general idea of topology optimization is explained. In Section 4, the design case is discussed. The design process which is divided into three steps is described in Section 5. These three steps are 5.1. Topology optimization, 5.2. Design and 5.3. Manufacturable design. In Section 6, the new concept is evaluated against the requirements. The results are shown in Section 7. Section 8 discusses whether the use of topology optimization was useful for this design case. Section 9 provides the conclusion. Finally, in Section 10, the recommendations for further development of the design and for the topology optimization process are given.

3. Topology optimization

Topology optimization is inspired by the growth of bones. Bones adapt themselves to their loads, they have the ability to remove material in under loaded areas and add material in overloaded areas. By mean of topology optimization, material is removed from or added to a given design domain based on the stress level in the material. The design domain is defined as the maximum space in which the design can be shaped. The stress level in the material is analysed on the base of a finite element analysis (FEA). In this way, topology optimization allows to find the optimal material distribution in a given design domain that minimizes an objective function satisfying a number of constraints (Sigmund, 2013). The objective function is often a compliance minimization, but it can also be a minimization of the amount of material. Optimizing for a compliance minimization requires a volume constraint. Material minimization requires a constraint on the maximum compliance. The design outcome of topology optimization is known as the initial design.

To solve the optimization problem the design domain needs to be discretised into a large number of structural elements, finite elements (continuum) or nodal points (discreet). All the structural elements in the design domain are assigned to a design variable.

The design variables can be either continuous or discreet. Continuous variables can take a value between 0-1. A value of 0 means that there is no material left and a value of 1 means that there is solid material left in the initial design. A value between 0-1 indicates so-called “grey areas” where the material has not been removed, but is not completely solid anymore. Discreet design variables are binary, they can only take a value of 0 or 1. Therefore, the use of discreet variables will result in a more clear design, but will also lengthen the computing time.

The most commonly used definition for the design variables are density variables. These density variables are coupled to the Young’s modulus of a solid material. When the initial design will be used as an inspiration to create a new design, continuous variables can be an extra source of inspiration. The density variables in grey areas show elements with a lower density and Young’s modulus. This can be interpreted as different material. Therefore, these grey areas could inspire a different choice of material than the input material for the design or for a part of the design.

Topology optimization is sensitive to different load cases. A slightly different load case than the input load case can already result in failure of the design. Therefore, different load cases should be used as input for topology optimization. Different load cases can be combined to shorten the computing time, but this could result in over-dimensioned design. The load cases can also be made linear to each other. With that approach, the design will not be over-dimensioned and so the optimal design in terms of mass can be found.

Nowadays different software programs are available to perform topology optimization.

Different finite element software programs feature an extra function to perform topology optimization, for example one might think of ABAQUS and COMSOL. The advantage of using this kind of software for topology optimization is that finite element analysis can be performed without too much effort. Another option is to perform the optimization with Matlab for which Sigmund (Sigmund, 2001) has written a code base of only 99 lines. This basic code can be adapted to more complex optimization problems.

4. Design assignment

In collaboration with a commercial material handling company, a design case is defined. The design case concerns the frame of a new baggage cart that will be used in the baggage handling systems at airports. Adapting the current baggage cart to an additional function resulted in a too heavy cart. New designs created by the company are clearly based on previous designs. The four concepts of the company have broadly the same shape adapted to specific production methods, a tube frame concept, a sheet metal frame concept, a composite frame concept and an aluminium cast frame concept.

The fact that the current designs are based on previous designs makes this design case suitable to test and to see whether the use of topology optimization will result in a more innovative lightweight design.

4.1. The baggage cart

Function

The baggage transport system consists of three parts: cart, the carrier and one piece of baggage. The focus will be on the cart, the carrier will not be redesigned.

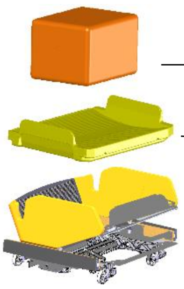

Figure 1 - Part of the baggage systems.

At the airport, a piece of baggage is coupled to a carrier. During the time at the airport, the baggage and the carrier stay together. To allow for fast baggage transport, for instance through a tunnel to another terminal, the carrier with the baggage is loaded onto a cart. A cart transports a carrier and one-piece of baggage over rails, like a roller coaster. To transport at high speed and to ensure that the carrier and the baggage remain in the cart, they are placed at an angle on the cart. In this way a V-shape is created, which allows for a stable carrier position during transport.

Operation environment

Figure 2 – Current baggage cart environment

The new cart will be used in the environment of the current baggage system (Figure 2). For the cart, this means that the wheelbase has already been defined. Besides the position of the wheels, the wheelbase determines also the position for the guiding wheels and the guiding cams. The use of the existing environment defines the propulsion for the new cart as well. This propulsion is contact-free and requires a steel plate with an aluminium cover over the whole length of the cart.

The propulsion creates two forces on the cart, a force that propels the cart and a down force. The down force can apply everywhere on the steel plate. The maximum deformation in the steel plate due to the downforce and the forces of the carrier and baggage is 0.5 mm, in order to be able to control the speed. To meet this requirement, the cart frame needs to give support to the steel plate.

The part of the cart where the carrier and baggage are placed is called the support. The deformation in the support is a maximum of 1 mm to avoid difficulties with loading/unloading of the carrier and the baggage. Therefore, the supporting part needs to be stiff enough to satisfy this requirement.

Mass

The maximum mass of the cart is 50 kg to ensure that the performance of the new cart is similar to the performance of the current cart. The maximum speed is 50 km/h and it should be possible to drive up a slope of 30 degrees (incline). This maximum mass is also required to allow two people to lift the cart off the track manually. According to the Occupational Health and Safety (OHS), one person is allowed to manually lift a maximum mass of 25 kg (CEN, 2008).

In recent years, more attention is being paid to the environment and to creating more energy efficient products (U.S. department of Energy, 2014). Therefore, a lighter baggage cart is desired. Every kilogram lighter results in a more energy efficient baggage carts. Another factor that plays an important role in the energy efficiency of the cart is the aerodynamics (A2TE, 2015).

