Tampere University

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SLING INTEGRATED ROLLER GUIDE STUDY

Master's thesis
Faculty of Engineering and Natural Sciences
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ABSTRACT

Tuukka Tuomi: Sling Integrated Roller Guide Study
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The objectives of this master's thesis were to study different options of integrating a roller guide shoe into the elevator car sling and to design a suitable roller guide shoe concept based on the findings. By integrating the roller guide shoe into the sling, the height of the sling could be significantly reduced. The reduced height of the sling would mean that the overall height of the elevator shaft could also be reduced, which would bring many benefits. Building a smaller shaft would be cheaper and would take up less space in the building that could be used for apartments.

In the theoretical background of the thesis, the components related to the mechanical guiding of the elevator and their functions were introduced. In addition, the concepts of ride comfort and ride quality were introduced. Books, Kone's internal documents, standards, conference papers, and journal articles were used as source materials for the theoretical background. The design process model developed by Gerhard Pahl and Wolfgang Beitz was also introduced in this thesis for the relevant parts.

The presented design process model was used in the design part of the thesis. The design process began with creating a requirements list. The requirements were collected from Kone's internal documents, standards and discussions with experts. The main requirement was to fit a roller guide shoe inside the tight spatial constraints introduced by sling integration. After gathering the requirements, abstraction of the task and creation of function structures for the guide shoe were done to determine the core problems of the task and basic overall functions of the guide shoe. Based on the functional structures, possible implementation alternatives were explored, which were concretized in stages, and at appropriate intervals the number of variants was limited by an evaluation-based selection procedure. As a result of the design project, one concept was selected for possible further development.

The results of the design process were evaluated from the perspectives of different design rules, design principles, and design guidelines. The proposed roller guide shoe concept seemed to meet all the requirements that could be assessed within the scope of the thesis. The concept was also in many ways in line with the design rules, principles and guidelines, so the design process was stated to be successful.

In order for the concept itself to prove adequate, a few more procedures would be required. Structural analysis should be performed on the roll guide structure to ensure adequate strength. In addition, the concept still requires some of development work in order to build a prototype for testing. For example, a new axle, that works with the chosen damping method, should be designed for the rollers. Decisions on how to proceed with the roller guide could be made based on the results of prototype testing.

Keywords: roller guide shoe, elevator, design process, product development, ride comfort

TIIVISTELMÄ

Tuukka Tuomi: Rullaohjaimen integroiminen hissin korikehikkoon
Diplomityö
Tampereen yliopisto
Konetekniikan diplomi-insinöörin tutkinto-ohjelma
Huhtikuu 2022

Tämän diplomityön tavoitteena oli tutkia erilaisia mahdollisuuksia integroida rullaohjain hissin korikehikkoon sekä kehittää löydösten perusteella sopiva rullaohjainkonsepti. Rullaohjaimen integroimisella korikehikkoon voisi korikehikon korkeutta laskea huomattavasti. Matalampi hissi korikehikkoineen tarkoittaisi sitä, että myös hissikuilun kokonaiskorkeutta voitaisiin vähentää, mikä toisi monia hyötyjä. Pienemmän kuilun rakentaminen olisi halvempaa ja se veisi rakennuksesta vähemmän tilaa, jota voitaisiin käyttää esimerkiksi asunnoissa.

Diplomityön teoreettisissa taustoissa esiteltiin hissin mekaaniseen ohjaukseen liittyviä komponentteja sekä niiden funktioita. Lisäksi perehdyttiin ajomukavuuden ja ajon laadun käsitteisiin. Teoreettisen taustan lähdemateriaaleina käytettiin kirjoja, Koneen sisäisiä dokumentteja, standardeja, konferenssijulkaisuja ja tieteellisiä artikkeleja. Työssä esiteltiin myös Gerhard Pahlin ja Wolfgang Beitzin kehittämä suunnitteluprosessimalli tätä työtä koskevin osin.

Työn suunnitteluosuudessa käytettiin esiteltyä suunnitteluprosessimallia. Suunnittelu aloitettiin vaatimuslistan tekemisellä, johon kerättiin vaatimuksia Koneen sisäisistä dokumenteista, standardeista ja asiantuntijoiden kanssa käydyistä keskusteluista. Tärkein vaatimus oli ohjaimen mahtuminen integroinnin luomiin tiukkoihin tilarajoitteisiin. Tämän jälkeen pyrittiin täsmentämään ydinongelmat ja ohjaimen pääfunktiot abstraktoinnilla ja funktiorakenteiden luomisella. Funktiorakenteiden perusteella ideoitiin mahdollisia toteutusvaihtoehtoja, joita konkretisoitiin vaiheittain ja sopivissa väleissä varianttien määrää rajoitettiin arviointiin perustuvalla valintamenettelyllä. Suunnitteluprojektin tuloksena valittiin yksi konsepti mahdolliseen jatkokehitykseen.

Suunnittelun tuloksia arvioitiin eri suunnittelun perussääntöjen, suunnitteluperiaatteiden ja suunnitteluohjeiden näkökulmista. Ehdotettu rullaohjainkonsepti vaikutti täyttävän kaikki vaatimukset, joita työn rajoissa pystyttiin arvioimaan. Konsepti oli myös monin tavoin suunnittelun perussääntöjen, periaatteiden ja suunnitteluohjeiden mukainen, joten suunnitteluprosessi todettiin onnistuneeksi.

Jotta konsepti itsessään voitaisiin todeta hyväksi, vaadittaisiin vielä muutamia toimenpiteitä. Rullaohjaimen rakenteelle tulisi tehdä lujuuslaskennat lujuuden varmistamiseksi. Lisäksi konsepti vaatii vielä hieman kehitystyötä, jotta siitä voitaisiin rakentaa prototyyppi testausta varten. Esimerkiksi rullille tulisi suunnitella valitun vaimennusperiaatteen kanssa toimiva akseli. Prototyypin testaamisen perusteella voitaisiin tehdä tarkemman jatkosuunnitelmat.

Avainsanat: rullaohjain, hissi, suunnitteluprosessi, tuotekehitys, ajomukavuus

PREFACE

This master's thesis was commissioned by KONE Corporation, so I would like to first thank Perttu Luukkonen for finding an interesting topic for the thesis and facilitating the start and the end of the project with KONE. Many thanks also to Sami Janhunen who as the KONE-side thesis supervisor helped me throughout the whole process by helping with concept ideation, sharing his expertise and giving constructive comments regarding the thesis. Also, thanks to Mikko Vanhatalo for helpful comments. Finally, special thanks to Emmi for being helpful and supportive through the whole process by being my cheer-leader and proofreader.

Tampere, 27 April 2022

Tuukka Tuomi

CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

BTF	Back to front
DBG	Distance between guides
DFA	Design for assembly
DFM	Design for manufacturing
DFMA	Design for manufacturing and assembly
DFX	Design for X

1. INTRODUCTION

The elevator industry is more competitive than ever. Safety and reliability are simply not enough anymore. Companies are constantly seeking new ways to differentiate and win market share. All aspects of performance, costs, environmental impacts and broader user experience are explored in order to obtain competitive advantage. Many of these properties could be improved with higher space-efficiency of elevators.

The goal of this master's thesis is to explore different options of integrating roller guides into the elevator sling and develop a concept based on the findings. Sling integration would bring several benefits by reducing the height of the sling. Height reduction would allow use of more space-efficient elevators, which would reduce building costs and increase the usable volume for apartments in buildings. This space-efficiency, however, is already possible with sliding guide shoes, but having roller guide shoes instead of them would have many benefits. Firstly, roller guide shoes enable significantly higher travel speeds. And secondly, roller guide shoes do not need oil lubrication unlike sliding guide shoes [1]. Using oil has obvious negative environmental impacts and the use of lubricant necessitates frequent maintenance work.

The structure of this master's thesis is as follows. In Chapter 2 guide shoes along with other relevant elevator components and their functions are introduced to give a broad overview of the system. Then, the concepts of ride comfort and ride quality are introduced, and how guide shoes relate to them is explained. In Chapter 3 Pahl and Beitz's design process model is introduced along with reasoning behind the choice. The model includes suggestions and tools about collecting and structuring requirements, finding the core problems, and forming and evaluating concepts at different levels of concretization. Then introduced are the different design rules, principles and guidelines, that were deemed to be useful for developing a guide shoe. In Chapter 4 the design process of a guide shoe is executed using the introduced process model and utilizing the introduced design rules, principles and guidelines. The process spans from creating a requirements list to late embodiment design phase. In Chapter 5 the results of the design process are reviewed with all the design rules, principles and guidelines in mind. Finally, in Chapter 6 the concluding thoughts including suggestions about further work are given.

2. ELEVATOR GUIDING AND RIDE COMFORT

An elevator car travels vertically inside an enclosure called the shaft, which is typically an integral part of the building. The elevator guiding system, comprising of many components, ensures that the travel is conducted in a controlled way. A key function of the elevator guiding system is to allow vertical movement while restricting horizontal movement. Restricting horizontal movement is essential for safety of the elevator and passengers' ride comfort.

2.1 Guiding Components

The most important components in mechanical elevator guiding are the sling, guide rails and guide shoes. A visualization of the components is shown in figure 1.

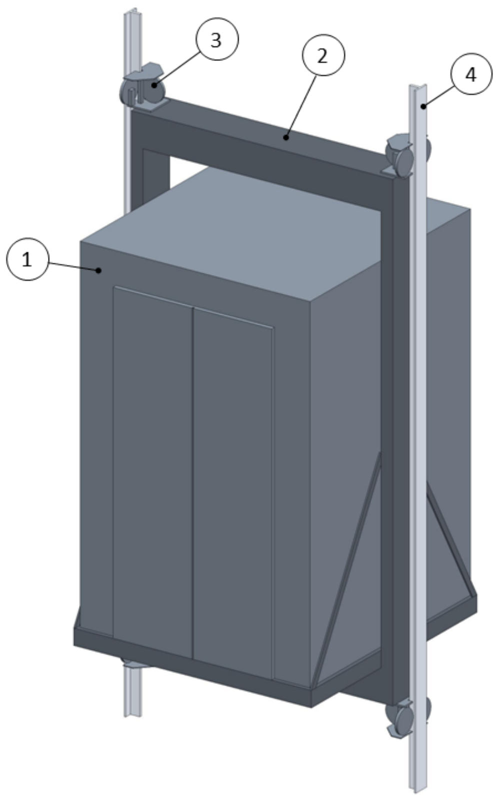


Figure 1. *A visualization of the main components of elevator guiding system with a car enclosure. Components as numbered: 1 – car enclosure, 2 – sling, 3 – guide shoe, 4 – guide rail*

2.1.1 Sling

The sling, or sometimes called the car frame, is the load-bearing structure of the elevator. It serves as the base module to which many other components, such as guide shoes and various safety components, are attached. The car enclosure, inside which the passengers travel, is located inside the sling frame. [2][3][4]

2.1.2 Guide Rails

Guide rails are usually T-shaped rigid metal profiles that are located in the shaft. They are attached to shaft walls with adjustable brackets. As their name suggests, guide rails serve as guiding elements along which the elevator car travels. [2][3] Together with guide shoes, guide rails restrict the horizontal movements of the elevator car [5]. Guide rails can be seen as analogous to train tracks, but for elevators. [5]

Guide rails are installed from separate guide rail pieces that are attached to each other with fish plates [5]. Guide rails have to be assembled from multiple pieces because of the obvious impracticalities of manufacturing, transporting and installing rails that are tens or even hundreds of meters long. The standard guide rail piece length is 5 m [6].

2.1.3 Sliding Guide Shoes and Roller Guides

Guide shoes are the interface between the guide rails and the sling. In an elevator there are four guide shoes in total, two on each side, and they operate as the upper pair and the lower pair. The primary function of the guide shoes is to keep the car aligned with the guide rails. [7] Guide shoes are commonly regarded as a part of the sling, but in this thesis a distinction is made for clarity. As the guide rails can be seen as the train tracks for the elevator, guide shoes can be thought of as the wheels and suspension system.

There are two types of guide shoes: sliding guide shoes and roller guide shoes. As their name suggests, sliding guide shoes slide along the guide rails. The contact surface of sliding guide shoes is made of a low-friction material to reduce friction. Still, in order to reach acceptable service life and noise levels, the friction has to be lowered further by utilization of lubrication on the guide rails. Even with low-friction materials and guide rail lubrication, friction is such a problem that sliding guide shoes can only be used in low-speed elevators. [7] In fact, friction using sliding guide shoes can be over 10 times higher than with roller guide shoes [8]. Roller guide shoes, also known as roller guides, use rolling motion instead of sliding [7]. Because roller guide shoes use rolling wheels, also known as rollers, no rail lubrication is needed. Using roller guides also enables higher travel speeds for elevators. [7]

2.1.4 Current Roller Guides

Roller guides consist of three main parts: body, rollers and suspension. The body is the supporting structure that is attached to the sling, rollers are the interface to the guiderails and suspension conducts and damps forces between the rollers and the body. Traditionally suspension consists of axles, levers and springs, but there are also designs where the traditional suspension is replaced by structures incorporating elastic material between the rollers and the body. [7] A traditional type of roller guide is depicted in figure 2. Often suspension designs include stoppers that limit the amount that suspension lets the rollers move in relation to the sling [5]. In hard stoppers metal-to-metal contact occurs. Before the hard stop, a rubber soft stop contact happens. [5] More of the functions of the main components of a spring suspended roller guide are presented in table 1.

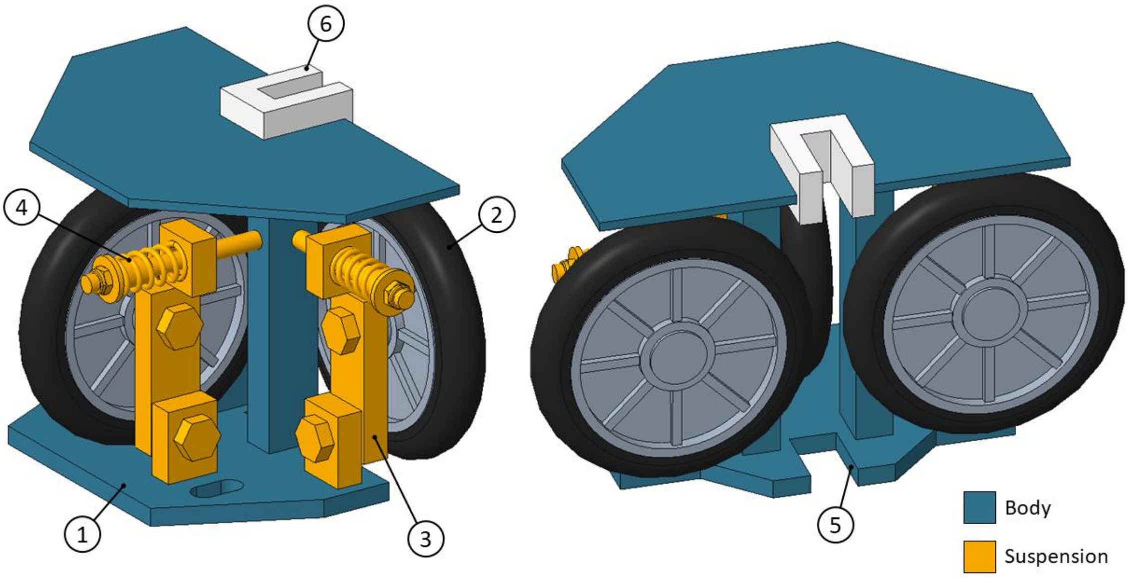


Figure 2. *Model of a traditional type of spring suspended roller guide. Components as numbered: 1 – body, 2 – roller, 3 – lever arm, 4 – spring system, 5 – safety throat, 6 – removable slider*

Table 1. *Functions of roller guide components.*

Component	Functions
Body	Provide an interface to sling Conduct guide shoe forces to sling without deformation Participate in damping
Roller coating	Provide radial vibration damping Provide friction damping axially Provide friction to ensure rolling contact instead of sliding Provide low contact noise Resist flat spots
Roller wheel hub	Provide a stiff frame for the roller
Lever arm	Connect roller to body Participate in damping
Spring assembly	Isolate vibrations Provide appropriate compression force Allow pre-tension adjustment Allow spring rate adjustment
Safety throat	Keep sling on guide rails under extreme loading or roller failure Provide running clearance to shaft equipment Provide symmetric running clearances to safety gear
Removable slider	Align roller guide during installation Serve as guide shoe during installation to protect rollers

Current roller guides are separate assemblies that are attached to each corner of the sling. This design is great for modularity and ease of installation and maintenance. However, in the perspective of space efficiency, the design is not optimal. If a way to integrate the roller guides into the sling was found, significant reductions in the height of the elevator car could be made. Figure 3 illustrates how sling integrated roller guides could reduce height from both ends of the car.

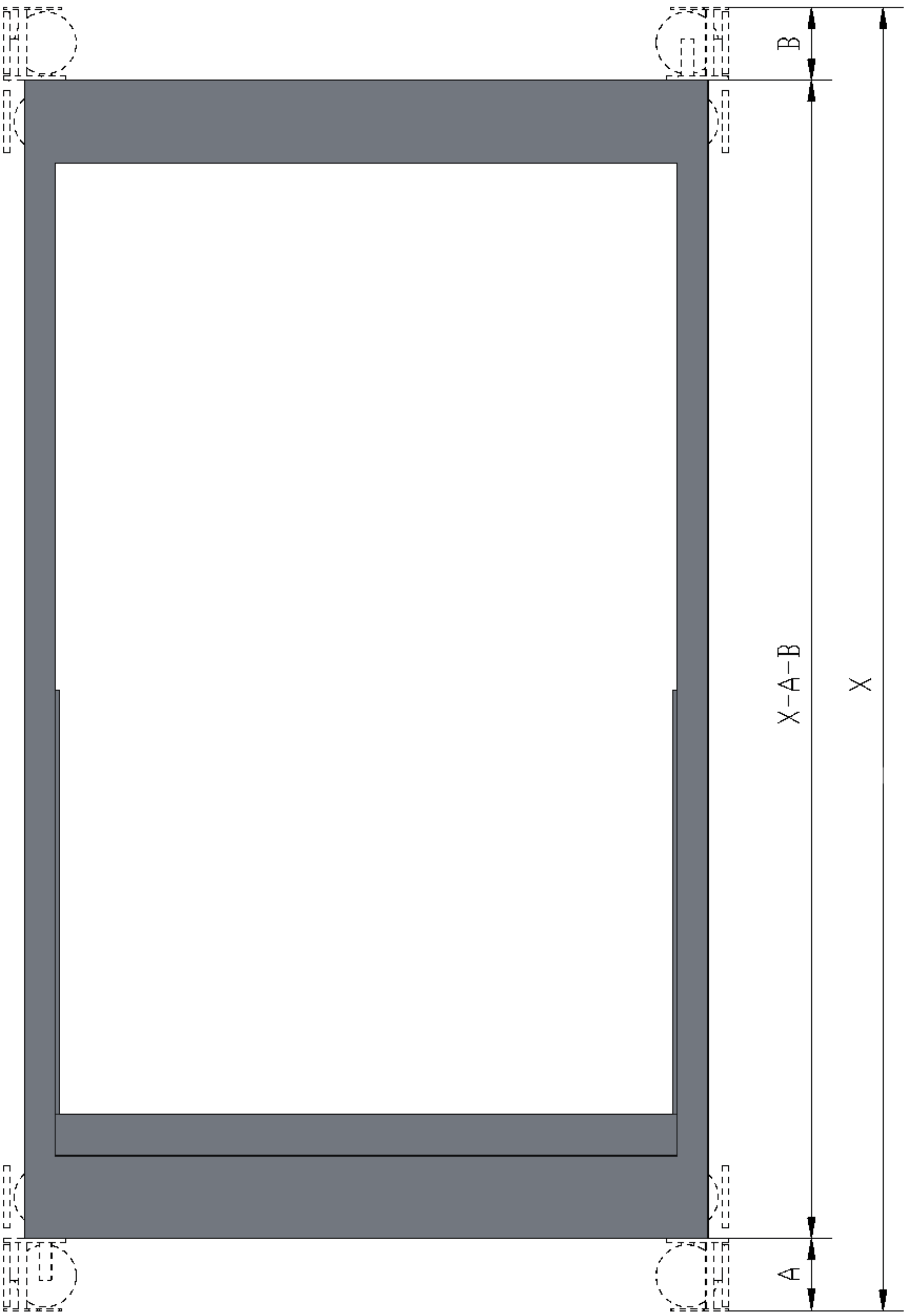


Figure 3. *Possible height reduction enabled by sling integrated guide shoes*

Each guide shoe restricts movement in both directions of the x-axis and one direction of the y-axis. As a pair, guide shoes then restrict movement in both directions of the y-axis. Restricted directions are depicted in figure 4 as arrows. Each arrow also represents a contact surface where a guide shoe touches the guide rail.

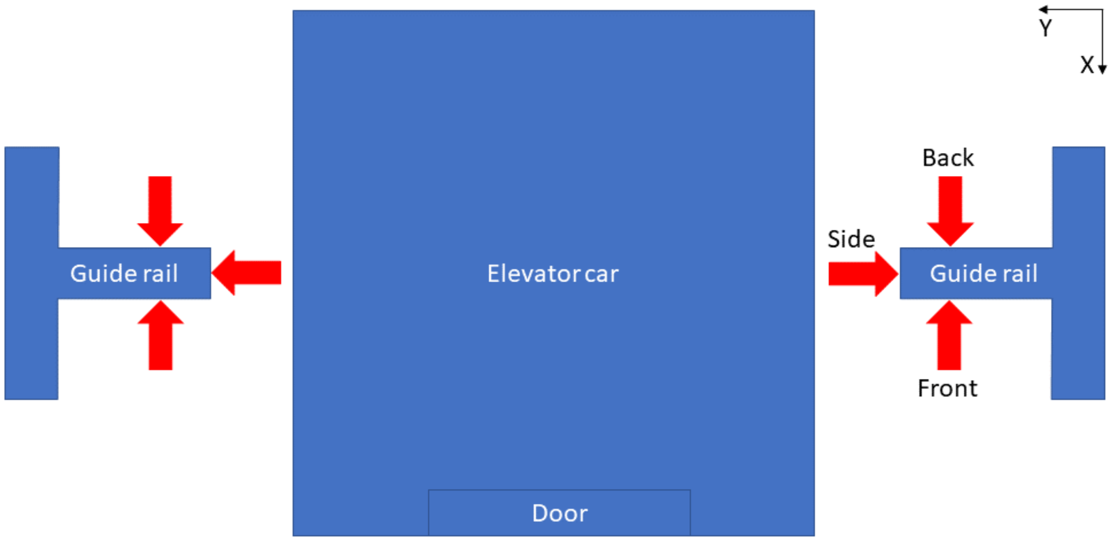


Figure 4. *Directions of restriction. NOTE: not in scale*

2.2 Ride Comfort and Ride Quality

Ride comfort and ride quality are two closely related terms that are often used interchangeably. However, KONE makes a distinction between them. Ride quality is the measurable part of elevator travel experience. It is determined by measuring accelerations, vibrations and noise inside the elevator car [9]. Quantifiable ride quality parameters are horizontal vibrations, vertical vibrations, overall acceleration, jerk, sound and tympanic pressure, which is the pressure in the middle ear. [6] Another name for horizontal vibrations is lateral quaking. [10] Ride comfort, on the other hand, is a more comprehensive and complex entity [9]. In addition to accelerations, vibrations and noise ride comfort also includes other experience affecting factors such as temperature, smells and feeling of spaciousness [5]. It comprehends the whole experience from stepping into the elevator to stepping out of it. [5] Ride comfort is based on user's perception and is therefore subjective [11].

Size, shape, mass, proportions and body composition vary from person to person. This is partly the reason why sensitivity to vibrations also varies. In extreme cases of bad ride quality and high sensitivity vibrations can cause significant physiological stress. [6] A standing human body is relatively immune to high-frequency horizontal vibrations since they tend to be damped in legs [10][11]. Low-frequency vibration, on the other hand, is more impactful since it moves the whole body. [10][11] Like with vibrations, noise sensitivity also varies with frequency [6], and acceptable noise levels vary greatly from person to person and with contextual factors [10]. A person's perception of ride comfort depends also on multitude of other factors such as age, culture and well-being. [10]

Ride comfort is a significant part of the user experience. Special care should be taken with design and installation to ensure satisfactory ride comfort since bad experiences can affect users' perception of the whole brand for a long time [11]. Good ride comfort also reduces the amount of negative feedback and the following maintenance leading to lower maintenance costs and higher uptime. [11] Of course, vibrations do not only affect the ride comfort; they can also cause high dynamic stresses in the components [6]. At worst, vibrations can cause component failures and so risk the safety of the passengers. [6] Ride comfort is often conflicted with performance and space efficiency, which is why it is important to understand the customer's preferences to provide the optimal solution [11][12]. To users ride comfort indicates safety and quality of the elevator [6][11][13].

2.2.1 Sources of Vibration and Noise

Some factors that contribute to horizontal vibrations are guide rail misalignment, guide shoe configuration, static balancing, shaft configuration and travel speed [14]. The biggest contributing factor is guide rail alignment [10][13][14]. Guide rails are never perfectly straight because of irregularities and deformities from manufacturing and misalignments from installation [6]. Bends and especially misaligned joints cause bumps during the travel. [6] Even if guide rails are installed perfectly their condition is bound to deteriorate [15]. In new buildings the structures tend to settle and shrink vertically, which naturally causes deflections in the guide rails that are fixed to the building. Also, in modernization cases the re-used guide rails are already worn to some extent. [15]

Guide shoes try to combat imperfections of guide rails. Well-functioning guide shoes can increase ride quality greatly but a misaligned guide shoe, damaged bearings or a roller with a flat spot can significantly worsen ride quality [14][15]. Flat spots are caused when an imbalanced elevator stands still for an extended period of time [8][16]. If the elevator car is significantly off-balance, the resulting forces may cause deflections in guide rails [14]. Since the stiffness of a guide rail is not constant over its entire length due to the fixing brackets, the guide rails deflect differently in different points of travel causing horizontal car movement. [14] A major cause of dynamic car imbalance are the passengers [6]. Some amount of imbalance is always present since the passengers' behaviour is unpredictable. When the elevator car travels in the shaft it passes landing doors, the counterweight and other shaft equipment [14]. Passing these changes of space causes changes in pressure surrounding the car. These pressure changes then cause vibrations and noise. [14] In taller buildings, building sway also becomes an issue [6]. All these negative effects are amplified by higher travel speed [14]. The sources of noise are mostly same as the sources of vibration [17]. Good ride quality and comfort are a sum of good design, proper component selection, precise installation and thorough verification [12].

2.2.2 Measuring Ride Quality

ISO 18738-1 provides standardized terms, definitions and testing, recording, evaluation and reporting methods for elevator ride quality. ISO 18738-1 does not, however, define what values constitute good or poor ride quality. [10][12][18]

It has been found that peak-to-peak vibration levels are a particularly important factor in passenger ride comfort. Peak-to-peak vibration level is assessed as maximum peak-to-peak and A95 peak-to-peak. [18] Vibration acceleration amplitude is measured in milli-g (m-g) or in Galileo (Gal) [10][18]. Below are some terms and definitions important to ride quality as presented in ISO 18738-1:

- A95: “Value of acceleration or vibration, within defined boundaries or limits, which 95 % of found values are equal to or less than.”
- Lift ride quality: “Sound levels in the car, and vibration of the car floor, relevant to passenger perception, associated with lift motion.”
- Peak-to-peak vibration levels: “Sum of the magnitudes of two peaks of opposite sign separated by a single zero crossing.”
- Sound pressure level, $L_{p,A}$: “Sound pressure level using frequency weighting A as defined in IEC 61672-1: $L_{p,A} = 10 \lg \left(\frac{{p_A}^2}{{p_0}^2} \right) dB(A)$”, where p_0 is the reference sound pressure level and p_A is the measured sound pressure using frequency weighting A.
- Equivalent sound pressure level, L_{Aeq}: “Average sound pressure level, using frequency weighting A and time weighting “fast”, determined within defined boundaries.” [18]

Vibration frequency weighting factors presented in ISO 8041 are used to simulate how the human body responses to vibration [18].

ISO 18738-1 divides an elevator ride with four boundaries to define signal calculation regions. Boundary 0 is at least 0,5 s before closing of the door. Boundary 1 is after the first 500 mm of travel. Boundary 2 is before the last 500 mm of travel. Boundary 3 is at least 0,5 s after the completion of opening the door. Boundaries 1 and 2 have been defined so that elevator motion can be evaluated separate from door operation. [18]

Both the maximum peak-to-peak vibration level and A95 peak-to-peak level are evaluated between the defined boundaries 1 and 2 using the weighted acceleration signals. Vibration levels are measured for both horizontal axes, that is, the x-axis and the y-axis. [18] Direction of x-axis is from back to front (BTF) meaning that direction of y-axis is then side to side, and it is also known as distance between guides (DBG) [12]. The horizontal axes are also depicted in figure 4. ISO 18738-1 also presents methodology for evaluating vertical vibrations but those are not assessed in depth in this thesis since guide shoes have very little effect on vertical vibrations.

Evaluation of sound levels uses same boundaries as vibration evaluation meaning that maximum $L_{p,A}$ and L_{Aeq} are evaluated between boundaries 1 and 2 [18]. The A-weighting is a filter that changes the signal to represent reception properties of the human ear [12].

To sum up, ride quality results that shall be reported are the maximum $L_{p,A}$, L_{Aeq}, maximum peak-to-peak and A95 vibration levels for x- and y-axes, maximum peak-to-peak vibration level for z-axis during non-constant acceleration and A95 vibration level for z-axis during the constant acceleration. [18]

A survey demonstrated that measuring vibrations, accelerations, jerk and noise alone cannot completely determine the ride comfort of an elevator and that the passengers' subjective perceptions are therefore also very important [10]. The level of acceptable ride comfort is thus also subjective [6]. Additionally, companies have different ride quality acceptance levels for different products depending on product segmentation. [6]

2.2.3 The Role of Guide Shoes in Ride Comfort

In mechanical systems, there are three ways to reduce effects of noise and vibration:

1. Prevention: Reduce noise and vibrations emitted by the source.
2. De-coupling: Remove noise and vibration transmission paths.
3. Damping: Absorb the energy of noise or vibration. [6]

Roller guides prevent noise and vibration by providing a low friction contact with the guide rails and by utilization of proper tolerances and structures in a way that the structure of roller guides itself does not act as the source of noise and vibrations. The suspension of roller guides aims to mechanically de-couple the roller from the body. Damping is mainly done by the roller coating and springs or elastic material in the suspension.

A key task of a guide shoe is to run smoothly over guide rail joints which are a major cause of ride comfort issues. As previously mentioned, guide shoes have a responsibility in damping horizontal vibrations. [19] Particularly important is to damp vibrations around eigenfrequencies to prevent resonance, which is of particular concern in terms of ride comfort [6]. Any component can start to vibrate strongly if external excitation is close to one of its natural frequencies. [6] Natural frequencies of an elevator car can be tweaked with component optimization [13]. For example, stiffness of guide shoe springs or the rubber coating on a roller can affect the natural frequencies. Therefore, adjustable guide shoe springs have an obvious advantage. [13]

The coating of the roller resists axial slipping to the extent that the rollers function as friction dampers reducing horizontal vibrations [20]. The hardness of the coating also has an effect on noise levels; harder coating generates louder noise [16]. Typical coating materials are synthetic rubber and polyurethane [20]. Rubber has better shock absorption and friction damping properties and its contact noise is lower while polyurethane is less susceptible to wear and thus provides longer lifetime. [20] Polyurethane also has higher rebound resilience which means that it is also less susceptible to flat spots, but this comes with the cost of worse damping capabilities.

The ride comfort functions of the roller guide can be summarized in the following manner: The wheel coating damps vibrations. The springs or other elastic suspension components isolate wheel from the body providing further damping. The elasticity of the suspension allows some sling movement relative to the guide rails. If the forces grow too great, a soft stop limiter is hit and finally a hard stop limit prevents any further movement relative to the guide rail line in order to maintain safe clearances. [19] Generally, the lower the spring rate of a guide shoe is the better the ride comfort is as long as the hard stop limit is not reached [20].

Like with guide rails, the installation quality is very important with guide shoes as well. Incorrect alignment of roller guides and, in the case of sliding guide shoes, insufficient lubrication cause excess friction that worsen the ride comfort [8]. If the guide shoes are not placed in the same plane, frictional forces can easily rise to hundreds of newtons. [8]

Due to their considerably lower friction factor and better shock absorption capability, roller guides should be preferred over sliding guide shoes in terms of ride comfort [16]. As they are the interface between the sling and the guide rails that are fixed to the shaft walls, guide shoes affect not only the ride comfort inside the elevator car but also the noises and vibrations transmitting to the building [20].

Generally, the larger the diameter of a roller is, the better it performs [16]. Larger diameter means lower rotation speed which leads to less wear and lower noise levels [20]. Also, flat spots caused by extended period of poorly balanced elevator standing still have more pronounced effects on smaller diameter rollers [16].

Maximum nominal speeds for different sizes of rollers were plotted in figures 5 and 6. In figure 5 are plotted the roller guides used on the car side, and in figure 6 are plotted the roller guides used on the counterweight side. The plots were fitted with appropriate curves. The graphs show a clear correlation between the wheel diameter and the maximum nominal speed. Since the nominal speeds are determined partly by ride comfort parameters, it can be concluded that noise and vibration levels also correlate with wheel diameter.

A point was drawn on the curve on elevator side to set expectations about nominal speeds achievable with 80 mm diameter rollers. The point landed at about 1,3 m/s nominal speed which would mean that the minimum goal of 1 m/s nominal elevator car speed should be achievable. Since the data points do not all fall directly on the fitted curve it might also be possible, although unlikely, to achieve the optimistic goal of 1,75 m/s as well.

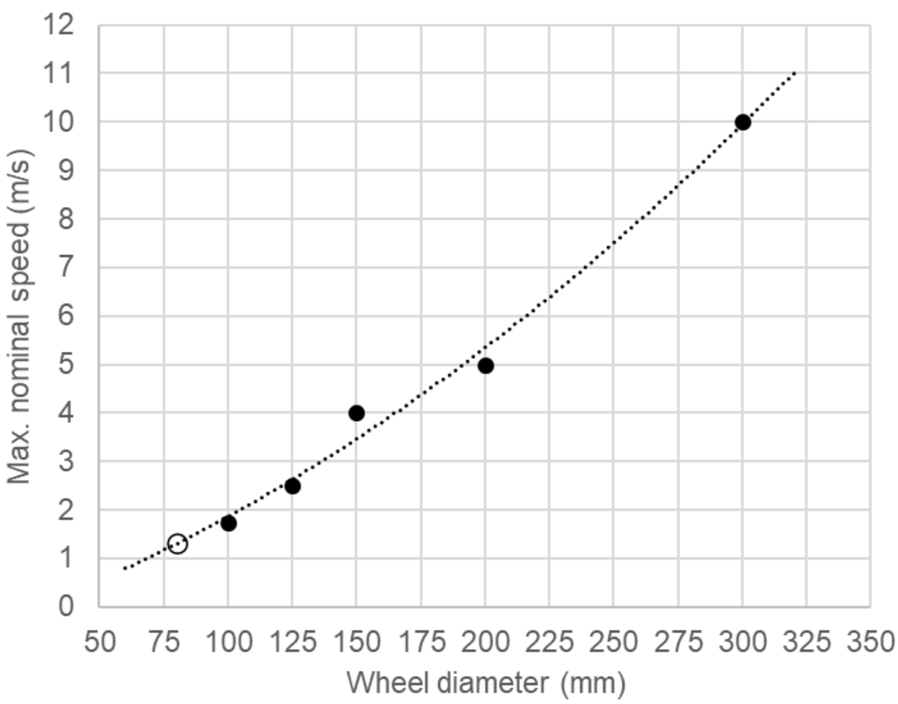


Figure 5. *Extrapolated plot of maximum nominal speed in relation to wheel diameter on elevator car side*

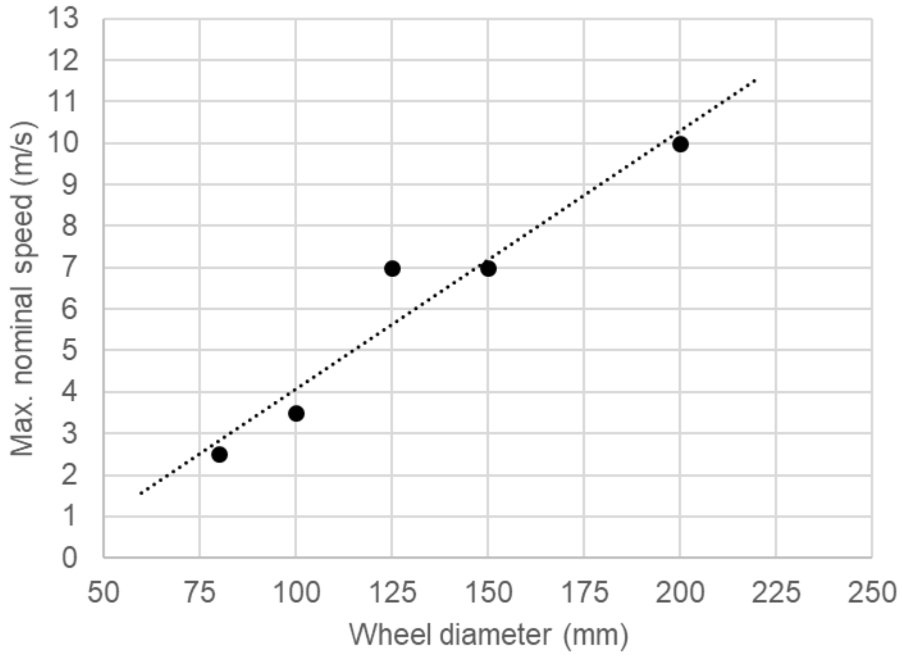


Figure 6. *Extrapolated plot of maximum nominal speed in relation to wheel diameter on counterweight side*

3. DESIGN PROCESS

There is almost a countless number of ways to develop products. For this reason, many models for product development process have been developed to make the development work more systematic and thus more reliable. Although many designers naturally proceed in a similar, systematic way, process models can be tremendously useful. Process models work as guidelines to aid designers in producing good solutions in a timely and effective way.