4.2. Cart frame

The cart consists of different parts; the tilt frame, the front and rear guards, the undercarriage, the bumpers and the wheels. The focus for the new design will be on the cart frame that consists of the undercarriage with the front and rear guards. This part gives the most opportunity to change into a new innovative lightweight design. Figure 3 shows all the parts of the cart including the baggage and the carrier. The blue box shows the focus part for the design assignment

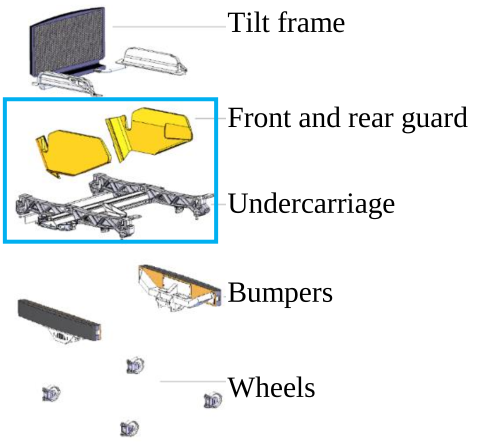

Figure 3 – Parts of the cart

The function, environment and the maximum mass results in a list of requirements for the cart frame. The most import requirements for the cart frame performance are:

Functional requirements

- Fixed position of the wheels, guiding wheels and guiding cams on the cart frame.
- Give support to the carrier and one-piece of maximum allowed baggage (50 kg).
- Ensure that the carrier and one-piece of the maximum allowed baggage (50 kg) remain in the cart during transport.

Performance requirements

- Maximum deformation in the steel plate with aluminium cover of 0.5 mm.
- Maximum deformation in the supporting part of 1 mm.
- A lifetime of 15 years. This is equal to $28 \cdot 10^6$ cycles that includes loading/unloading of the baggage, horizontal and vertical curves, diverts and merges.
- The cart should be aerodynamic.

Mass Requirement

- Maximum cart frame mass of 20 kg.

These requirements are the input for the topology optimization for the cart frame. Unfortunately, the aerodynamics cannot be taken into account in the topology optimization process.

4.3. Load cases

The cart operates in the current environment that means that the cart uses the existing rails to transport the baggage. The rails is divided into different zones for different functions, like transport and load/unloading the baggage. The zones that can be differentiated are the track zone, the divert/merge zone, the charge/discharge zone and the storage zone. The different zones result in different load cases for the cart frame.

In the track zone, the cart drives over the rails to transport the carrier and the baggage. The track zone consists of straight track parts, horizontal curves (to the left and right) with a minimum radius of 2 meters, inclines and declines with a maximum slope of 30 degrees. The cart might also make an emergency stop on the straight track.

In the divert/merge zone, one track diverts to more tracks or two tracks merge. This results in an extra centrifugal force on the cart. The carrier and the baggage are loaded or unloaded to the cart in a charge/discharge zone. In a storage zone, baggage carts are stored when they are not being used. Empty carts are stored at an angle of degrees and full carts are stored flat or at an angle of 1.5 degrees.

In the existing environment a combination of zones or combination of a decline with a horizontal curve are not possible. Therefore, a combination of load cases is excluded.

4.4. Design goal

Create a lightweight cart frame design, maximum 20 kg, which satisfies the requirements.

5. Design process

The design process was divided into three steps, the topology optimization, the translation into a new design and the translation into a manufacturable design.

5.1. Topology optimization

The topology optimization will be performed in COMSOL, which features a built-in optimization tool. First, the objective function, constraints, the design domain, the design variables and the load cases need to be defined based on the requirements to perform the topology optimization.

The input material for the topology optimization is aluminium, the current cart is also made of aluminium. Aluminium is a relatively cheap, light and stiff material and therefore the optimization will start with this material.

Objective and constraints

For the cart frame design, the objective function is to minimize the amount of material. In this way, the minimum mass of the cart frame can be established. The objective function consist of two parts. The first part is the minimization objective function that minimizes the amount of material, $\frac{\int_\Omega \rho_i(x)d\Omega}{V_d}$, and the second part is the regularization objective function that ensures that the solution is independent of the mesh, $\frac{{h_{max}}^2}{V_d} \cdot \int_\Omega |\nabla\rho_i(x)|d\Omega$. This results in the following objective function:

$$\min_x \; (1-q)\cdot\frac{\int_\Omega \rho_i(x)\,d\Omega}{V_d} + q\cdot\frac{{h_{max}}^2}{V_d}\cdot\int_\Omega |\nabla\rho_i(x)|d\Omega \qquad (1)$$

Here $\int_\Omega \rho_i(x)\,d\Omega$ is the volume of the initial design, V_d is the volume of the complete solid design domain and h_{max} is the maximum mesh size. A regularization factor q is added to the function to create a balance between the two parts of the objective functions.

The objective function is subject to three constrains to satisfy the requirements for the cart frame. The first constraint ensures that the deformation in the steel plate with the aluminium cover is not more than 0.5 mm. This constraint is defined as:

$$-v_{max} \le v \le v_{max} \qquad (2)$$

Here v is the deformation in the initial design and v_{max} is the maximum deformation of 0.5mm.

The second constraint concerns the lifetime of the cart frame. The cart frame should have a lifetime of 15 years. Factors that determine the lifetime of a product are the maximum fatigue stress, wear and corrosion. For the cart frame, wear plays no part. The corrosion of the frame depends on the choice of material and post processing. The most important factor for lifetime of the cart frame is the fatigue stress at 28 million cycles. Therefore, the maximum stress needs to be lower than the fatigue stress level. For aluminium, this results in a maximum stress level of 65 MPa (CES, 2016). The constraint on the maximum fatigue stress can be written as:

$$\frac{\int_\Omega \sigma_{vonmises}(x)d\Omega}{\sigma_{fatigue}} \le 1 \qquad (3)$$

Here $\int_\Omega \sigma_{vonmises}(x)\,d\Omega$ is the von-misses stress in the initial design and $\sigma_{fatigue}$ is the maximum allowed stress at $28\cdot10^6$ cycles. When the stress in the design is lower than the maximum fatigue stress level, the stress is also below the yield strength, which means that no plastic deformation will occur.