Many process models are very similar in the sense that they follow the same basic framework [21]. The differences between different models are mostly in how they are represented visually, which terms they use, and how descriptive or prescriptive they are. Descriptive models are more general and focus more on explaining what happens in a design process while prescriptive models include suggestions about procedures and methods. [21] Descriptive models are great for explaining the process for non-designers and students [22]. One such model is the double diamond model which is depicted in figure 7.

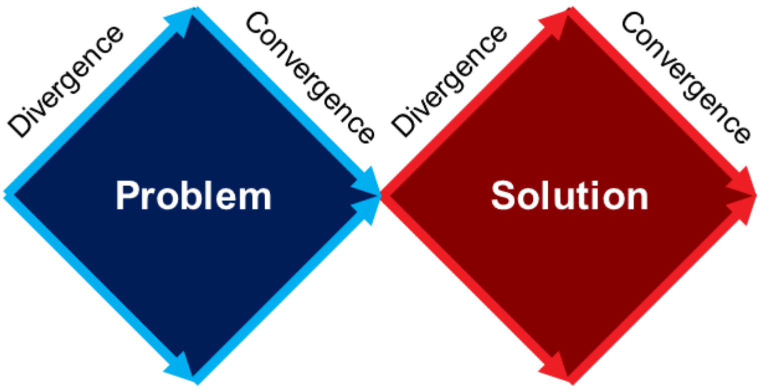


Figure 7. *The double diamond design process model [22]*

The double diamond consists of two distinct parts: the problem diamond and the solution diamond [22]. This highlights the importance of comprehensive problem formulation. Each diamond has a divergent thinking phase, where the scope broadens, and a convergent thinking phase, where the scope narrows [22]. For example, in the divergent phase of the solution diamond, all ideas are expressed freely expanding the solution space, and in the convergent phase, the solution space is narrowed by elimination and selection of ideas. [22] The double diamond model explains the idea of divergence and convergence well, but it is quite simplified. In reality, there are often several phases of divergence and convergence before the desired outcome is achieved.

As said, prescriptive models not only explain the process as a concept, but they also present tools for the designer to use at different points of the process. Prescriptive models guide the designer through the development process. To sum up, descriptive models explain “the what” while prescriptive models explain also “the how”. Because the purpose of this master’s thesis project is to go through an actual development process, a prescriptive model was deemed more appropriate. The one process model that was selected is developed by Gerhard Pahl and Wolfgang Beitz, and the model is explained in detail in the book “Engineering Design: a Systematic Approach”. The model is well established and widely referenced around the industry. The original book in German was published in 1977 and the book and the model have been updated throughout the decades to keep it up to date. The process model was developed for mechanical engineering needs specifically and as such it fits the purpose of this master’s thesis. Also, Lehtonen et al. [23] suggest that a systematic iterative process would be best suited for projects with similar level of complexity as this one further confirming the selection.

Pahl and Beitz [24] divide product development process into four main phases, which are planning and task clarification, conceptual design, embodiment design and detail design. Each phase consists of main working steps which can be further divided into lower-level working steps. For example, the main working step “develop the construction structure” can be divided into preliminary form design, preliminary layout selection, layout improvement and evaluation. After each main working step, there is a decision-making step. In these steps, the results of the main working step are assessed. Depending on how satisfactory the results are, the process may proceed or loop back to earlier steps for iteration. The borders of the phases are often not clear, and sometimes working steps normally assigned to later phases are carried out earlier due to reasons specific to the task. For example, parts of the layout might have to be considered during the conceptual design phase. [24] The product development process is illustrated in figure 8. The feedback loops in the figure highlight the iterative nature of the product development process.

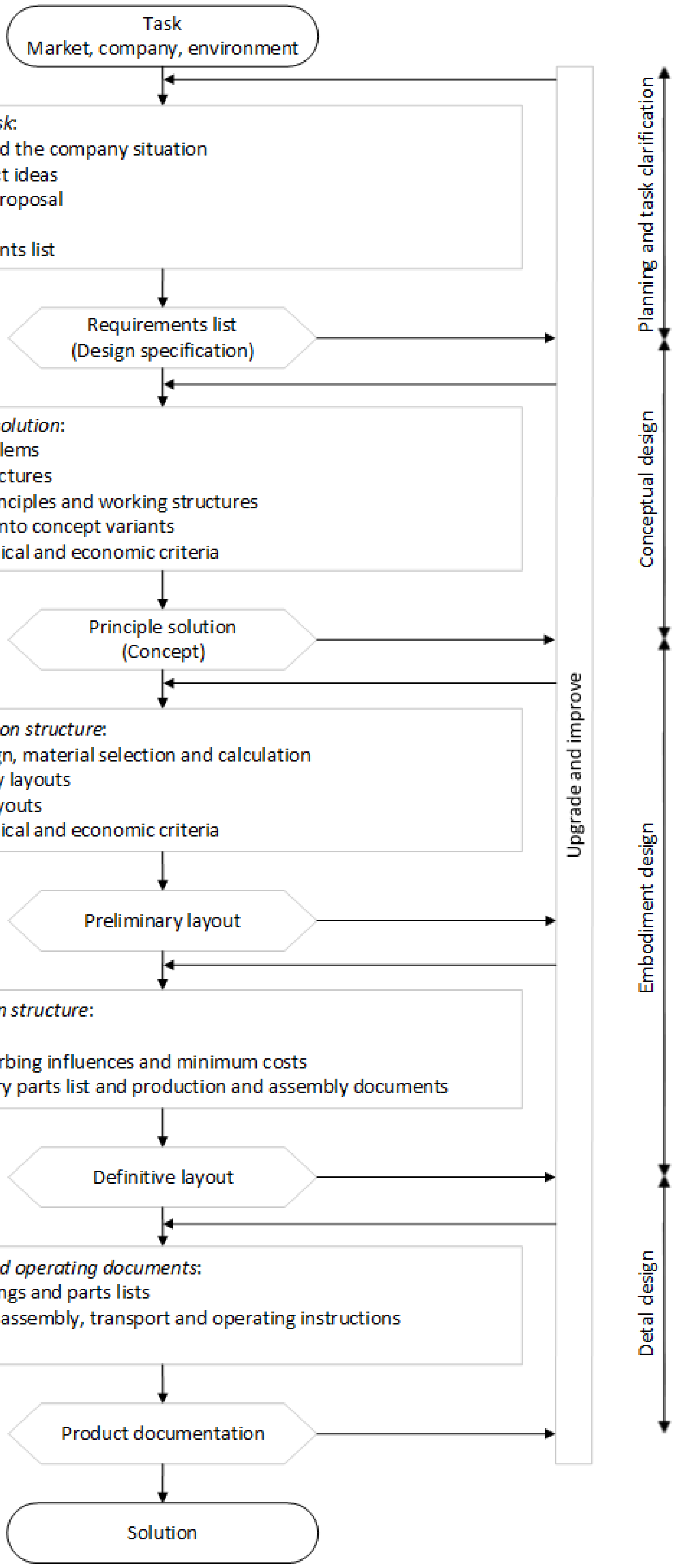


Figure 8. *The product development process adapted from [24]*

Next, the process is elaborated to the extent, that is relevant to this thesis. The development work of this thesis spans from working step “clarify the task” to working step “eliminate weak spots”, so the process description mainly consists of the same portion of the product development process.

3.1 Planning and Task Clarification

Product development tasks can be classified into three categories: original design, adaptive design and variant design. Original designs solve new or existing problems with new solution principles. Adaptive designs use previously established solution principles, but the embodiment is changed according to new constraints and requirements. Variant designs are variations of existing designs, in which sizing or arrangement of parts and assemblies are changed to meet new requirements. However, the boundaries of these categories are somewhat fluid and often development projects do not fall strictly into just one category. [24]

A company’s goals for the product affect greatly the development process and the design of the product. Company may aim to cost leadership or performance differentiation. These goals introduce different kinds of requirements, which have an impact on product properties as well as the project deadlines. Therefore, designers must know the goals of the company regarding the product in order to focus on the right aspects. [24]

Before the product can be designed, the task must be clarified in detail. Task clarification consists of collecting information about the requirements for the product and the constraints that restrict the design. The end result of task clarification is a requirements list, in which the requirements for the product are collected and organized. The requirements list is updated throughout the process whenever new information emerges. [24]

When setting up a requirements list, a differentiation must be made between demands and wishes. Demands are requirements that are absolutely mandatory to be met. Wishes, on the other hand, are requirements that are not mandatory, but which the designers should try to fulfil whenever possible. It may also be useful to classify wishes based on their importance. The requirements list is a free-form document, that should be laid out in a clear and structured way. The requirements list should contain descriptions of all requirements with dates indicating the latest changes, labels that indicate if the requirement is a demand or a wish, issue date of the document and other important information about the project, such as the name of the project or product. [24] An example layout of a requirements list is illustrated in figure 9.

Company	Requirements list for …		Issued on: dd/mm/yyyy
Changes	D/W	Requirements	Responsible
dd/mm/yy		<u>1. Geometry (dimensions etc.):</u> <u>2. Kinematics:</u> <u>3. Forces:</u> <u>4. Energy:</u> <u>5. Materials:</u> <u>6. Safety:</u> <u>7. Production:</u> <u>8. Operation:</u> <u>9. Maintenance:</u> <u>10. Schedule:</u>	
Replaces issue of dd/mm/yyyy			

Figure 9. *An example layout of a requirements list according to [24]*

When formulating requirements, basic requirements must also be taken into account. Basic requirements are implicit requirements, which means that they are not explicitly articulated but which are assumed to be fulfilled. Basic requirements are often present especially when designing a follow-on product. Examples of basic requirements could be better efficiency and lower operating costs. [24]

Using a checklist can be very beneficial when setting up a requirements list. A checklist ensures that all relevant factors are taken into account in the requirements list. Going through the checklist can help with identifying which relevant requirements are still missing. [24] A snippet of a checklist for setting up a requirements list is presented in figure 10.

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
…	…

Figure 10. *Snippet of a checklist for setting up a requirements list adapted from [24]*

Many requirements are often too broad and general to be useful when they are first acquired. For example, a requirement of "simple maintenance" is a very general statement and may be affected by a number of factors. Here, a refinement of the requirement can be useful. Refinement can be performed in three steps:

1. Statement: State the initial requirement.
2. Development: Divide the initial requirement into more specific sub-requirements.
3. Refinement: Further clarify and divide sub-requirements until the initial requirement can be satisfied with the acquired list of quantifiable requirements. [24]

The initial requirements list is often not complete and comprehensive enough to be used as such for the whole development process. The list grows and goes through changes during the process when new problems arise, and new factors become relevant. For example, the finishing paintjob of the product does not need to be specified during the conceptual design and consideration of such properties can be left for later phases of the process. In fact, it can even be beneficial to leave some requirements out of the current working requirements list to avoid wasting time considering requirements that lack the adequate information to be successfully satisfied. [24]

The following general process can be used to compile a requirements list:

1. Identifying the requirements: Define and document technical requirements, create scenarios to consider the possible life cycles of the product, refine vague statements into quantitative requirements, use checklist to ensure that the list is comprehensive, and specify if requirements are demands or wishes.

2. Arranging the requirements: Divide the requirements into distinct subgroups, for example, according to the main headings of the checklist shown in figure 10.
3. Making a list. Use the gathered requirements to set up a requirements list, and circulate the list among relevant departments or colleagues.
4. Update the list. Make corrections and additions to the list based on the acquired comments. [24]

Sometimes incomplete requirements lists are used on purpose. These partial lists are used when not every requirement is relevant to the user of the list. This helps, for example, the designers to focus only on the tasks for which they are responsible and not waste time collecting irrelevant information. [24]

Even though some requirements may seem obvious, it is still necessary to include them in the requirements list, so they are not forgotten. Not all requirements can be specified exactly at first, so they have to be clarified and new arising requirements have to be added to the list as the development process progresses. New solution ideas often come up during the whole process. New ideas are always welcome, but the ideas should not influence the requirements list in a way that makes the list biased. Anyway, the ideas should be recorded for later consideration. The scope of the requirements list varies depending on the type of the case. With original designs, the lists are more comprehensive, and with variant or adaptive designs a designer's personal partial requirements list may be sufficient. [24]

When the initial requirements list is set up, a decision on how the process proceeds must be made. A few questions need to be considered:

- Are the task clarification and the requirements sufficient to allow designing a solution?
- Does the task require conceptual elaboration, or can the key problems be solved with only embodiment and detail design?
- If conceptual design is necessary, how systematically it is necessary to go through it? [24]

If the task clarification and the requirements list seem comprehensive enough, the process may proceed to the next phase. If the principle solutions already available seem sufficient for the product, conceptual design phase may be skipped or just briefly visited to review alternative solution principles.

3.2 Conceptual Design

The goal of the conceptual design phase is to determine the principle solution, also known as the concept. The solution is found through abstraction of essential problems, establishing function structures, selecting working principles, and combining the working principles into a working structure. Often the working structure cannot be evaluated sufficiently, and for that reason, it needs to be concretized, for example, by means of drawing creation, preliminary material selection, establishing rough dimensions and rough 3D-model creation. This concretized working structure can then be regarded as the principle solution. Even though the design process is introduced as a linear series of working steps, the actual processes rarely are as straight forward. [24]

3.2.1 Establishing a Function Structure

In conceptual design, it is essential to try to overcome prejudices and open one’s mind for all possible solutions. Prejudices along with aversion to take risks may inhibit the designers to come up with novel, optimal solutions. Abstraction is used to overcome fixation and excessive precaution by generalizing the problem, which leads designers to the core problems of the task. By abstracting the task step-by-step, one can see the problem in a new perspective and define the task in a solution-neutral way. The level of useful abstraction depends on the constraints that limit solution possibilities. [24]

When the problem is abstracted, a function structure can be formed. This is facilitated by the solution-neutral formulation because it already describes the task as a function. This overall function can then be broken down into more manageable subfunctions. Solutions can then be searched for each of the subfunctions individually. The combination of all subfunctions determines the function structure that satisfies the overall function. A useful starting point for the creation of a function structure is determining the main flow in the system. The flow can be, for example, flow of energy, flow of material, or flow of signals. The auxiliary flows can be determined and added to the function structure later. If the design task is closer to the adaptive design type than the original design type, then the existing solution can be analyzed to form a function structure. So, when establishing a function structure for an original design the abstracted task based on the requirements list is used as the starting point. With adaptive designs, the function structure can be established by analyzing the existing solution. [24]

Like many other parts of the product development process, creating a function structure is also an iterative process. First a rough function structure is established and then it is reformed further by division or combination of subfunctions, rearrangement of the subfunctions and moving the system boundaries. Anyway, it is advisable to keep function structures simple since simple function structures lead designers to come up with simple solutions. [24]

3.2.2 Forming Working Structures

When the function structure is established, work for forming a working structure can begin. First, working principles for each of the subfunctions must be found. By a working principle, Pahl and Beitz [24] mean a physical effect that is often accompanied by a sketch of the geometry. Some useful ways for searching working principles are, for example, literature searches, analyzing natural systems, different intuitive methods like brainstorming, and, again, analyzing the existing solutions. If it is obvious that a working principle will not work in the product, it must be rejected early to minimize wasting time. These working principles are eventually combined to form the working structure. [24]

A good tool for systematic combination of working principles into working structures is the morphological matrix, which is a type of classification scheme. In a morphological matrix, subfunctions are entered as row headings and corresponding working principles are entered into the columns. Working structures are formed by selecting one working principle for each of the subfunctions and combining them together. Combination methods present the problem of compatibility. Only those working principles, that are geometrically compatible and allow smooth flow of material, energy, and signals, should be combined together. A compatibility matrix can be used here to aid with the combination. Also, technological and economic feasibility should be considered as a way to limit the number of possible combinations. [24]

As implied, combination of working principles can lead to a large number of possible working structures. In this case, the pool of solutions must then be narrowed down to a more manageable amount. First, all incompatible working structures should be eliminated. Then all working structures should be checked against the requirements list, and those working structures that do not fulfil the requirements list should once again be eliminated. If there are still too many working structure alternatives, other selection criteria such as utilization of direct safety measures and utilization of company preferred solutions can also be considered. If the pool of working structures is particularly wide, a systematic selection procedure with a selection chart may be used. Anyway, this working step should lead to multiple solution variants, so there is no need for too strict elimination. [24]

A distinct search for new working principles may not always be necessary. When the design case is adaptive in nature, the working principles and working structures of previous solutions should be checked against the new requirements to see if they can still be used. Also, especially experienced designers often intuitively come up with working principles and working structures that fulfil the overall function. [24] However, systematic process can still be used to verify that the solution field is wide enough and no solution is overlooked.

3.2.3 Forming and Evaluation of Concepts

When multiple promising working structures have been selected, an evaluation takes place. The evaluation determines which solutions are developed further. During the selection of the working structures, it may become obvious that more information needs to be collected in order to perform comparative evaluations that have any accuracy. The essential structures should be defined qualitatively or even quantitatively if possible. At least approximate information about properties such as expected performance, failure proneness, space requirement and weight is needed to perform a somewhat reliable evaluation. Multiple rounds of information collecting and selection can be done if necessary. [24] The information can be collected in many ways. Some examples of proven information collecting methods are:

- rough dimensional and layout sketching
- rough calculations
- creating different types of models for analysis or visualisation
- experimenting and testing. [24]

With this information known, the working structures can now be called concepts and they can be evaluated as such. The evaluation should be comprehensive and include consideration of all aspects of the solution instead of focusing on just one aspect, for example, only evaluating the costs. In the evaluation, the value of a solution is determined in respect of how likely it is to fulfil the objective. [24]

Before the evaluation can be done the evaluation criteria must be chosen. Most criteria can be derived from the requirements list and the general objectives and requirements. At this point, the solution variants may not yet be concrete enough to consider the evaluation to be precise. Instead, the evaluation should be thought of more as the probability of fulfilling the requirements. The criteria should be represented in positive terms to help with scoring. For example, a criterion of “low noise” should be used instead of “loudness level”. [24]

Each criterion’s importance to the overall value must be assessed in order to determine which criteria should be included in and which should be left out of the actual evaluation.

In guideline VDI 2225, the included evaluation criteria are generally regarded as equally important. However, if some criteria are clearly more important than others, weighting factors of 2 or 3 can be given to them. In guideline VDI 2225, each criterion is evaluated on a scale of 0 to 4, where 0 corresponds to unsatisfactory and 4 corresponds to very good. [24] The full scale is depicted in table 2. The overall scores of all variants can then be determined by adding up the points [24].

Table 2. *Guideline VDI 2225 value scale adapted from [24].*

Value scale	
Points	Meaning
0	unsatisfactory
1	just tolerable
2	adequate
3	good
4	very good

When the overall values have been determined, a search for weak spots takes place. A weak spot means a below average value on an individual evaluation criterion. Finding the weak spots is particularly important for otherwise promising solution variants because the weak spots may cause problems later in the development or in use. These weak spots should be tried to be eliminated in the further development, for example by adopting principles from other variants. Anyway, a balanced value profile is preferred, and if a decision is to be made at this point, a variant with lower overall score may be chosen over a higher-scored variant with a serious weak spot. [24]

At this point there might be a concept that is clearly better than the others and in that case the development process can proceed using only this one concept. Often, however, many concepts seem equally promising, and they require further development in order to decide which variant should be chosen. [24]

3.3 Embodiment Design

In the embodiment design phase, the concept is developed further up to a point where only detail design is left to be done. If the overall layout of the product was not already considered at the conceptual design level, this is where it is developed. In this design phase, general arrangement of components must be considered as well as shapes and materials of the components, and spatial compatibility must be ensured. Also, production processes of the components must be considered. Embodiment design is a particularly iterative process. It involves a lot of trial and error, and new information keeps surfacing while trying out new ideas feeding the iteration loop. [24] Here, a somewhat linear process is introduced again. However, due to the iterative nature of the embodiment design phase, real projects rarely proceed in a strictly linear manner [24].

3.3.1 Preliminary Layouts and Form Designs

It is important to start embodiment design phase by going through the requirements list once again and find all the requirements that effect things like size, arrangement and materials. With this information from requirements, a rough layout is formed based on the concept developed in the conceptual design phase. First, it needs to be determined, which functions and function-carrying components dictate the overall layout. Then the preliminary shapes, sizes and places of main components can be laid out forming the rough layout. [24]

Many different layout options may emerge. If the number of options needs to be reduced, a selection procedure can be used in the same way as in conceptual design, only this time more criteria, such as expected performance and costs, can be assessed with some accuracy. Developing preliminary layout continues with adding auxiliary functions and function-carrying components into the mix. Preliminary shapes, places and sizes are determined for auxiliary function-carrying components. A selection procedure can once again be performed if necessary. [24]

3.3.2 Detailed Layouts and Form Designs

When a rough overall layout has been established, more detailed design can begin. Again, starting from main function-carrying components and working one's way down to less important components, the form and the layout are now designed in more detail. Design principles and guidelines should be followed to achieve the best results. [24] Some of these are introduced in Sections 3.4, 3.5 and 3.6. Also, it might be useful to divide the overall layout to smaller assemblies and focus on one assembly at a time to keep the task on hand more manageable [24].

When detailed layouts are done, they have to be evaluated against technical and economic criteria in order to locate strengths and weaknesses and to compare the layout alternatives to each other. The evaluation and selection procedure can be performed again in a similar way as was done in the conceptual design phase but with better information and greater accuracy. As the outcome of the evaluation and selection the chosen preliminary overall layout is fixed. This overall layout is the product’s complete construction structure. [24]

After choosing the overall layout comes the optimization and finalization of layout. Possible weak spots that have been found need to be eliminated, and the design must be checked with the design principles from the proceeding section in mind. When the layout is deemed satisfactory, a preliminary parts list and production and assembly documents can be created. After this the layout is fixed forming the definitive layout. [24]

3.4 Basic Rules of Embodiment Design

The basic rules of clarity, simplicity and safety are the basis for creating a successful solution [24]. In this section, the basic rules and ways to utilize them are introduced.

3.4.1 Clarity

Clarity, in this case, means that the functions and the design are unambiguous [24]. Listed below are some ways that clarity should be considered in design and development.

- Working principle: The flow of energy, material and signals must be unambiguous for behaviour to be predictable.
- Layout: The load cases must be clearly defined in order to design a layout that behaves predictably.
- Assembly: The product should be designed in a way that the assembly sequence is clear.
- Operation and maintenance: Inspection and maintenance intervals and procedures should be defined clearly, and they should require minimal tooling. [24]

3.4.2 Simplicity

With simplicity, is meant, a small number of components with simple shapes, which facilitates faster and easier production and, hence, lower costs [24]. Listed below are some ways that simplicity should be considered in design and development.

- Working principle: Only those working principles, that involve few components and processes, should be considered.
- Layout: Arrangement and shapes of components should be simple. This can lead to lower production costs, less wear and less maintenance.

- Production and quality control: Simple component shapes enables use of well-established simple production methods. Choosing shapes that require minimal number of production operations and that are easy to inspect facilitates simplicity in production and quality control.
- Assembly: Easily identifiable components and simple assembly procedures make assembly faster and more reliable.
- Operation and maintenance: Operation must not require complex instructions. Maintenance must not require too much effort and time.
- Recycling: Easily recyclable materials should be used. Disassembly should be easy and fast. [24]

3.4.3 Safety

Safety means careful and systemic consideration of strength, reliability, accident prevention and protection of the environment. [24] Listed below are some ways that safety should be considered in design and development.

- Function and Working Principle: Chosen working principles must retain safe functioning even with the presence of faults and disturbances in the structure, operation or the environment.
- Production and Quality Control: Components should be designed in a way that their properties do not change unexpectedly during production creating possibly dangerous weaknesses.
- Assembly and Transport: Assembly processes should include functional checks. Loads and other circumstances during the transportation should be considered, so that the product's properties are not affected.
- Cost and Schedules: Costs should not be cut at the expense of safety. The costs of accidents usually outweigh the costs of implementation of safety measures by a large margin. [24]

3.5 Design Principles

In this section, some important design principles are introduced. Not each principle is necessary or even useful in every design case. Only those principles should be utilized that can be seen to benefit the most [24]. Some of the principles conflict with each other, so the decision to use the principles depends on the goals of the product and sometimes compromises between competing requirements have to be made. [24]

3.5.1 Principles of Force Transmission

Forces often have a very large role in mechanical design [24]. It is necessary to consider their effects thoroughly to create safe and effective designs. Some principles of force transmission are:

- Flowlines of force: Visualization of flowlines of force aids in perceiving the force transmission paths through the components. Sudden changes in cross-section and sharp corners should be avoided to provide smooth force transmission and avoid stress concentrations.
- Principle of direct and short force transmission path: Shortest possible force transmission path should be pursued, so that the number of areas under load is minimized. Utilization of the principle leads to smaller deformations and use of less material.
- Principle of matched deformations: Components must be designed in a way that their deformation behaviour is similar in magnitude and direction, so that stress concentrations caused by deformation can be avoided.
- Principle of balanced forces: Forces that do not serve a function directly should be balanced as close as possible to their origin by use of balancing elements or symmetrical structures. [24]

3.5.2 Principle of the Division of Tasks

Generally, it is impossible to optimize a function carrying structure to be ideal for carrying out multiple different functions. This is why principle of division of tasks should be considered. Principle of division of tasks enables better optimization of components and promotes unambiguous behaviour. This is also in line with the basic rule of clarity. However, the principle of division of tasks necessitates usage of more components, which is against the basic rule of simplicity, and it can cause problems in meeting space and weight requirements. [24] Principle of the division of tasks can be utilized in two ways:

- Division of tasks for distinct functions: An example of this is the use of two different types of rolling element bearings in one assembly, where a roller bearing takes the radial load and a deep-groove ball bearing takes the axial load. With this, the force transmission paths are more predictable, and the service life is increased.
- Division of tasks for identical functions: In some cases, increasing load capacity of a system cannot be achieved by simply using bigger components, because of

different physical properties scale differently and sometimes bigger components are just not practical. In these cases, the task can be divided between multiple smaller components that work in parallel. [24]

3.5.3 Principle of Self-Help

In self-helping designs, a supplementary effect is used to reinforce an initial effect or to provide relief by counteracting forces. [24] There are a few ways to utilize principle of self-help:

- Principle of self-reinforcing: In self-reinforcing designs the supplementary effect reinforces the initial effect. For example, in self-reinforcing seals, the pressure difference is used to push the seal even tighter.
- Principle of self-protecting: In self-protecting designs, the load paths are altered for protecting the structure. A primary load-carrying component elastically deforms only up to a certain point where a secondary load-carrying component makes contact and the flowlines of force start going through it increasing the overall load-carrying capacity. [24]

3.5.4 Principle of Stability and Bi-Stability

System stability is an important property that designers must consider. Disturbances can cause system to become uncontrollably unstable which can lead to dangerous situations. Systems should be designed in a way that possible disturbances cancel each other out or that disturbances push the system into another stable state. [24] Stability in design can be facilitated by principles of stability and bi-stability:

- Principle of stability: System stability is maintained by design in which disturbances cancel each other out.
- Principle of bi-stability: When a system reaches a certain limit it moves from the initial stable state to another stable state without a possibility to stop at an in-between state. Bi-stability is utilized in switches and protective systems. [24]

3.6 Design for X

Design for X (DFX) is a set of guidelines each of which is aimed to aid designers to fulfil specific type of requirements [24]. The “X” in “design for X” is replaced by whatever the objective is for the specific guideline. For example, design for assembly is a guideline focusing on minimizing costs and maximizing quality of assembly process [24]. In this section, design for wear resistance and a couple other guidelines important for designing a guide shoe are introduced briefly.

3.6.1 Design for Wear Resistance

Wear is damage occurring at the surface of a solid material caused by relative movement of surfaces [25]. Wear is a significant contributor of shortening the service life of components, reduced performance and increased losses [24]. Some factors that affect wear resistance are materials, type of relative motion, type of loading and shapes and roughnesses of the contact surfaces [25]. By modifying these factors, wear behaviour can be changed. For example, the use of lubrication is a very common method of wear reduction. Lubrication can reduce wear rates by multiple orders of magnitude, but it cannot be utilized in every situation. Fortunately, there are also many other ways to design for wear resistance. [25] Listed below are some other rules and criteria for wear resistant design:

- minimize contact stresses by aligning components correctly and rounding corners and edges
- use rolling motion instead of sliding
- use materials that remain mechanically, thermally and chemically stable in operation
- contact stresses should not exceed the elastic limits of the materials
- minimize amount of abrasive particles
- avoid rough contact surfaces
- use designs that prevent fretting
- use easily replaceable parts when sufficient wear resistance cannot be achieved by other means. [25]

Harder materials typically are more wear resistant, but hardness alone should not be the selection criteria for materials. This is because other material properties affect wear behaviour too and wear resistance of materials varies by types of wear. [25]

3.6.2 Design for Assembly

Design for manufacturing and assembly (DFMA) is the combination of two design guidelines that are design for manufacturing (DFM) and design for assembly (DFA) [26][27]. DFM and DFA are closely connected since their results greatly affect each other [27]. However, since their goals are different and the guidelines are specific for each, they are introduced in their own sections. This section is about DFA, and the next section is about DFM.

Designers have a huge impact on the costs and quality of the assembly of a product. Therefore, how the product is assembled should be carefully considered during the design. Designers determine how many and what kind of parts the product is assembled from and how they all attach to each other. All these affect how many and what kind of operations need to be performed in assembly process, which in turn determine the cost and to an extent the quality of the assembly process. It is very important to consider all possible different operations of the assembly process. [24] Some of the important operations to be considered are:

- Handling of the components: How the components can be identified, picked up and moved.
- Positioning and aligning the components: How the parts can be positioned correctly and aligned to correct orientation.
- Joining parts: How the parts are attached to each other.
- Inspecting: How the results of the assembly can be verified. [24]

The easier and faster the operations can be done, the lower the assembly costs are [27]. Generally, the quality and costs of the assembly process are facilitated by using structured and standardized operations and reducing and simplifying them [24]. Simplifying product structure and reducing part count often also lead automatically to a more efficient assembly process [27].

The design of assembly interfaces also affects the assembly process greatly. In the case of interfaces, reduction, standardization and simplification are again ways to improve the design and the process. An example of facilitating assembly in design is to divide the main assembly into smaller subassemblies instead of all separate parts connecting directly to the main assembly with various different interfaces and an ambiguous order of assembly. Other examples of good principles are using identical connecting elements like same size screws and providing reference geometry to aid placement. These kinds of improved interfaces lead to needing fewer connecting elements and assembly operations. [24] Some additional things to consider when designing for assembly are:

- production and assembly constraints
- maintenance and recycling imposed assembly and disassembly requirements
- available production and assembly equipment and processes

- combined costs of manufacturing and assembly. [24]

3.6.3 Design for Manufacturing

Design for manufacturing aims to minimize the manufacturing time and costs without decreasing product quality. Even though, assembly is often regarded as a part of manufacturing a distinction is made here to highlight the design guideline specific to non-assembly manufacturing and the guideline specific to the assembly process. [24]

How the overall layout of the product is designed can have big consequences on production. It affects, for example, manufacturing procedures, dimensions and batch sizes of components and defines appropriate tolerances. On the other hand, production capabilities and preferences impose limitations on the design. Construction method, meaning the division of the overall layout, affects manufacturing greatly. Main construction methods to consider are differential construction and integral construction. Both of them have their strengths and weaknesses, so one is not always better than the other and therefore construction method should be chosen to best suit the needs of the current case. Differential construction method means breaking down components into smaller, easier-to-manufacture parts. [24] Main advantages of differential construction are:

- use of easily available and low-cost standard parts
- larger component batch sizes
- benefits to transport, assembly and maintenance due to smaller, more easily handleable components
- shorter production time. [24]

Main disadvantages of differential construction are:

- higher machining and assembly costs
- increased need for quality control due to larger number of tight tolerances
- possible reduction in performance due to loss of stiffness and sealing and increased vibrations. [24]

Building block construction method is a specific type of differential construction in which the smaller components are designed in a way that enable their use as parts in other products as well. [24] This can be seen also as a type of modular design.

Integral construction method, on the other hand, means combination of parts into bigger, more complex components. With integral construction, products can be better optimized in terms of performance, weight and size. Since integral construction is basically the opposite of differential construction, the advantages and disadvantages are also the same but flipped. [24] As said, both construction methods have their own advantages and disadvantages, so it is up to the designers to find the optimal compromise.

The manufacturing costs of the part are determined by which part-processing method is used and the shape of the part. Various materials and processing methods should be considered to find the most economical suitable combination. Estimating the costs is difficult before detailed design has been done, because not all important information is yet available and assumptions have to be made. A simple way to roughly estimate the manufacturing costs is to deduce material costs by determining the size of the original workpiece and calculate processing costs by multiplying average material removal cost with the volume of material to be removed. A more accurate way of estimation would be to use process-specific machine and operator costs, include non-productive times such as handling, positioning, attaching et cetera and include surface areas that are finish-machined. [27]

To summarize: DFA aims to reduce assembly costs by simplifying the product, and DFM aims to minimize manufacturing costs. DFMA then combines these two iteratively alternating between them until an optimal solution is found. [27] A typical process of utilizing DFMA is presented in figure 11.

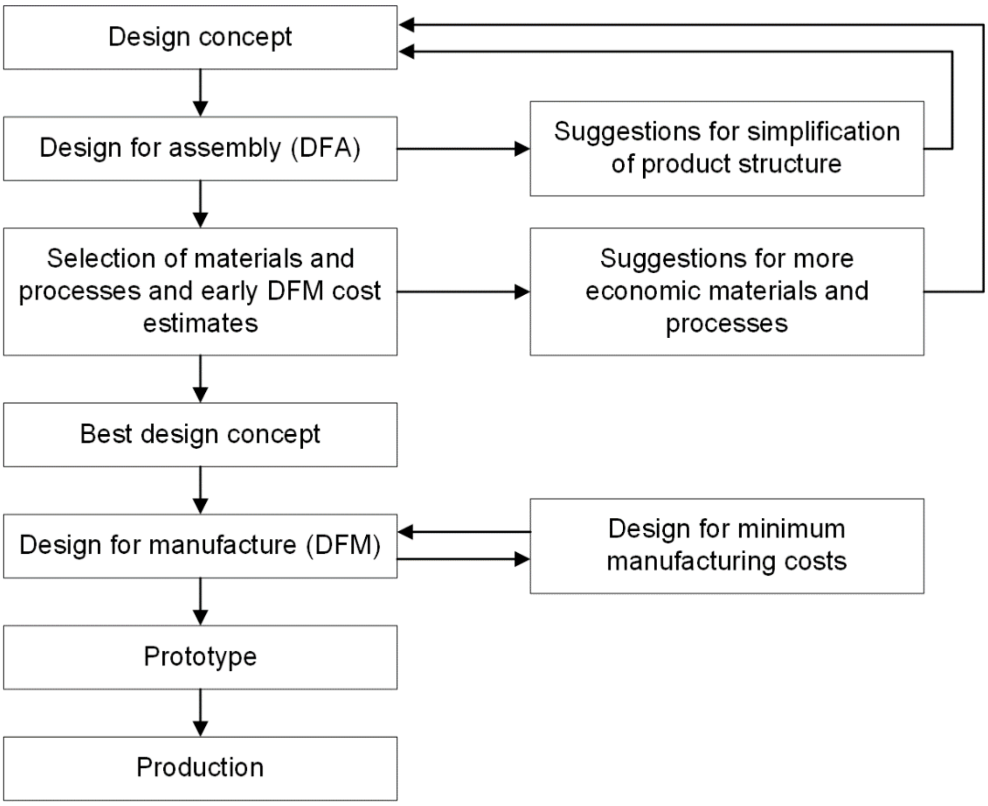


Figure 11. *A typical process of utilizing DFMA according to [28]*

4. DESIGNING A ROLLER GUIDE

The impetus of this design project was the need to have a roller guide that would fit the tight spatial constraints of a new type of space efficient elevator sling. As shown in Section 2.1.4, the new type of elevator sling equipped with space-efficient integrated roller guides would significantly reduce the height of the sling. The height reduction would mean that the shaft height could also be reduced which would bring down the building costs as well as increase the usable volume in the building for apartments. In the case of modernizations of elevators in existing buildings, the space-efficient elevators would allow optimizing elevator capacity. Integration of the roller guide in this case means that the roller guide does not increase the vertical space occupied by the sling. It would still be preferable that the roller guide was be a discrete removable module.