The third constraint affects the strain energy. Strain energy is the energy stored in the material undergoing a deformation, which is a way of expressing the compliance. The maximum allowed strain energy defines the stiffness in the design. The maximum allowed strain energy, $W_{s_{max}}$, depends on the load case.

$$W_{s_{max}} = \frac{1}{2}\cdot F\cdot u_{max} \qquad (4)$$

Here F is the applied force and u_{max} the maximum allowed deformation.

The strain energy constrained will ensure that the deformation in the supporting part is a maximum of 1 mm in every load. The strain energy constraint can be written as:

$$\frac{\int_{\Omega} W_s(x) d\Omega}{W_{s_{max}}} \leq 1 \quad (5)$$

Here $\int_{\Omega} W_s(x)\, d\Omega$ is the strain energy in the design after the optimization. No other constraints are needed for the stiffness of the cart frame or the maximum deformation in the support when using a constraint on the maximum strain energy.

Design domain (Ω)
The design domain is defined by the maximum design envelop for the cart frame with the V-shape cut out for the carrier and the baggage. At the left side of the cart frame, an open space is required to allow for loading/unloading the baggage. In the design domain the front and rear guard are integrated, which ensure that the carrier and the baggage remain in the cart during transport, as two solid rectangular walls. The design domain is divided into a large number of finite elements, a continuum design domain.

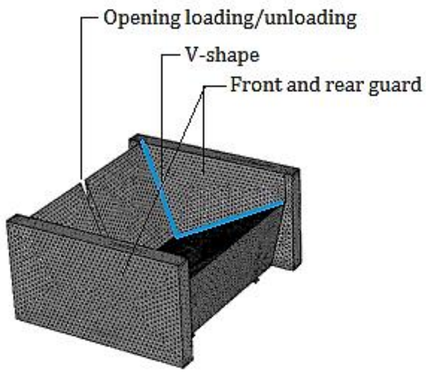

Figure 4 – Design domain

The steel plate with aluminium cover for the propulsion is integrated in the design domain. The stiffness of the steel plate can be used in the design. In the topology optimization, the steel plate with the aluminium cover is defined as solid and no material can be removed from or added to it.

Design variables (ρ_i)
The design variables will be continuous density variables. The computing time with continuous design variables is shorter than with discreet variables. Since the initial design will be used as source of inspiration to create a new design, the grey areas that arise using continuous variables could be an extra inspiration to apply a different material than aluminium.

Load cases
The cart frame has different load cases due to the different functional zones. Two different load cases, for instance a horizontal curve and a decline, do not occur at the same time. Therefore, the input of the load cases is linear to ensure the design will not be over dimensioned.

The fixed points in all load cases are defined by the position of the wheels. The forces of the carrier and the baggage are divided into two forces on the two planes of the V-shape as showed in the intersection of the design domain in Figure 5. In some load cases, a force on the front or rear applies as well.

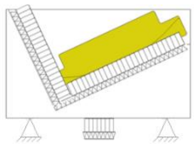

Figure 5 – The two main forces and fixed points

Initial design
First, the topology optimization was performed in 2D, side view and front view, in this way the critical load cases were determined. For the 3D topology optimization, only the five most critical load cases where used to shorten the computing time. The number of load cases could be reduced because the main difference between the load cases is the amount of force that is applied. By taking the most critical load cases into account, it is ensured that the maximum forces apply on all the possible planes.

The initial design of the 3D topology optimization is showed in Figure 6 and 7. The black areas have a value of 1, solid material. All elements with a value of 0 are removed from the design domain for a more clear view.

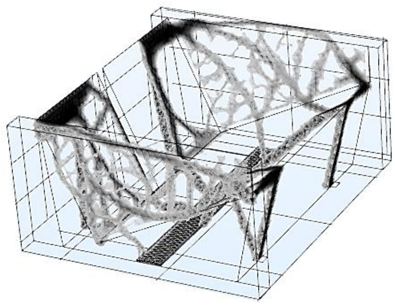

Figure 6 - Initial design 3D

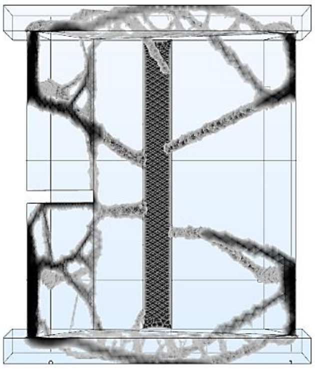

Figure 7 - Initial design, top view

The solid fraction of the initial design, the percentage of the remaining amount of material of the solid design domain, $\frac{\int_{\Omega}\rho_i(x)d\Omega}{V_d}$, is 0.010 (1.0 %). For the initial design, this results into a mass of 12.2 kg.

Note that, performing the topology optimization with different input material results in the same material distribution in the design domain, only the density of the material changes depending on the young's modulus of the material.

5.2. Design

Inspired on the initial design domain a new design for the cart frame is created. The translation of the cart frame can be differentiated into two parts; 1. The basic shape and 2. The front with bumper. The new design first consist of sheet materials instead tubes. Sheets material allows for less different parts. In addition, it is easier to translate a sheet concept into a tube concept than vice versa.

Basic shape

The basic shape can be divided into four different parts to get a better understanding how the cart frame is developed from the initial design. Differentiated are the ground shape, the middle beams, the front and rear guard and the additional ribs.

Ground shape

The top-view of the initial design shows similarities with a sort of X-profile, the current cart design has an I-profile as ground shape. Changing the ground shape into an X-profile has some great advantages for the design. Frist, an X-profile creates more stiffness in the middle of the steel plate where the deformation is the largest due to the down force. Another advantage is that with an X-profile the movement of the four wheels is less depended on each other than with an I-profile. Therefore, a frame with an X-profile as ground shape can better compensate for imperfections in the track.

In the initial design, the legs of the X-profile are ripped apart as the third profile of Figure 8. With as results that the support for the steel plate with aluminium cover is better divided over its full length. In this way the down force of the propulsion, which is applied everywhere on the steel plate, can be better captured and the deformation will be minimal.

In the initial design, the connections on the steel plate are not symmetrical. In the new design, the connections will be at the same position for ease of manufacturing.

One last modification is made for the X-profile of the ground shape. In the initial design, the legs of the X-profile are bended shapes. The disadvantage of this shape is that local stress can occur in the edges. To avoid these local stresses, the legs of the X-profile are curved in the ground shape.

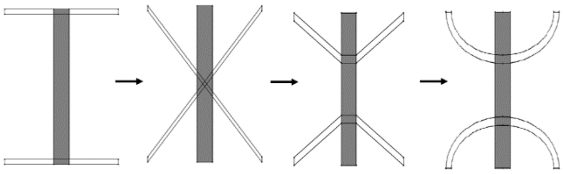

Figure 8 – Development of the ground shape

The development of the ground shape profile is showed in Figure 8. Figure 9, shows the result for the ground shape for the cart frame design.

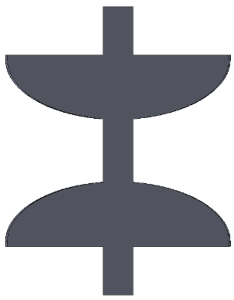

Figure 9 - Ground shape

Middle beams

The middle beams are extrusion of the legs of the X-profile from the ground shape and have as function to support the carrier and the baggage. Therefore, the middle beams are V-shaped. The curved shape arising from the ground shape creates stiffness in the middle beams (Figure 10.A).

In the initial design, the material is placed at the top of the V-shape. This inspired us to apply extra material on top of the extruded middle beams for the basic shape. The extra material on top increases the distance of the outermost fibre that results in an increase of the moment of inertia. An increase of the moment of inertia provides more stiffness in the middle beams.

The additional stiffness that is created with the material on top of the middle beams allows to apply holes in the middle beams. To achieve maximum stiffness with the maximum mass saving it is best to apply many small holes in the middle beams with honeycomb or round shape. (Figure 10.B)

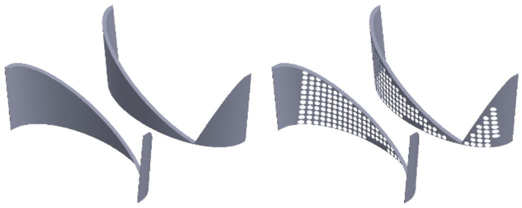

Figure 10 - Middle beams; A. closed, B.. with holes

Front and rear guard

The initial design shows material with a lower density at the front and rear of the design domain. This lower density material has the shape of beams which from together a sort of shell. From nature is known that shell structures have a high load capacity compared to the material input through their bended shape. Based on this and the inspiration for the initial design, the front and rear guard will become shell structures (Figure 11).

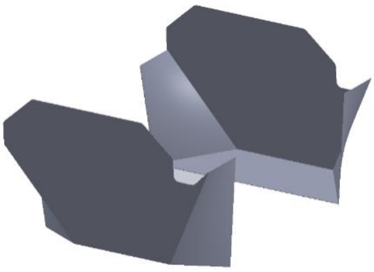

Figure 11 - Front and rear guard

The front and rear wall obtain their stiffness by their shell structure. This stiffness is required for the load of the carrier and the baggage on the front and rear at decline and inline in the rails during transport. The shells also ensure that the carrier and the baggage remain in the cart during transport.

In terms of aerodynamics, the shells create an advantage as well. The shell structures guide the air sideward and below the cart frame with as result less air friction for the cart (A2TE, 2016).

Integration of the shell shapes with the middle beams will create two closed shapes (front and rear). With closed shapes, more stiffness will be obtained according to basic mechanic rules, which explain that a closed shape is more stiff than an open shape. (Hibbeler, 2011).

Ribs

To improve the stiffness of a structure, ribs can be added to the design, as in Figure 12. Ribs allow for adding material where the design needs extra stiffness instead of increasing the complete material input. Ribs give the possibility to apply extra stiffness in a desired direction, but therefore the orientation of the ribs is important. This makes ribs suitable as application to create extra stiffness in lightweight designs.

In the initial design, material is present at the tip of the V-shape over the complete length of the cart frame. This is the point where the middle beams are thinnest. To ensure that the stress at this point will not be too high a rib will be added along the complete length of the cart frame. The rib will distribute the forces of the carrier and the baggage that apply at the V-tip over the full length of the cart.

Around the steel plate with aluminium cover, extra material is presented in the initial design. This indicates that the stiffness of the steel plate with aluminium cover itself is not enough to ensure that the deformation of the plate does not exceed 0.5 mm. To create enough stiffness two ribs will be added to the basic shape over the complete length of the cart frame. These ribs will be integrated with the aluminium cover. That results in a U-shape aluminium cover around the steel plate.

To complete the basis shape, the front and rear guard will be connected to create an integrated design. At the left and right side, aluminium sheets material will be used to connect the front and the back. On one side of the cart free space is needed to allow for loading/unloading of the carrier and baggage, therefore the sheet is places low on the cart frame. The completed basic shape of the cart frame design is showed in Figure 12.

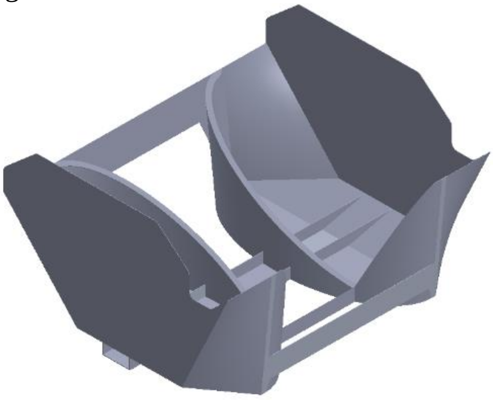

Figure 12 - Basic shape

Front with bumper
Developing the cart frame design based on the initial design, resulted into a design optimization to integrate the bumper and bumper suspension in the front and rear guard. In the initial design, the shape of the front and rear form a closed shell. This shell shape gives the opportunity to integrate the bumper suspension. Therefore, the front will be further developed for the aerodynamics of the cart and the integration of the bumper.