The same space efficiency would be achievable simply by using sliding guide shoes. However, there are several reasons why using roller guides would be preferable over sliding guide shoes:

1. Sustainability: Sliding guide shoes require oil lubrication to work properly. Using roller guides eliminates the need for oil.
2. Maintenance: Lubricated guide rails require frequent maintenance. Oil reservoirs need to be filled, dripped oil needs to be collected and oil puddles and stains need to be cleaned.
3. Service life: Roller guides might last for the entire service life of the elevator while sliding guide shoes typically need to be replaced multiple times during the service life due to wearing out.
4. Performance: Roller guides allow for faster elevator speeds as sliding guide shoes start to cause ride comfort issues at much lower speeds.
5. Efficiency: Roller guides cause far less frictional losses which leads to smaller energy consumption and thus also lower operating costs.

4.1 Design Specification

The formation of a requirements list started with going through relevant standards that may have requirements regarding the functions and structure of guide shoes. The two standards that were relevant are the European elevator safety standard EN 81-20 and the American “Safety Code for Elevators and Escalators” ASME A17.1. More requirements and other important information were then collected from KONE’s internal documents. The main sources of requirements were design guidelines and product description documents. Additional requirements were formed based on discussions with company-side thesis supervisor and the designers of the sling into which the roller guide is to be integrated. A first draft of the requirements list was formed from the gathered requirements. The list was then circulated and then refined and expanded based on received comments. The final requirements list is available in appendix A.

Next, the space requirements and constraints were acquired by inspecting the 3D-model of the sling. Available space with main dimensions is depicted in figure 12. The available space in 3D and the available sling interface surfaces are depicted in figure 13. The space is divided into three parts, corresponding roughly to space available for each roller. Detailed dimensions of each of the sections are available in appendix B.

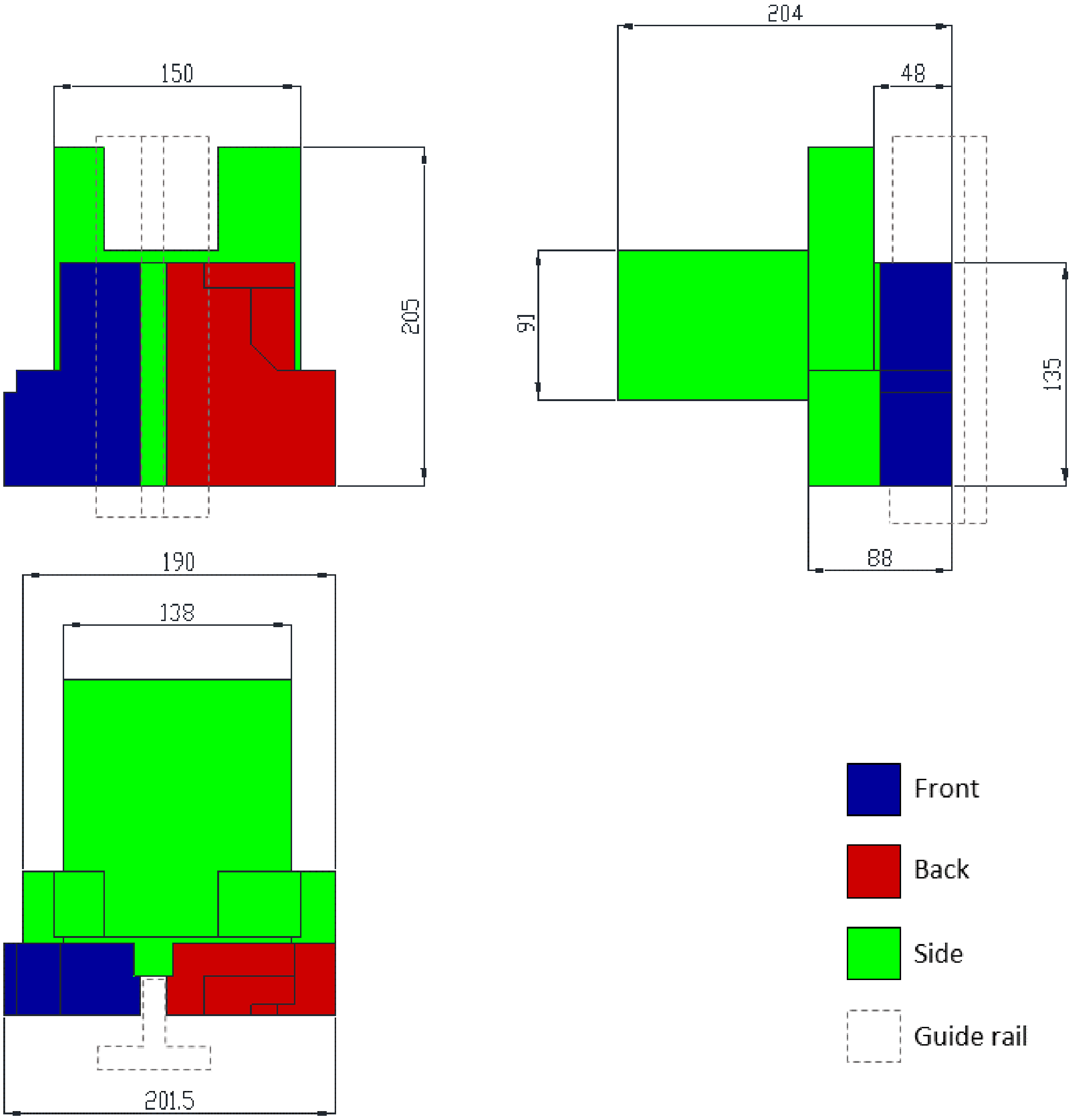


Figure 12. *Space available for roller guide with some main dimensions*

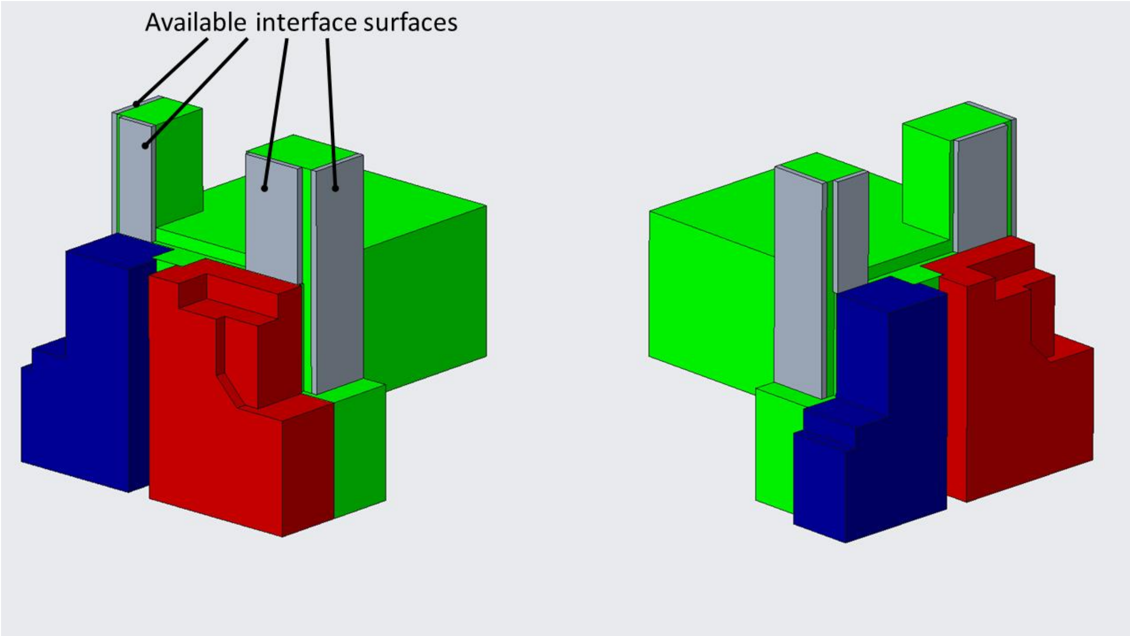


Figure 13. *Available space with available sling interface surfaces*

4.2 Conceptual Design

The functions of a roller guide shoe were abstracted to a useful level. The same was also done for a contacting element, which in this case meant a roller.

Abstraction of a roller guide shoe:

1. Roll along guide rail on three surfaces, receive forces, compress to decrease sudden forces, transfer forces to sling.
2. Touch guide rail on three surfaces, accept forces, transform z forces to rolling motion, minimize frictional losses in z-direction, damp horizontal forces, transfer forces to sling.
3. Interact with guide rail, accept x and y forces, do not accept z forces, damp forces, transfer forces to sling.

Abstraction of a contacting element (roller):

1. Roll along guide rail, receive forces, compress to decrease sudden forces, transfer forces to axle.
2. Touch guide rail, accept forces, transform tangential forces to rolling motion, minimize frictional losses in z-direction, damp axial and radial forces, transfer forces to suspension components.
3. Interact with guide rail, accept x and y forces, do not accept z forces, damp forces, transfer forces to suspension components.

The overall functions for both would be along the lines of “transfer forces between guide rail and sling”, but since force damping is an essential function of the guide shoe that level of abstraction is not useful. Based on abstraction and analyzing the current guide shoes, function structures for a guide shoe and a contacting element were established. The function structures are depicted in figures 14 and 15. The axial force flow in figure 15 is an auxiliary flow that is significantly present only in rollers, since the coating of the rollers grips the guide rail to some extent acting as a friction damper.

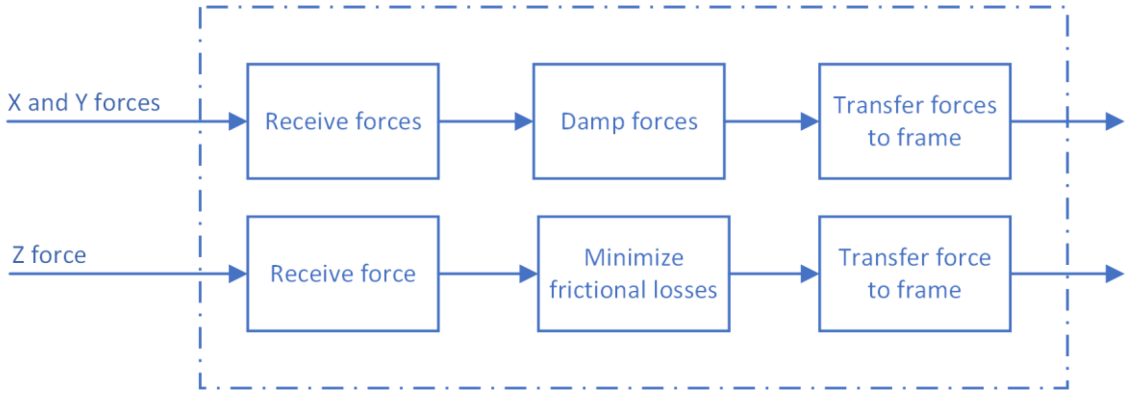


Figure 14. *Function structure of a guide shoe*

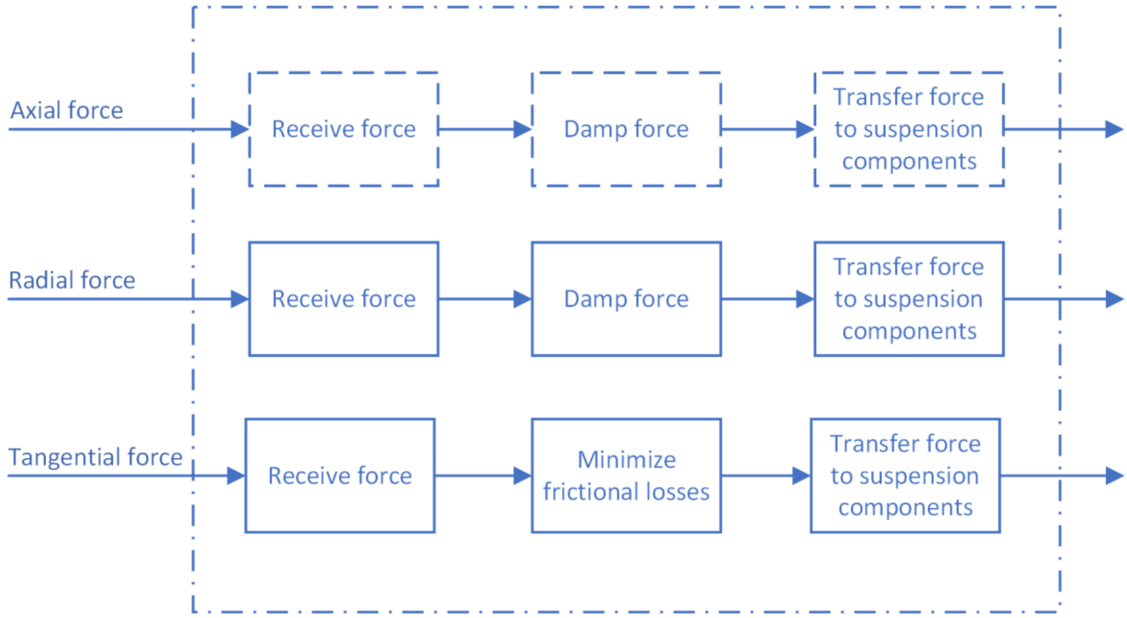


Figure 15. *Function structure of a guide shoe contacting element*

Search for working principles begun by analyzing existing solutions. Additional ideas were gathered by brainstorming and analyzing different technical systems, like train wheels, that perform similar functions. The gathered working principles for the main functions:

- Receive forces: sliding or rolling contacting element, magnetic interaction.

- Damp forces: coil spring, elastic material, elastic roller coating, gas spring, leaf spring, magnetic damping.
- Minimize frictional losses: bearing, lubrication, magnetic levitation.

Working principles that use magnetism would require far too much research and development for this project and for that reason they were not considered further. The particular sling for which the roller guide is to be designed, uses parallel pulley arrangement meaning that the hoisting rope diverting pulleys are on one side of the sling in the BTF direction. Since the lifting force is unsymmetrical in the BTF direction, the forces are generally more on the opposite side. In this case, it means that the front contacting element is subjected to significantly lesser forces than the back contacting element. This means that it may be possible to use a sliding contact element in the front even with an unlubricated guide rail. Using a slider is an interesting option since it probably would bring cost savings and it is very space efficient.

For forming working structures, a morphological matrix was used. Working principles for each of the contacting elements were laid to corresponding rows. Total number of possible combinations in this morphological matrix were 40. However, due to some side rollers integrating front and back direction contact elements, the actual number of compatible combinations were significantly lower. The total number of compatible combinations was 15. Next, the combinations were checked against the requirements list. Concerns regarding wear resistance, strength and noise generation along with the wish to use existing parts led to elimination of working structures with designs that integrate two or three contacting elements into one. In this case it meant elimination of side variants 2–5. This reduced the number to eight. Also, the wish to use minimal number of parts led to disregarding variants with multiple rollers as the back contacting element reducing the total combinations to four. Final morphological matrix is depicted in table 3. The remaining working structures were concretized by 3D-model creation. The models were gathered into table 4.