Front shape
A spherical front shape should results in the best aerodynamically performance for the cart (A2TE, 2016). The maximum length of the cart determines the size of the bulging on the front. Making the back more flat allows for a larger bulge at the front without increasing the cart length. This gives the cart frame the shape of a bullet.

The bumper
Integration of the bumper with the front allows for better aerodynamic performance of the cart than a separate bumper. A separate bumper will results in a larger frontal area and a less aerodynamic shape. For the aerodynamics, the shape is the most important factor (A2TE, 2016). Integration of the bumper allows also for combining the bumper suspension with the reinforcement. The reinforcement of the front and rear in the basic shape is required to create enough stiffness to absorb the force of the carrier and the baggage on the front and rear guard.

Bumper size
Before the bumper can be designed the width of the bumper and on which height the bumper should be placed need to be defined. The width of the bumper is determined by the horizontal curve with the smallest radius in the track. The height of the bumper is determined by the height of the centre of mass of a cart with carrier and one-piece of maximum allowed baggage.

The smallest radius of a horizontal curve is 2 meters. In a horizontal curve, the corners of the cart frame are not allowed to hit each other. In this way the minimum width of the bumper is defined

The height of the bumper on the cart is at least the height of the centre of the mass of cart with carrier and one piece of maximum allowed baggage to provide the cart from overturning by a bump. A full loaded cart has the highest centre of mass, in this situation the most mass is placed on top. However, the centre of mass for the new cart frame cannot be determined, since the cart design is not finalized. Therefore, the position of the centre of mass of the existing cart is used.

Bumper shape
The shape of the bumper will be in line with the shape of the front, which suits aerodynamics. This means that no parts can be extend from the front. For that reason, the shape of the bumper cannot be a rectangular block. A possible shape for the bumper will be a boomerang shape. A boomerang shape gives also the possibility to shape the bumper in line with the carrier. Shaping the bumper in line with the carrier gives the advantage that the stiffness of the carrier can be used to absorb bumping forces. When the bump force applies at the stiffest, strongest place the deformation and the stress in the cart frame will be minimal. Therefore, the shape of the bumper becomes a boomerang that is in line with the front and parallel with the carrier (Figure 13).

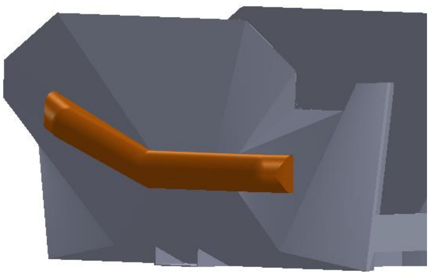

Figure 13 - Front with bumper

Bumper suspension

As suspension for the bumper, the bulging front shape can be made from aluminium to allow for this function. An aluminium front creates extra stiffness, but results in a higher cart frame mass. Applying ribs at the front guard creates extra stiffness as well. At the same time, these ribs can be used as bumper suspension. Applying ribs makes it unnecessary to make the front shape out of aluminium to obtain enough stiffness. The use of ribs instead of an aluminium front creates a lighter front. However, removing the spherical shape is not possible for the aerodynamics of the cart, but the front can be made of plastic to be light weighted.

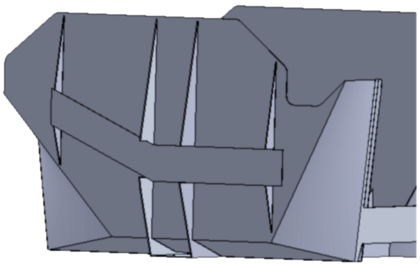

Figure 14 - Ribs for bumper suspension and stiffness

5.3. Manufacturable design

To create a manufacturable design, it should first be decided if aluminium or a different material is used. Thereafter the production method can be defined.

Material

For the cart frame, there are two different sorts of materials suitable for this design. The first option is aluminium, which has a relatively low density compared to other metals. The other option is to use a composite material. Composite materials consist of two or more different components, materials or structures, combined in one structural unit that allows for creating a new material with a low density and high stiffness (Callister, 2007). The disadvantage of composite materials is the cost price of the materials and the corresponding production method. Compared to composite materials, the cost price of aluminium is low.

For example, an aluminium cart frame design without holes, excluding the front and bumper, has a mass of 18.2kg. The same design in composite has a mass of 13.5 kg. The introduction of the composite material has resulted in a mass reduction of 5 kg. However, a composite cart frame will be four times more expensive than an aluminium cart frame in terms of material cost (CES, 2016). The production cost for a composite cart frame will be higher as well.

Composite has a low maximum fatigue stress level compared to aluminium. A lifetime of 15 years is required for the cart frame, to ensure that a composite cart frame complies to this requirement extra material is required to reduce local stresses, with a result that the mass reduction is less than 5 kg for a composite design.

According to the requirements, the maximum mass for the cart frame is 20 kg. An aluminium cart frame conforms to this requirement and has relatively low material costs. The maximum fatigue stress level for aluminium is high enough to prevent extreme changes in the current design. Therefore, the cart frame will be produced in aluminium.

Production method

It is best to keep the cart frame closed to improve the aerodynamics. Therefore, it is desirable to make the cart frame of aluminium sheets instead of tubes. A production method that is suitable for a cart frame made of aluminium sheets is rubber pad forming. Rubber pad forming is a variant of deep drawing and operates with one mould, called the form block. The sheet metal is pressed between the form block and a rubber block. The rubber block is locked in a press box to achieve the maximum force (van de Put, 2011). Compared to the traditional deep drawing process the mould costs by rubber pad forming are low. This makes this production process suitable for small series. The drawback of this production method is that the maximum sheet thickness is 3mm and that it is hard to obtain sharp details. These restrictions should have no negative effects for the cart frame.

To manufacture the cart frame with rubber pad forming the design needs to be divided into different parts. Four different parts are differentiated which will be produced with rubber pad forming, the front and rear guard (shells) and the two middle beams. The remaining parts to complete the design are flat metal sheets and do not need to be produced with rubber pad forming. In Figure 15, the different parts of the cart frame for production are showed. The cart frame will be welded together.

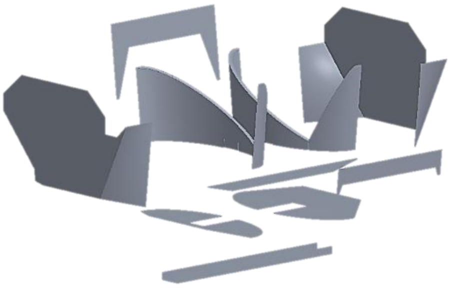

Figure 15 - Different parts for production

Wall thickness
A finite element analysis of the most critical load cases is performed to determine the minimal required wall thickness for the cart frame. The deformation of middle beams is allowed to be maximum 1 mm, and the maximum deformation of the bottom is 0.5 mm. The maximum stress should be lower than the maximum fatigue stress. With a wall thickness of 2 mm, the cart frame design is sufficient for the maximum deformation and stress.

6. Proof of the concept

The new cart design will be evaluated against the given requirements: performance requirements and mass requirement. Stress and deformation from the critical load cases are part of the performance requirements. The weight reduction for the cart with integrated bumpers are reviewed as a total mass. The cart frame design with holes applied in the middle beams will be used for the evaluation.

6.1 Cart performance

The evaluation of the cart performance is done with the finite element method. The steel plate with aluminium cover for the propulsion is applied to the design. The steel plate gives additional stiffness to the bottom of the frame. The solid works model is evaluated for the most critical load cases (decline, inline, divert/merge to the left, divert/merge to the right and an emergency stop).

Stress
At an emergency stop, the carrier and the baggage shift to the front and create an impact force on the front. The impact force is high due to the short stopping time that results in a high deceleration of the carrier and the baggage. This impact force will results in deformations in the front and high stresses in the cart frame design. The high value of the impact force causes the highest stress in the cart of all different load cases. Figure 16 shows the areas where the stress is higher than fatigue stress level (65 MPa). These areas are small, by curving the edges these local stresses in these areas will probably disappear. However, an emergency stop is not a situation that often occurs during the lifetime of the cart frame. Therefore, the stress can be slightly higher than the maximum fatigue stress level as long the stress is lower than the yield strength (180 MPa). Still, the maximum stress in the cart frame at an emergency stop is lower than the maximum yield strength.

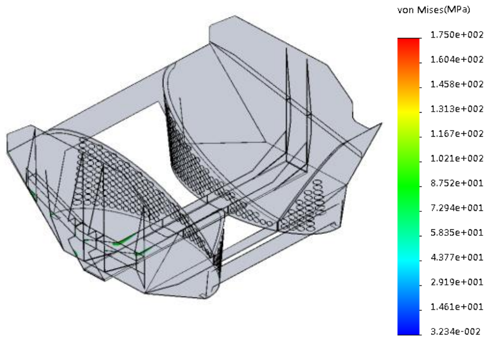

Figure 16 – Stresses higher than 65 MPa by a stop

Deformation
Divert/merge is the most critical load case in terms of deformation. By diverting or merging, a centrifugal force applies on the carrier and the baggage that result in a reaction force on the middle beams. In a diversion or a merge to the left, the deformation in the middle beams and the bottom becomes maximal. Figure 17 shows that the deformation in the middle beams is smaller than 1 mm (left) and that the deformation in the bottom smaller than 0.5 mm (right) for the new cart frame design. The coloured parts indicate a higher deformation than 1 mm or 0.5 mm.

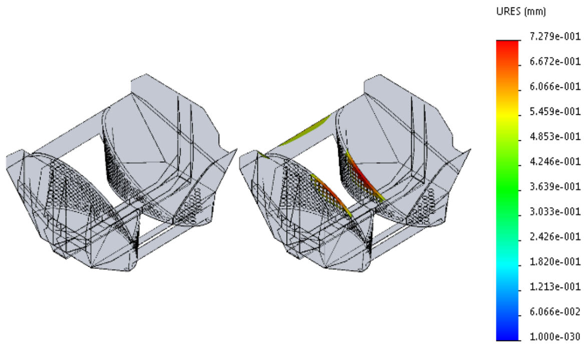

Figure 17 - Deformation, a. ≥ 1 mm, b. ≥0.5 mm

Bumping
When two carts bump, a high impact force applies on the bumper and directly disappears with as result that the carrier and the baggage shift to the front and create a force on the front guard. In solid works, it is not possible to model these impact forces on the cart frame correctly. The carrier, which should create extra stiffness during bumping, cannot be added to the cart frame for the evaluation. Therefore the maximum bump force is modelled as a constant force on the bumper, which is more critical, to evaluate the bump performance of the cart frame. Figure 18 shows where the stress is higher than 65 MPa in the cart frame design in a bumping situation. The stress in some parts is higher than the fatigue stress level. However, the stress is not higher that the yield strength (180 MPa). A bumping situation will occur just a couple of times in the lifetime of the cart frame, and is an exceptional situation. Therefore, the higher stresses are not a problem as long as they are lower than the yield strength.

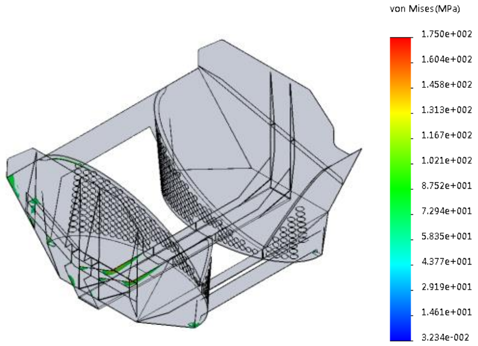

Figure 18 - Stress higher than 65 MPa by bumping

Figure 19 shows the deformation in the cart frame bigger than 0.5 mm under a constant bumping force. The deformation in the steel plate becomes higher than 0.5 mm, but this will be for a short time, and should have not much influence on the speed control. When the carrier in placed on the cart frame this deformation will be smaller.