Table 3. *Morphological matrix.*

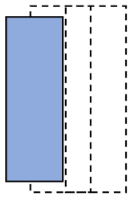
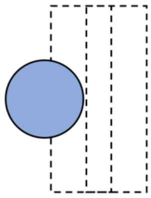
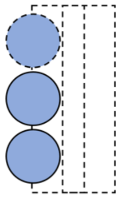
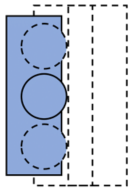
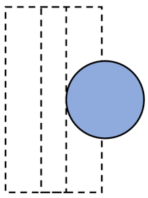
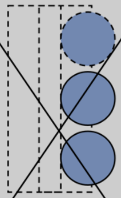
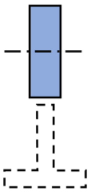
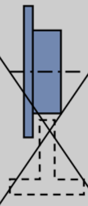
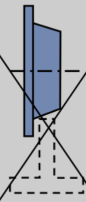
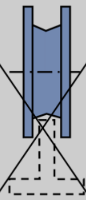
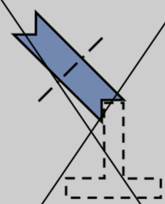
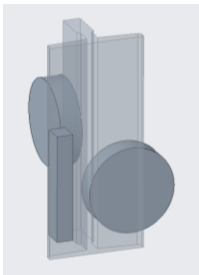
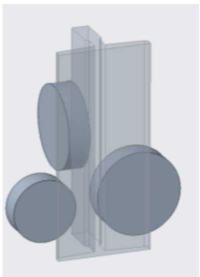
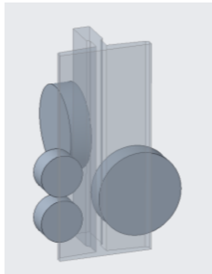
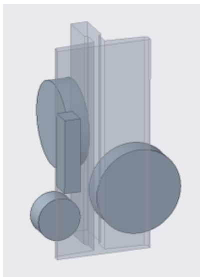
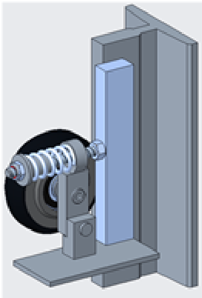
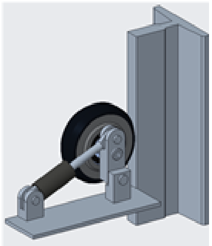
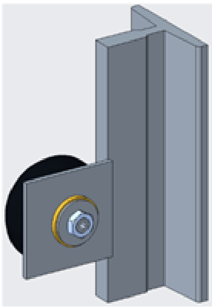
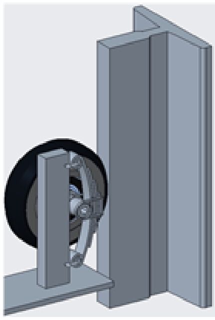
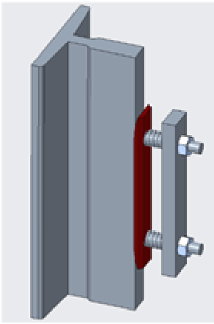
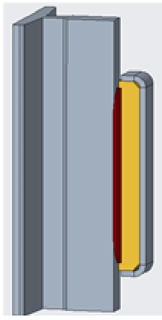
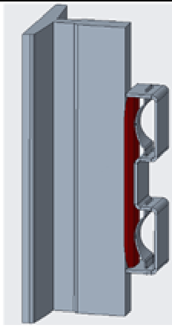
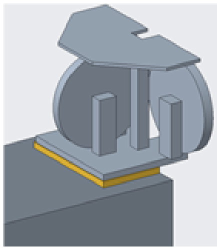
Variant / Contacting element	1	2	3	4	5
Front	 Slider	 Roller	 Multiple (smaller) rollers	 Roller(s) and slider	
Back	 Roller	 Multiple (smaller) rollers			
Side	 Roller	 Roller with flange	 Conical roller with flange	 Symmetrical conical roller with flanges	 Angled roller

Table 4. *Concretized working structures.*

Variant number	1.	2.	3.	4.
				
Explanation	Slider	Roller	Multiple smaller rollers	Slider + roller

No evaluation and further reduction of variants were done in conceptual stage since the variants could not be evaluated in a meaningful way without a rough embodiment. Working principles for damping were also concretized by creating simple examples as 3D-models. The 3D-models help to visualize the types of structures and rough space requirements of using different damping methods. The examples were gathered into a classification scheme that is depicted in table 5.

Table 5. *Classification scheme of damping methods.*

Working principle / Damping location	Coil spring	Gas spring	Elastic damper material	Leaf spring / elastic metal component
Roller suspension				
Slider suspension				
Body-sling-interface				

Another damping method is to rely solely on the elasticity of the contacting element. For example, sliders are typically made of somewhat flexible polymer materials and rollers already have an elastic coating. This, however, presents new possible problems. Since hardness of the material and its wear resistance are often linked, it may be difficult to have both sufficient damping and sufficient wear resistance on the same part. Furthermore, this kind of damping would not be able to damp vibrations emitting from the bearing of the roller. Since the spatial constraints are very prominent in this task, elastic material seems to be the most promising damping method due to its good space efficiency.

4.3 Embodiment Design

The key problems to solve in the embodiment design phase are:

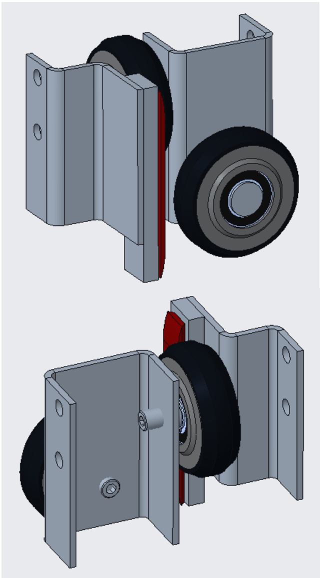
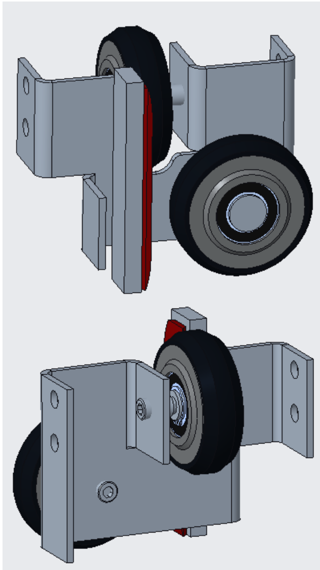
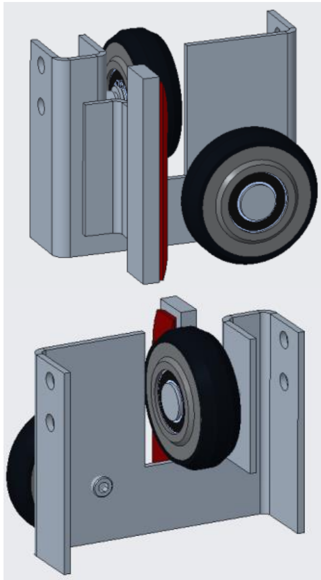
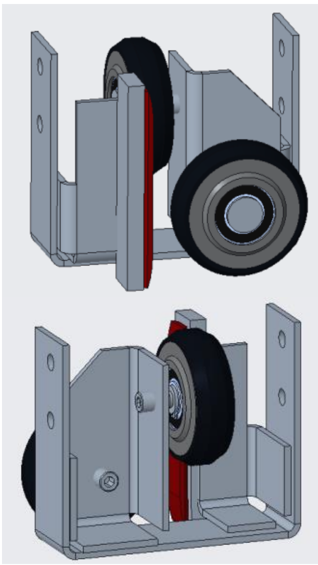
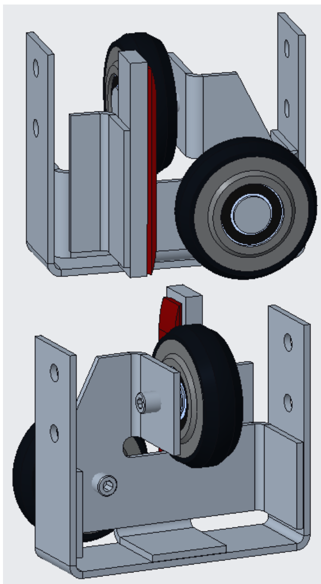
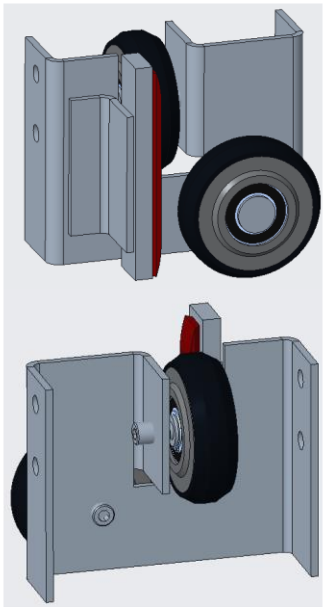
1. fit as big as possible rollers
2. create interfaces that facilitate assembly, installation and maintenance

3. make the structure adjustable to compensate tolerances.

Embodiment design phase started with figuring out the maximum diameter that the rollers could have. Studying the spatial constraints revealed that if a roller that was fitted as the front contacting element it could have a maximum diameter of 60 mm. If multiple rollers were installed instead, the maximum diameter they could have is 40 mm. This raised questions about performance, but also brought possible space savings at least in one dimension. The maximum roller diameter for back and side contacting elements was 80 mm. With this information, the design of rough layouts was started.

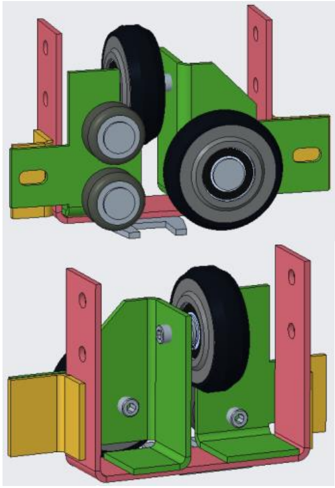
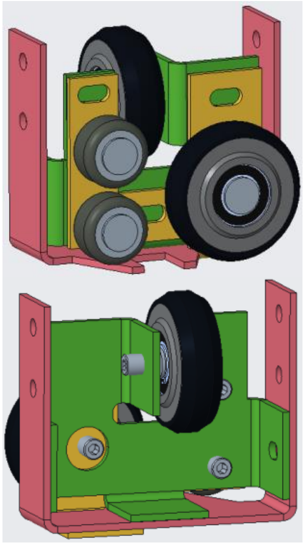
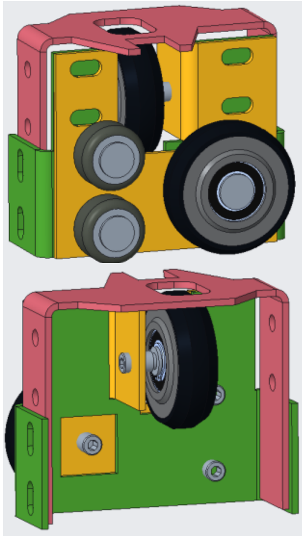
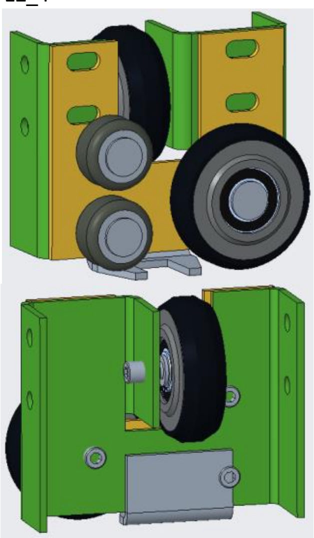
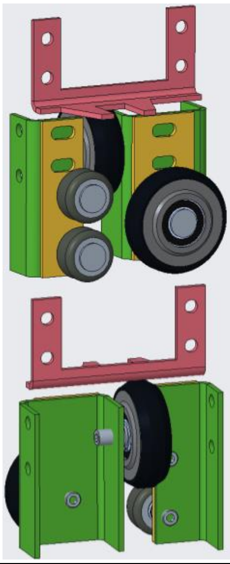
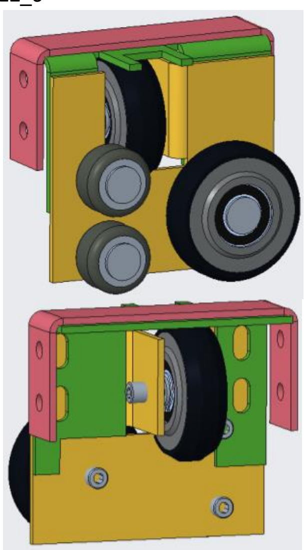
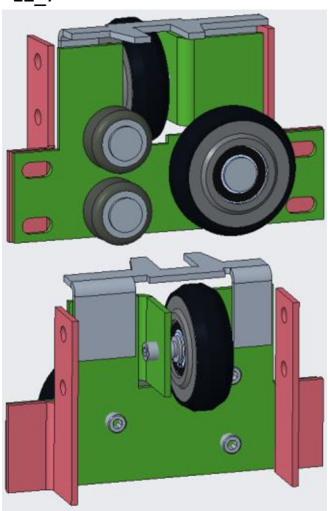
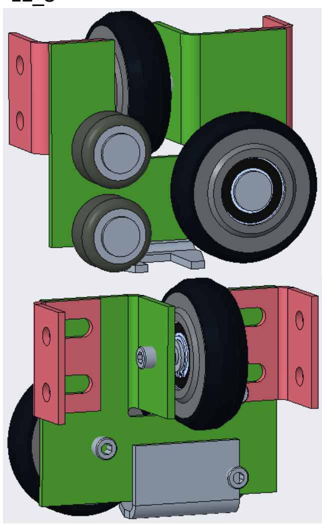
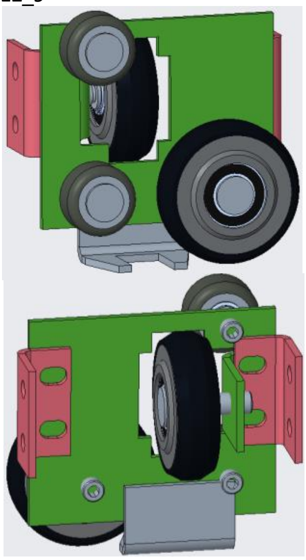
First round of design yielded 6 different variants. The variants were designed using a slider as the front contacting element, but the other concept variants were also kept in mind. The variants were named using a format EX_1_X_2, where E stands for embodiment, X_1 is the number of the design round and X_2 is the number of the variant. The variant number is not inherited from previous rounds, because some later round variants combine design elements from multiple different variants and thus have no direct relation to only one previous variant. The results of the first round of embodiment design are depicted in table 6.

Table 6. *Results of the first round of embodiment design.*

E1_1 	E1_2 	E1_3 
E1_4 	E1_5 	E1_6 

Variant E1_3 was eliminated because it did not comply with KONE's sheet metal guideline. E1_2 was also eliminated due to it being just slightly different to variant E1_6. More information was needed to perform selection based on evaluation. The best way to gather information was deemed to be performing another round of design. In the second round, the variants were refined, and new ideas were also modelled. Adjustability was also considered and different ideas for implementing the safety throat were explored. In this round, two 40 mm rollers were put as the front contacting element to see how they would fit. The results of the second round of embodiment design are depicted in table 7.

Table 7. *Results of the second round of embodiment design.*

E2_1 	E2_2 	E2_3 
E2_4 	E2_5 	E2_6 
E2_7 	E2_8 	E2_9 

After modelling different ideas, it became obvious that possible space saving benefits from having multiple smaller rollers would be minimal at best. When considering this and the facts that two 40 mm rollers would probably increase costs of manufacturing and assembly by having a larger part count, the idea of using multiple rollers as the front contacting element was also eliminated. This meant elimination of variant E2_9 since it was designed specifically for double rollers.

Sometimes during installation and maintenance it is necessary to run the elevator using temporary sliding guide shoes. At these times, the pressure of rollers pushing against guide rails should be lifted somehow. With spring-loaded rollers, clamps can be used to keep the springs compressed and lift the rollers from the guide rail. Other option that works with all damping methods is to make the rollers relatively easily removable. Since elastic damping material seems the most promising for this case, the latter option should be considered. This means that there should be a way to install temporary slider independently of the rollers. During installation the temporary slider is also used to help position the rollers accurately.

The tight spatial constraints also impose limitations on possible installation processes. Because installation process is tightly tied to structural design, it is important to define the process before further embodiment design. From analysis of current roller guides and their installation processes, and analysis of the sling, the following installation process was formed:

1. Install temporary slider to sling
2. Use slider during other installations
3. Adjust and install roller guide horizontally
4. Remove slider
5. Slide roller guide vertically to running position and finish installation

In the process, there should be a way to install the slider directly to the sling. Also, it would be preferable if the safety throat was also installed directly to the sling to make its position independent of possible deflections and dislocations of the guide shoe assembly. This led to a conclusion that the solution should have a safety throat that is directly attached to the sling and that there should be a way to attach the temporary slider to the safety throat. With minor changes all of the variants were compatible with this process.

Because all variants were compatible with the installation process, an evaluation process was done to select the most promising variants for further design rounds. The requirements list, design principles and DFX guidelines were studied to come up with evaluation criteria which are gathered in table 8 along with the results of the evaluation. The criterion of “ease of installation and maintenance” was evaluated based on how clear and easy to access the interfaces were and how much space there was to do installation and maintenance operations. Material costs were calculated simply by calculating the combined sizes of workpieces needed for each part. Processing costs were estimated by calculating how much material would have to be removed and how many different bending actions would have to be done to achieve the desired shapes of the parts. Perceived strength was based on heuristic estimation that comprised of estimates of force transmission paths, moment arm lengths and structure stiffnesses. Adjustability took into account the different directions of possible adjustments. The criterion “small part count” was weighted by a factor of 2, because part count reduction often brings large savings in manufacturing and assembly [29]. A large part count leads almost inevitably to more joining components and costly assembly hours. It should be noted that the values are largely based on estimations and as such they should not be taken as the definitive truth. However, they should help spotting clear deficiencies and trends.

Table 8. *The results of evaluation.*

Variant	E2_1	E2_2	E2_3	E2_4	E2_5	E2_6	E2_7	E2_8	Avg
Small part count	2	4	8	8	4	8	6	6	5,8
Small amount of different parts	1	1	3	3	1	3	2	3	2,1
Ease of installation and maintenance	0	1	4	2	2	3	4	2	2,3
Low material costs	2	1	1	3	3	4	3	4	2,6
Low processing costs	1	1	1	3	3	3	2	3	2,1
Perceived strength	3	3	3	3	1	2	1	2	2,3
Adjustability	2	2	3	2	2	4	2	2	2,4
Overall score	11	13	23	24	16	27	20	22	19,5

Of the top scoring variants, only one had an obvious weak spot. The variant E2_3, which otherwise had a good score, got low points on material and processing costs. This called for a closer inspection. The inspection revealed that the biggest reason for high material and processing costs was the frame part to which the safety throat is integrated. As one can see in figure 16, the workpiece needed for this part is quite large and under half of it is actually used in the part. Next, it was checked if the frame–safety throat part could be redesigned to eliminate the weak spots.

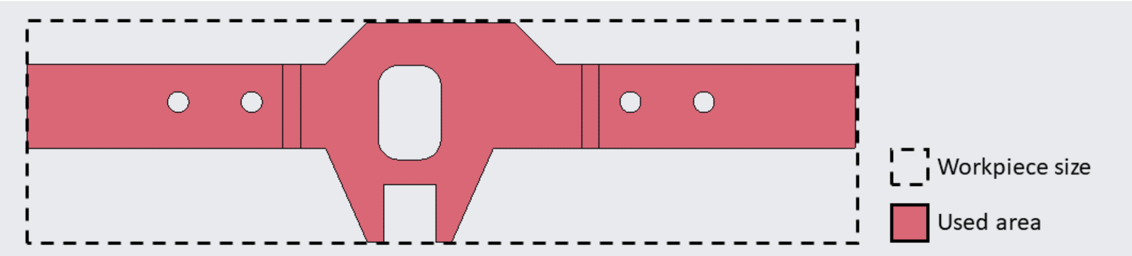


Figure 16. *Safety throat integrating frame part with required workpiece size*

The redesign yielded two variants: one (E2_3A) in which safety throat design was adopted from variant E2_5, and one (E2_3B) in which the original frame–safety throat part was split into discrete pieces. The variants can be seen in figure 17.

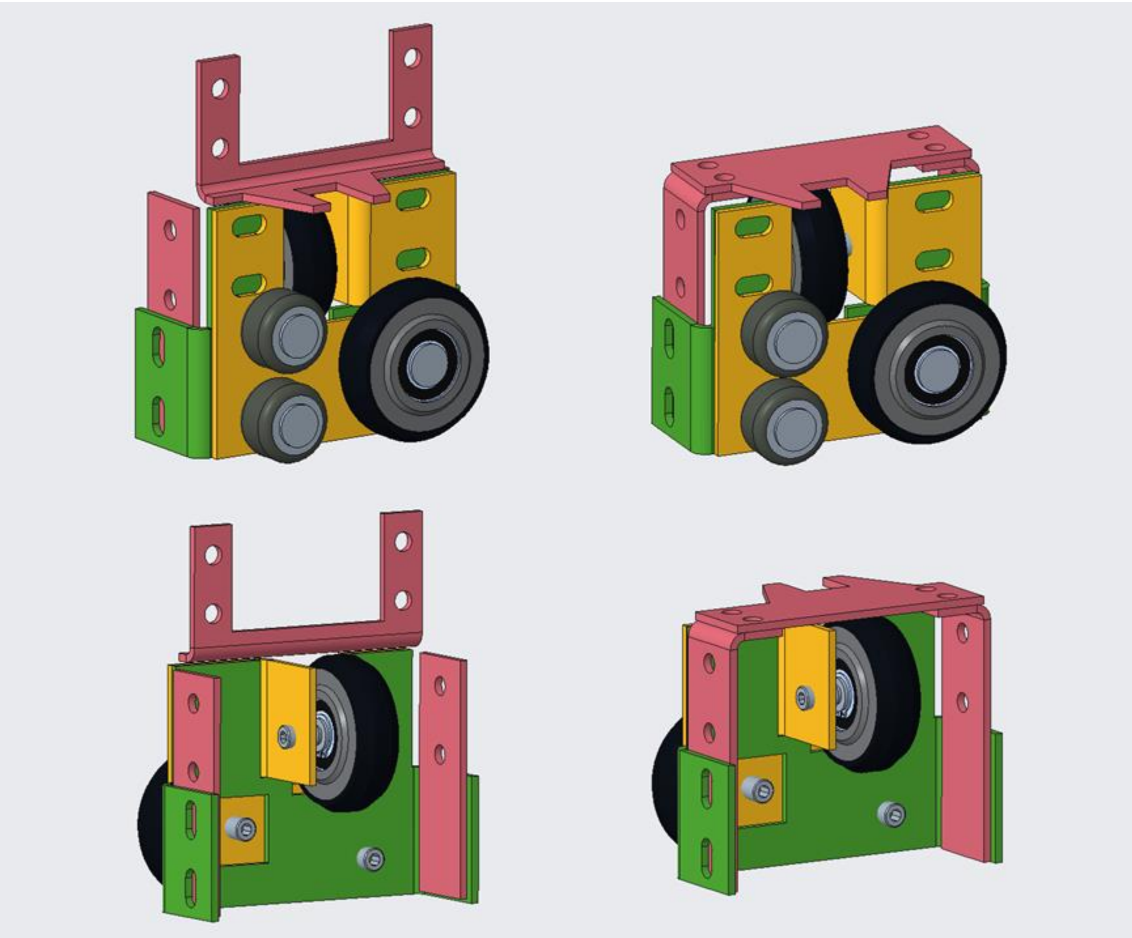


Figure 17. *Redesigned variants of E2_3. E2_3A is on the left and E2_3B on the right*

The two variants were then evaluated with the same criteria. Both variants managed to create a more balanced value profile by lowering material and processing costs and thus increasing the corresponding values. Unfortunately, the redesign also increased the part count which led to lower scores on corresponding evaluation criteria. The crammed interfaces of variant E2_3B dropped its ease of installation and maintenance score by one while the decoupled safety throat of E2_3A enabled better adjustability of the rollers increasing the value of the adjustability criterion. Between the two variants, E2_3A was the clear winner. Evaluation score comparison of E2_3 and its variants is depicted in table 9.

Table 9. *Variant E2_3 scores after redesign.*

Variant	E2_3	E2_3A	E2_3B
Small part count	8	4	4
Small amount of different parts	3	2	2
Ease of installation and maintenance	4	4	3
Low material costs	1	2	2
Low processing costs	1	2	2
Perceived strength	3	3	3
Adjustability	3	4	3
Overall score	23	21	19

Because of the high importance of part count, neither of the variants was able to reach the overall score of the original design. Now a decision between a balanced value profile and a higher overall score had to be made. Eventually a decision to stick with the original design was made. By utilization of nesting, the wasted material shown in figure 16 would greatly decrease which would bring down the material costs as well as the calculated processing costs which are artificially inflated due to simplified calculation method. The four strongest variants were then selected for further development meaning that variants E2_3, E2_4, E2_6 and E2_8 would go through another round of design.

Material thickness was increased to a value that a final product is more likely to use. Also, using thicker material in modelling helps to ensure that the design maintains proper clearances with different material thicknesses. This time a 60 mm roller was fitted as the front contacting element to verify that a suspension could be fitted. Attaching a slider would be simpler so it was not considered in detail.

Now a decision about damping method had to be made. It was already established that an elastic material would probably be the best from the perspective of meeting the strict spatial constraints. After consideration, a decision was made to locate the damping material between the connection of the axle and the body. The reasons that led to the decision were:

- Damping vibrations as close to the source as possible to minimize vibrating components. The higher the number of vibrating components, the greater the probability of rattling, resonance, fatigue and fretting.

- Damping structures located in the interface between the guide shoe and the sling would possibly make on-site installation and maintenance work significantly more difficult.
- Controlling the compression of each of the contacting elements individually would be difficult with a shared damper.
- This solution is already in use and has proven to be functional.

The currently in-use damping assemblies were fitted to the variants to see if the same parts could be used. The current dampers were too large to maintain sufficient structural strength, and some modifications had to be made. The height of the dampers was reduced, which brought significant improvements. This can be seen in figure 18.

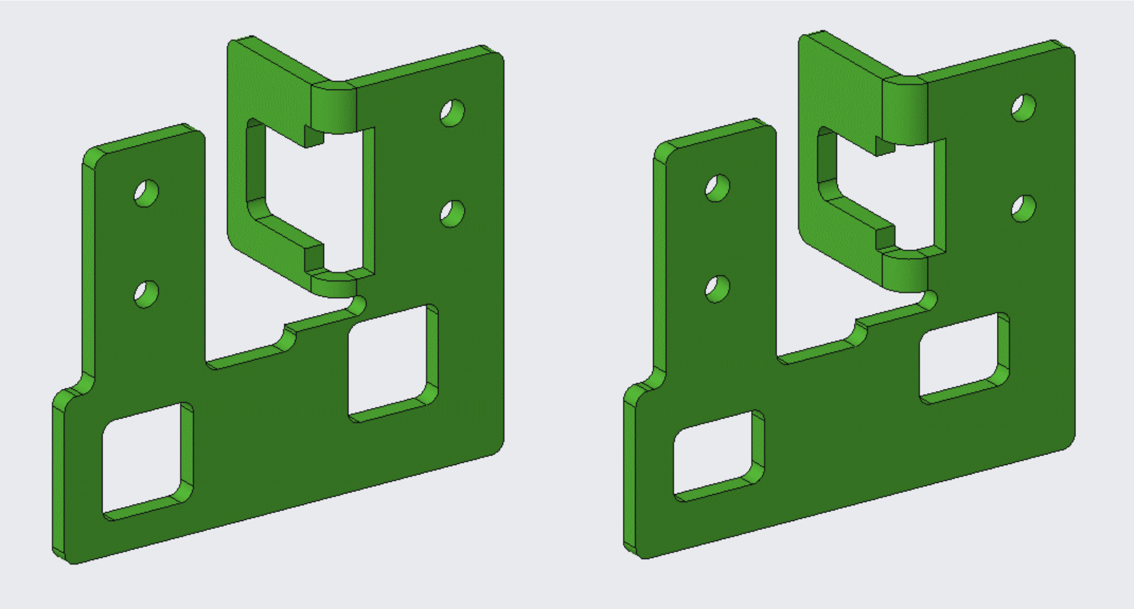
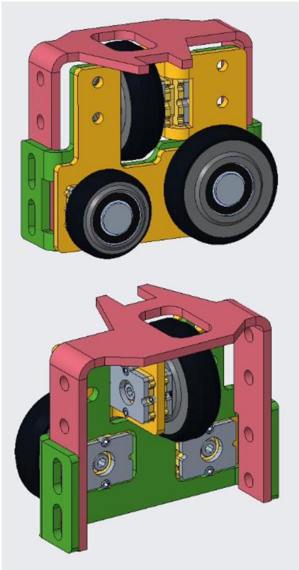
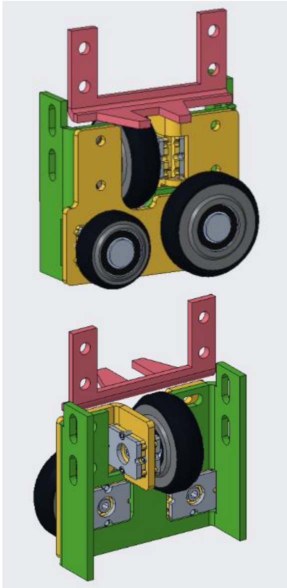
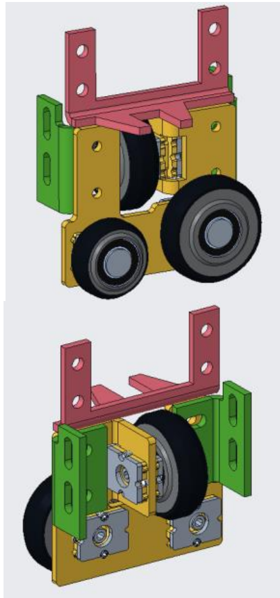
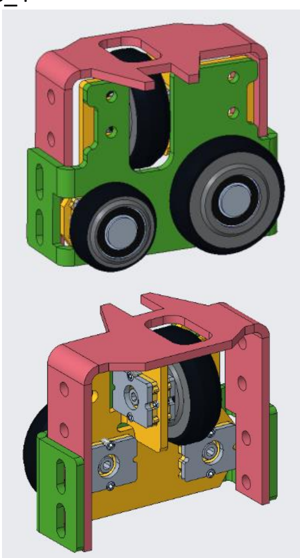
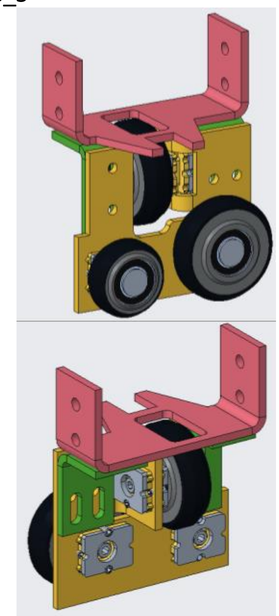
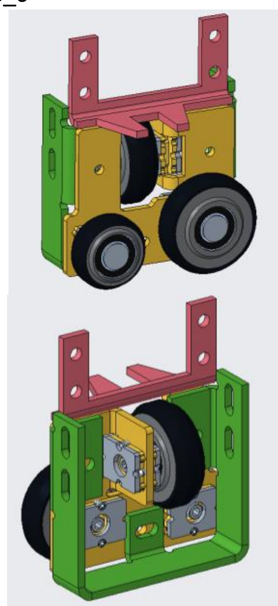


Figure 18. *Example of how reducing the height of dampers enables higher strength of structures. Original is on the left and on the right is the reduced height version*

In addition to adding the damping structures, all variants were now designed so that they would comply with the presented installation process. The third round of embodiment design yielded six variants that can be seen in table 10.

Table 10. *Results of the third round of embodiment design.*

E3_1	E3_2	E3_3
		
E3_4	E3_5	E3_6
		

An evaluation was done again. This time, the criteria “low material costs” and “low processing” costs were combined into “low manufacturing costs” to reduce the relative importance of the very simplistic calculation methods. The goal was to select one variant for further development. The results of the evaluation can be seen in table 11.

Table 11. *The results of the evaluation of the third round of embodiment design.*

Variant	E3_1	E3_2	E3_3	E3_4	E3_5	E3_6	Avg
Small part count	8	8	6	8	6	8	7,3
Small amount of different parts	3	3	2	3	2	3	2,7
Ease of installation and maintenance	4	2	2	4	4	2	3,0
Low manufacturing costs	2	3	4	2	4	3	3,0
Perceived strength	3	2	1	3	1	2	2,0
Adjustability	3	2	2	3	3	2	2,5
Overall score	23	20	17	23	20	20	20,5

The two top scoring variants, E3_1 and E3_4, scored the same points for each of the criteria, and thus their overall scores were also the same. This makes sense because the variants were very similar. To select the stronger variant, they were checked with the design rules and principles in mind. Variant E3_1 had advantages over E3_4 from the perspectives of clarity and simplicity especially when considering assembling. This led to choosing the variant E3_1 over E3_4. Now that only one variant was remaining, finalization and optimization of the layout took place. The selected variant is presented in figure 19 to help the reader follow the rest of the chapter.

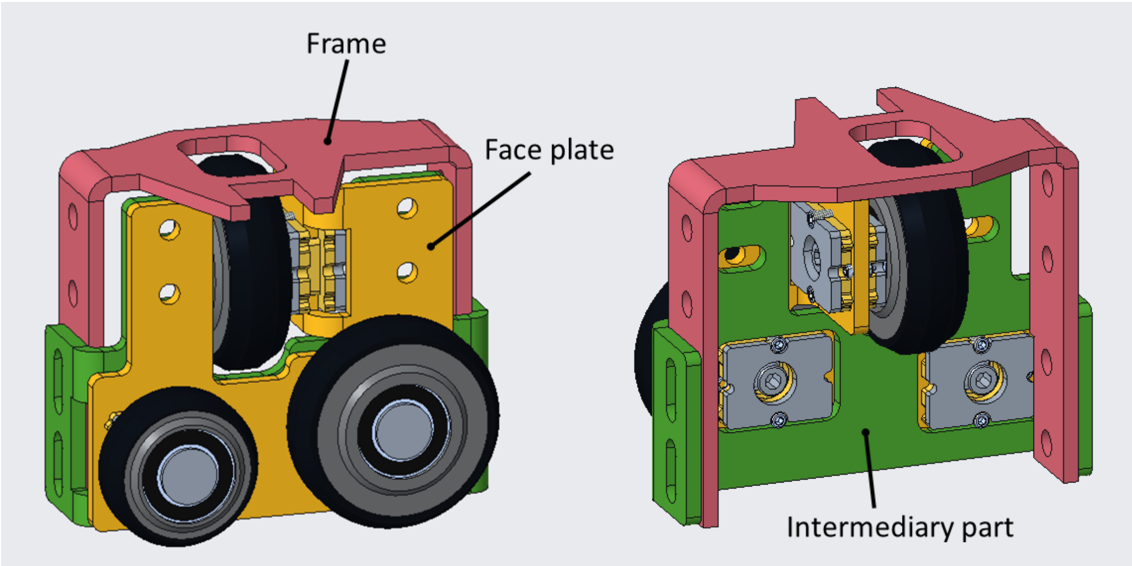


Figure 19. *Variant E3_1 body parts named*

Some optimization options mostly about strength and stiffness of the structure rose up. One concern was stiffness in DBG direction. The solution was to bring the intermediary part inside the frame part and extend the flanges higher, which increased stiffness and shortened travel distance of forces. These changes also brought manufacturing costs slightly down because the workpiece would be smaller and less material would have to be removed. Another benefit was that the frame part could be made deeper and thus stronger. Slot holes were moved from intermediary part to frame part which further shortened force travel distances. These changes are presented in figure 20.

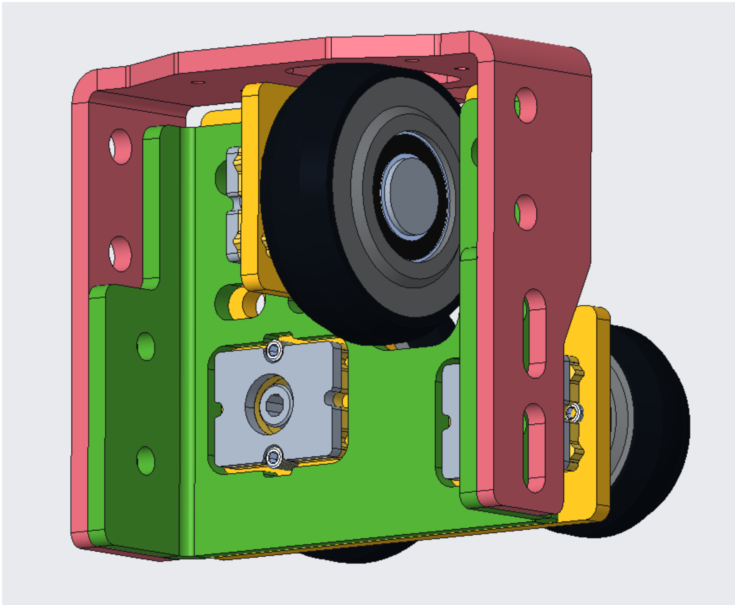


Figure 20. *Variant E3_1 with optimization changes*

Other possible ways to further strengthen the structure would be adding a connective flange from the top of the intermediary part to the roof of the frame and adding or moving a fixing point to the bottom of the intermediary part and the face plate. However, these changes would make the interfaces less clear, and for that reason they were left out for the time being. These possible changes are presented in figure 21.