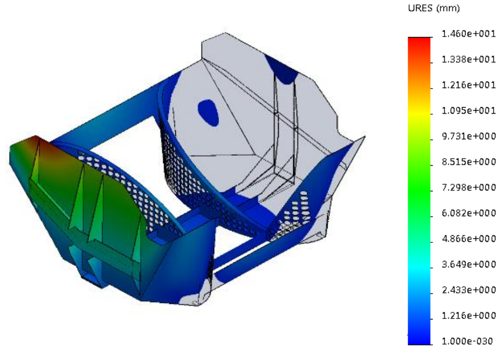

Figure 19 – Deformation ≥ 0.5 mm by bumping

7. Mass

The mass of the solid works cart frame model with holes applied in the middle beams is 17.2 kg. Without applying holes in the middle beams, the mass of the cart frame is 18.2 kg. This satisfies the mass requirement of 20 kg for the cart frame.

In the new design, the bumpers are redesigned as well. The bumpers including the bumper suspension and the plastic cover have a mass of 4.5 kg.

8. Results

Design
The initial design of the topology optimization is translated into the lightweight cart frame design showed in Figure 20. This design still allows for adjustments that will make the design even lighter.

Figure 20 – Cart frame design

8.1. Cart frame performance

The results of the cart frame performance are differentiated into the stress results and the deformation results.

Stress
Table 1 shows the maximum stress of the five most critical load cases. Here only the stress in an emergency stop becomes higher than the fatigue stress, but an emergency stop is an exceptional situation and is allowed up to the yield strength (180 MPa)

Load case	*Maximum stress*
Decline	21 MPa
Incline	52 MPa
Divert/merge left	23 MPa
Divert/merge right	28 MPa
Emergency stop	122 MPa

Table 1 - Maximum stress in critical load cases

Deformation

The maximal deformation in the middle beams and in the bottom in the critical load cases are showed in table 2. In all load cases, the deformation is smaller than the maximum deformation, even in an emergency stop.

Load case	*Deformation middle beams*	*Deformation bottom*
Decline	0.603 mm	0.318 mm
Incline	0.549 mm	0.320 mm
Divert/merge left	0.727 mm	0.434 mm
Divert/merge right	0.486 mm	0.238 mm
Emergency stop	0.710 mm	0.357 mm

Table 2 - Maximum deformation in critical load cases

8.2. Mass reduction

Cart frame

The concept described in this paper and the four company concepts all have a significant mass reduction compared to the reference model. In table 3, the mass reduction of all concepts compared with the reference model are listed. The new concept with holes in the middle beams is considered in this comparison. The cart frame of the reference model has a mass of 28.3 kg.

Concept	*Mass*	*Reduction*
Reference model	28.3 kg	
Tube	23.5 kg	17 %
Sheet metal	21.6 kg	23.7 %
Composite	21.6 kg	23.7 %
Aluminium casted	24.6 kg	13.1 %
Topology frame	17.2 kg	39.2 %

Table 3–Mass reduction compared to the reference model

The mass of the four company concepts is higher than the concept created with topology optimization. Table 4 shows the mass reduction in percent of the new concept created with topology optimization compared to the company concept3.

Company concepts	*Reduction*
Tube	26.8 %
Sheet metal	20.4 %
Composite	20.4 %
Aluminium casted	30.1 %

Table 4 - Mass reduction compared to company concepts

Bumpers

The bumpers of the four company concepts are redesigned as well. These bumper designs do not result in additional stiffness for the cart frame. In the reference model, the mass of the bumpers was 9.5 kg including the bumper suspension. The mass of the bumpers with suspension for the four company concepts is 4.5 kg. The mass of the bumper with suspension and plastic cover is equal to the four company concepts, 4.5 kg. Integration of the bumpers in the cart frame has no advantage in terms of mass. However, the integrated bumpers in the new design allow for extra stiffness at the front and the plastic cover result in better aerodynamic performance compared to the reference model.

Baggage cart

The total mass of the complete cart becomes 51.4 kg, based on the redesigned cart frame and bumpers. However, the new cart frame allows for more mass reduction in the other parts, which is required to satisfy the mass requirement of the complete cart (50 kg). Looking at the mass saving in other parts from the four company concepts, like the wheels and the tilt frame, the new cart mass can be further reduced to at least 45.9 kg.

9. Discussion

First of all, the mass of the new cart is lower than the mass of the four company concepts and the reference model of the company. The introduction of the new shape allowed for this mass reduction. The use of the topology optimization was a good method to design the new shape of the cart. The four company concepts show how difficult it is to create a concept that has a completely new shape. The new concept shows that a different source of inspiration makes it possible to create a new innovative design.

9.1. Cart frame

The results of the performance of the cart frame show that all the requirements are satisfied including a margin of safety. However, at some edges, the stress is too high due to direct transition between two sheets. Avoid these direction transitions in the manufacturable design and these stresses will not occur. In the manufacturable design, all edges need to be curved, since it is almost impossible to produce 90-degree edges with rubber pad forming.

The evaluation of the cart frame design is performed in the solid works model, which is not completely similar to the real life product.

The solid works model is made of one part aluminium, in real this will be different parts welded together. Therefore, production inaccuracies are not taken into account by the evaluation of the design. In the weld connections, the stress will be slightly higher. Since the effects of the production method are not included in the solid works model, it is important that there is some margin on the maximum stresses and deformation in the cart frame design. Fortunately, this is the case for the solid works model.

9.2. Topology optimization

The use of topology optimization to create a new design has some advantages and disadvantages for the design process.

One of the advantages of using the initial design of topology optimization as inspiration to create a new design is that it helps to be more innovative. Different tools are already used to help engineers to create innovative designs, but these are not always successful. The use of the topology optimization helps to get rid of the blockades of the benchmark designs and previous designs by using the initial design as inspiration. In the performed design case, this became very clear. The concepts created by the company were all based on the previous cart design adapted for the new function, translated in different designs suitable for different production methods. The shape of the new design is completely different from the other four concepts, previous designs and benchmark designs. Therefore, the new design can be seen as innovative.

Before performing the topology optimization it is important to have a critical view on the different load cases. Therefore, the engineer is forced to review the load cases and the planes/points where the forces apply on, which are not always optimal. Reviewing this can let the engineer change the place where the force applies if possible. For example by the cart frame, the support for the carrier and the baggage was positioned at the outside of the cart (front and back). This requires a greater support than when the support points were placed above the wheels. Topology optimization pointed out that is better to place the supporting points directly above the wheels. Therefore, in the new cart frame design they are positioned there.

Creating a design inspired on the topology optimization without defining the production method in advance resulted in more design freedom. In this way, the design process was about creating the optimal shape. The extra freedom that was created by getting rid of manufacturing constraints helped to think more out-of-the-box.

The topology optimization inspired for a completely different design that even lead to integrate other functions in the cart frame design. The integration of the bumpers and bumper suspension resulted in a higher mass reduction. This shows the impact of the inspiration of the topology optimization. It helps the engineer to create an open view on the design.

However, the use of topology optimization has some drawbacks as well. The biggest disadvantage, especially for commercial companies, is that the design process becomes more time consuming. First all load cases need to be analysed to perform the topology optimization. Than the topology optimization will be performed. This are two extra steps before the “real” design process begins. The time needed for the design process remains the same. Therefore, the total time of the process will be longer.

Another disadvantage is the computer memory available in the commercial company. The cart frame is a relatively large product that results in a design domain consisting of a very large number of elements. The more elements the more computer memory is required to solve the optimization problem. A way to reduce the amount of elements is to increase the mesh size. For the optimization of the cart frame this resulted in a relatively large element size ($h_{max} = 50$ mm) for the mesh, otherwise the computer ran out of memory. This resulted in many grey areas in the initial design. Whit a smaller mesh size, one grey element can be divided into a white and black element. However, the initial design was meant to be a source of inspiration and to that end it was still useful.

Topology optimization is sensitive for different load cases. Therefore, the choice of defining the forces as distributed loads or point loads has big influence on the initial design. A small mistake in a load case can already result in a useless initial design.

The aerodynamics of the cart is important for the performance of the cart, but could not be used as input for the topology optimization, which is a limitation of this approach. Thus, constant attention needs to be paid to the aerodynamics during the translation into a new design. In the design process, this was done on basic knowledge. Therefore, the design still need to be evaluated for the aerodynamics and probably some changes need to be made.

10. Conclusion

The mass of the new cart frame is below the 20 kg and satisfies the requirements. That means that the design goal is achieved. The use of topology optimization resulted in a more innovative shape for the cart design with a significant mass reduction compared to the four concepts of the company. The use of topology optimization helped to indicate where material should be placed and to get rid of blockades of the benchmark designs and previous designs. Not defining the production process in advance gave more design freedom and resulted in a design process that is optimal for the shape. The disadvantage of the use of topology optimization is a more time-consuming design process. However, without the inspiration of the topology optimization the same result would not be achieved. Therefore, it can be concluded that topology optimization is useful as a source of inspiration for commercial companies to create innovative lightweight designs.

11. Recommendations

For further optimization of the cart frame design recommendations are set. For performing a topology optimization, two recommendations are made as well.

11.1. Recommendations cart design

First, the cart frame design needs to be evaluated for its aerodynamics. According to the guidelines, the cart frame design should perform well on aerodynamics. Especially for the holes in the middle beams it is important to check the aerodynamic performance of the cart.

To save extra mass, it is recommended to apply more holes in the basic shape of the cart frame design. The initial designs in 2D can be used as source of inspiration, indicating where to apply these holes. The front view can be used for further optimization of the holes in the middle beams. The side view could help to apply holes in the ribs around the steel plate with aluminium cover.

The new cart frame design already supports the carrier and the baggage at the side. Therefore, the wall of the tilt frame can be designed to be less stiff. A less stiff design gives possibilities to make it lighter. Recommended is to redesign the tilt frame for the new cart frame design too save additional mass and to make the tilt frame more suitable for the new design.

A lighter cart frame design allows for a lighter wheel suspension and wheels. Therefore, it is recommend to redesign these as well to create an optimal design.

11.2. Recommendations topology optimization

The edges in the design domain for the cart frame are ± 90-degree, which results in the initial design in much material at these edges. To get rid of build-ups of material in these edges, the edges of the design domain should be curved.

To perform a topology optimization for a similar product, similar size and symmetry, it is recommend to do the optimization for one-half of the total design domain (over the symmetry line). For the cart frame design, the forces where almost symmetrical. Since the initial design is used as inspiration, the forces can be assumed symmetric for the topology optimization process. Performing the optimization on one-half of the design domain shortens the computing time. It also allows for a smaller mesh size that will result in a more clear initial design.

References

1. A2TE (Advanced Thermal Transfer Equipment) (2016). *Bagtrax air friction.* Eindhoven.
2. Callister, W. D., & Rethwisch, D. G. (2007). *Materials science and engineering: an introduction* (Vol. 7, pp. 665-715). New York: Wiley.
3. CEN (European committee for standardization) (2008). *Safety Of Machinery - Human Physical Performance - Part 2: Manual Handling Of Machinery And Component Parts Of Machinery, EN1005-2: 2003+A: 2008.*
4. CES EduPack (2016). *Materials Education across Engineering, Design, Science and Sustainable Development.* Granta Design.
5. Hibbeler, R.C. (2011). *Mechanics of materials.* Prentice Hall, Pearson.
6. Mattheck, C. (1990). *Design and growth rules for biological structures and their application to engineering.* Fatigue & Fracture of Engineering Materials & Structures, 13(5), 535-550.
7. Langelaar, M. (2016). *Topology optimization. Maximum performance, minimal restrictions.* Structural optimization & mechanics, Technical university of Delft
8. Put, van de, J. (2009). *Moderne industriële productie.* Pearson Education.
9. Schramm, U., & Zhou, M. (2006). *Recent developments in the commercial implementation of topology optimization*. In IUTAM symposium on topological design optimization of structures, machines and materials (pp. 239-248). Springer Netherlands.
10. Sigmund, O., & Maute, K. (2013). *Topology optimization approaches.* Structural and Multidisciplinary Optimization, 48(6), 1031-1055.
11. U.S. department of Energy (2014). *Vehicle technologies office: lightweight materials for cars and trucks.* Washington