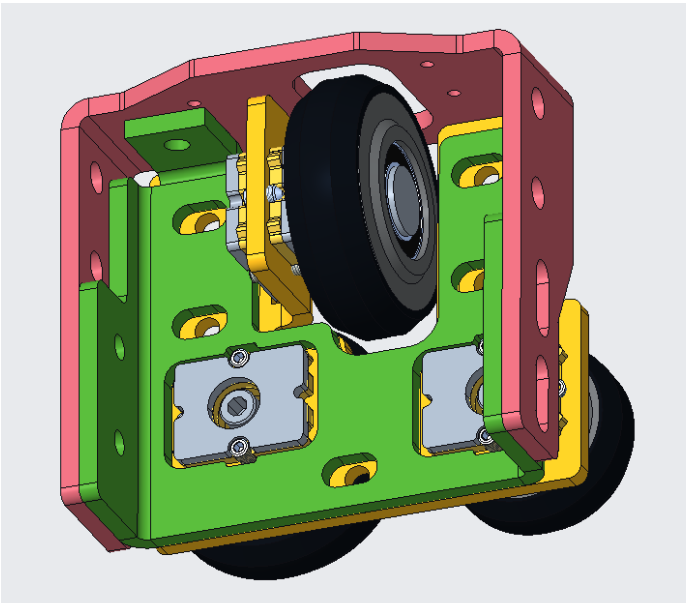
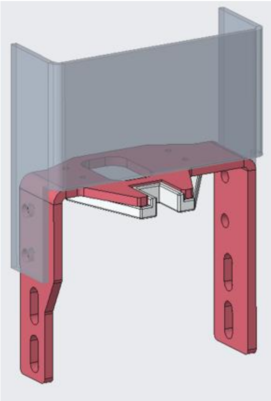
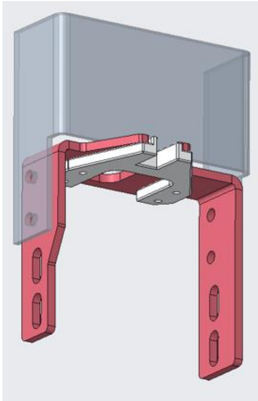
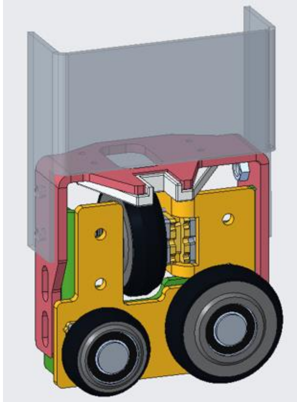
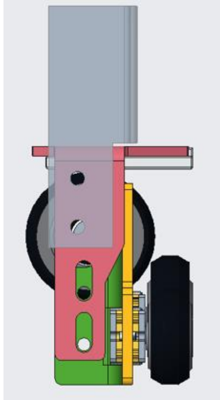
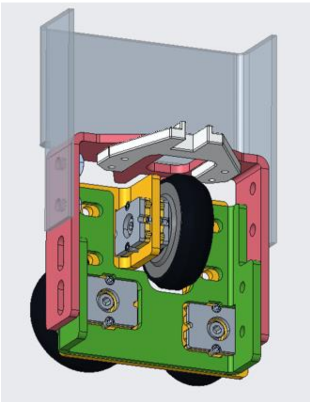
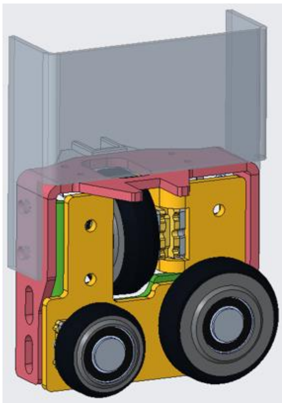
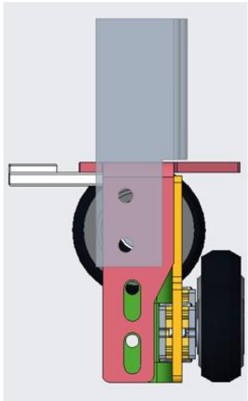


Figure 21. *Possible strengthening changes*

Lastly, it was verified that the designed roller guide complies with the presented installation process and fits inside the space reservation. The installation process with the roller guide is depicted in table 12 and spatial verification is depicted in figure 22.

Table 12. *Verification of installation of the designed roller guide.*

1. Install temporary slider to sling 2. Use slider during other installations  	3. Adjust and install roller guide horizontally - Use slider to locate roller guide  
4. Remove slider - Install slider backwards to avoid misplacing it 	5. Slide roller guide vertically to running position and finish installation  

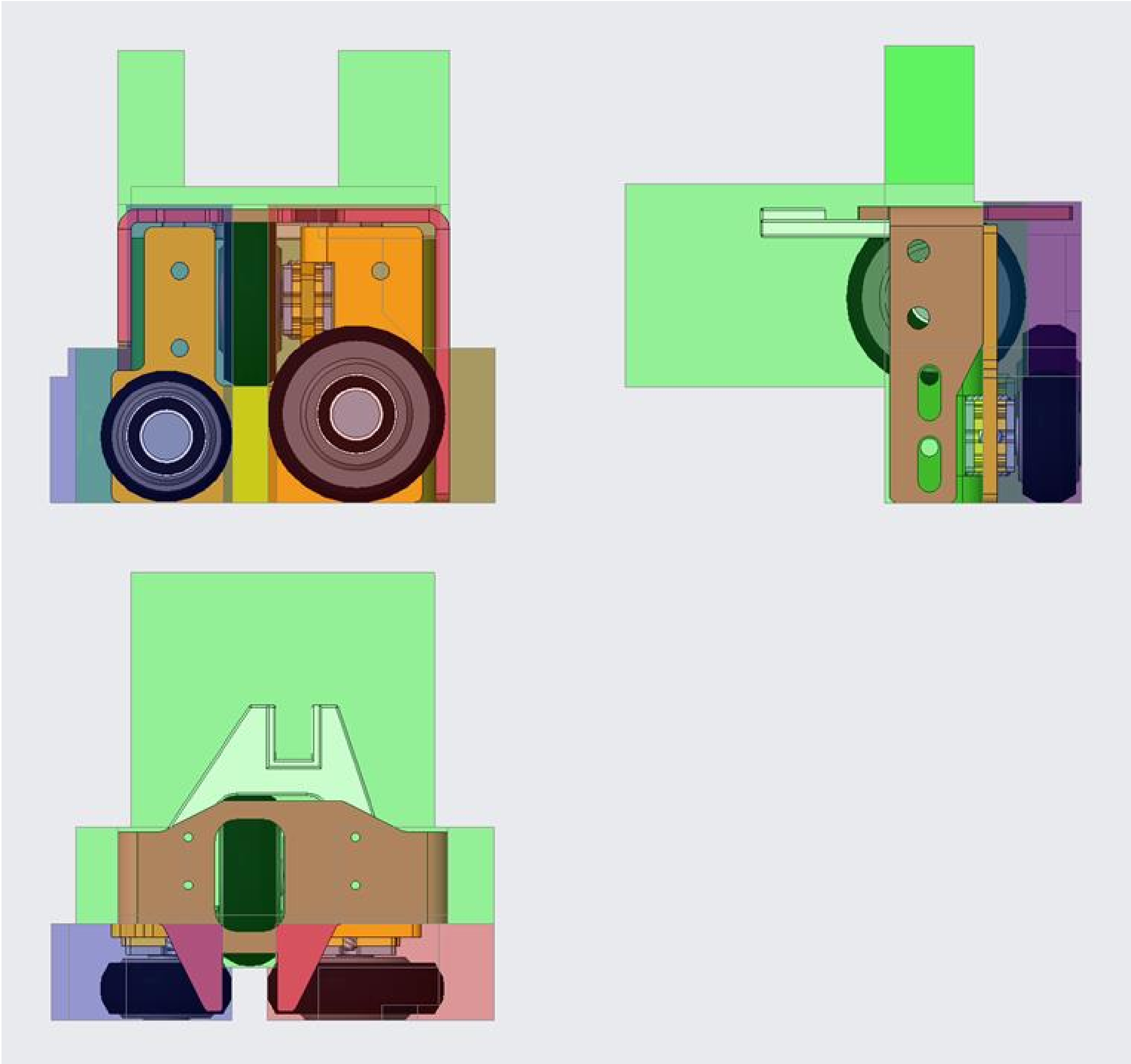


Figure 22. *Verification of meeting the spatial constraints*

5. RESULTS

It was already established in the last chapter that the roller guide meets the spatial constraints and is compatible with the installation process. In this chapter, we go through the results of the design process and check how well the selected roller guide matches the requirements, design rules, principles and guidelines.

First, it was checked how the concepts of divergence and convergence manifested during the process. The convergence and divergence phases were clearly present through the development process, most notably in the embodiment design phase. The divergent phase of embodiment design round 1 yielded 6 variants which was then reduced down to 4. In the second round, 9 variants were developed and then the number was reduced again down to 4. The last design round again diverged up to 6 and converged to the final variant. The divergence-convergence pattern can be seen in figure 23 where the dots represent the variants.

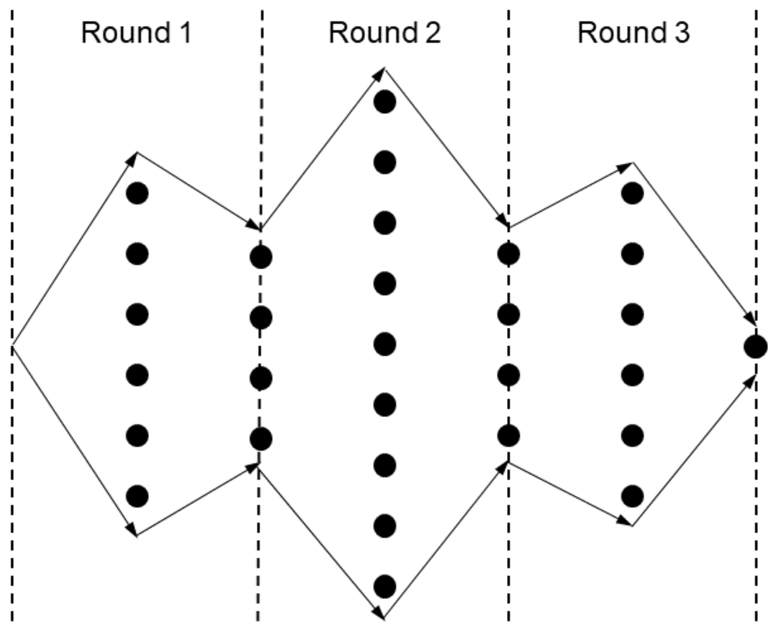


Figure 23. *Divergence and convergence through embodiment design phase*

Next, the final design variant itself was reviewed thoroughly. The design seems to fulfil most of the requirements from the requirements list to the extent that they are possible to assess at this point. Here are a few notes about a couple of important requirements:

- Requirement "Use d70 or d80 roller wheels":
    a. D80 rollers fit as the back and the side contacting elements. To the front side a D70 roller would fit nominally with both guide rail nose widths but

when accounting for possible deflections, and manufacturing and installation tolerances the clearances would be dangerously small with a 16 mm guide rail. With 9 mm guide rails D70 rollers may work without any problems.

- Requirement “Use existing parts when possible”:
    a. The existing 80 mm rollers will probably work with the designed roller guide. Only the axle needs to be redesigned.
    b. The damping assembly could not be used as such but with small modifications, like height reduction, they are probably usable.

To verify the fulfilment of requirements, load bearing capabilities should be calculated, maximum nominal speed should be validated with testing, and assembly, installation and maintenance processes should also be validated by testing.

Different directions of adjustability and the ease of adjustment work were considered extensively. Currently the roller guide is adjustable by ±4 mm in BTF direction (x-axis). To fully achieve this, the radii of the damping plates should be increased and the direction-indicating triangles on the polyurethane damping plate should be removed or a cut-out should be made for them to the intermediary part. Realistically, ±4 mm adjustment range is far more than enough and a range of about ±2 mm would probably suffice. Depending on the clearances of slots and holes some rotational adjustability can also be possible around the y-axis (DBG direction). Rotating the whole face plate would have an impact on the distance between the front and the back roller. However, even with 5 degrees of rotation the distance would be reduced by only about 0,3 mm. These adjustments are depicted in figure 24.

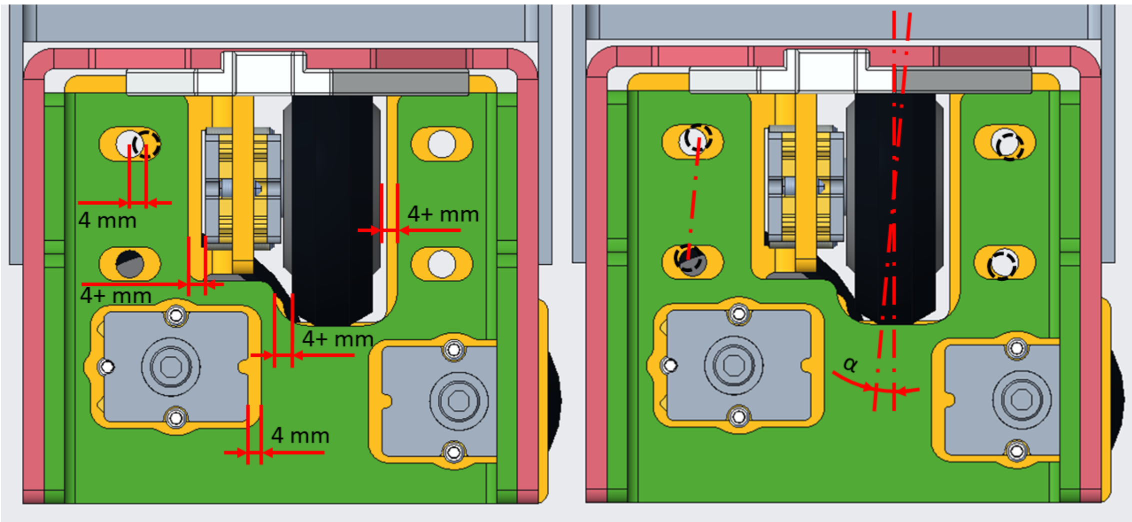


Figure 24. Some possible adjustments

The design allows for 15 mm vertical sliding of the roller guide to make room for the temporary slider when installing the roller guide. Depending on the hole clearances between the frame part and the sling some amount of rotational adjustment may be possible around the x-axis (BTF direction). Depending on the shapes and clearances of the holes linear adjustment in the DBG direction (y-axis) is also possible. These adjustments are depicted in figure 25.

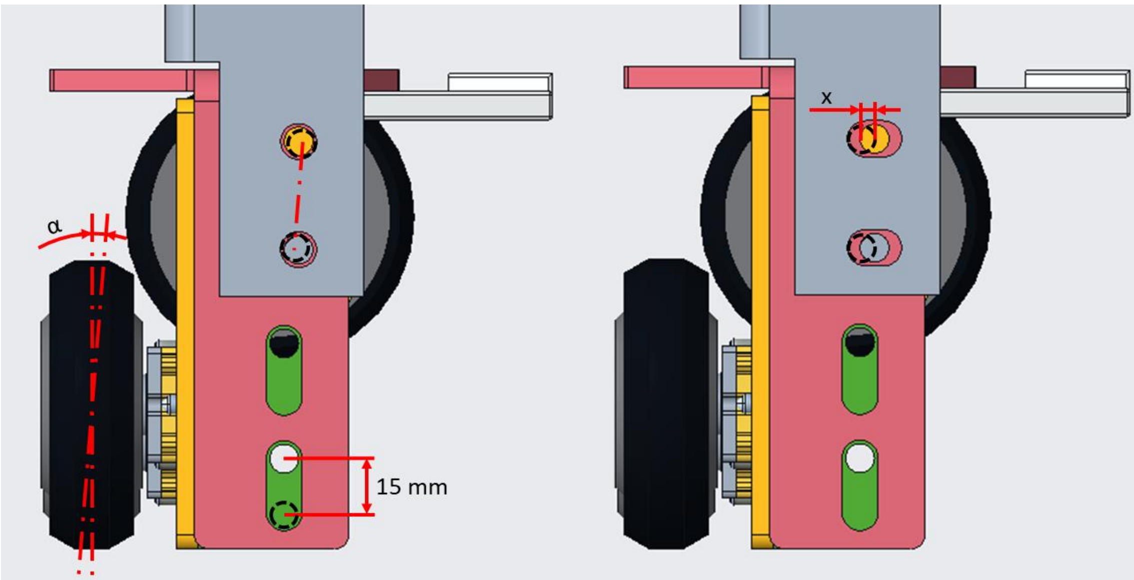


Figure 25. Other possible adjustments

The basic rules of embodiment design are the foundation on which successful solutions are built. For this reason, they were kept in mind during the whole design process. The basic rule of clarity was considered in the following ways:

- Assembly sequence is clear, it should not be possible to assemble parts in wrong order or it is clear which orientation is correct.

- Interfaces are well defined and separated, which reduces ambiguity about force transmission paths.
- Directions of external forces are well known, so strength of the structure can be estimated based on them. Actual calculations are needed to verify sufficient strength.
- The installation process could be a little more straight forward. It would be possible to have an installation process without the vertical sliding procedure, but this would make adjustment work significantly more laborious and tedious. Furthermore, this type of installation process is already in use so only minimal training is needed for the installers. These trade-offs make the proposed process well worthwhile.

The basic rule of simplicity was considered in the following ways:

- All sheet metal parts are simple to manufacture. Only basic processing operations are needed, and all material removal can be done before bending, so there is no need to alternate between material removal and bending, which would waste time and increase manufacturing costs.
- All parts are either completely identical or noticeably different, so they are easily identifiable.
- Bolt sizes are not yet defined but it is probably possible to use same bolts in every hole excluding the temporary slider for which large bolts may be unnecessary. The current design supports at least M8 bolts in all body interfaces. Not too much focus was put on defining bolt sizes since strength calculations may present reasons to use different size bolts in different interfaces. It is possible to use press nuts or threaded holes to minimize need for tools and part handling.
- The chosen installation process means that adjustments are not lost during maintenance saving labour costs.
- Disassembly is as easy as assembly. The design uses mostly recyclable and repurposable materials. Most of the guide shoe consists of steel which is notoriously well recyclable.

The basic rule of safety was considered in the following ways:

- In most loading cases, the structures push against each other instead of pulling apart.
- Suspension has stopper screws, so dampers do not compress too much.

- If by combination of damper and roller compression and deflections of the body too much movement would happen, the safety throat prevents the guide rail from contacting the gripping surfaces of safety gears.
- Roller guides are designed to be able to handle disturbances like uneven and misaligned guide rails; they roll over steps and bumps instead of getting stuck to them. Exceeding the maximum nominal speed does not break the roller guides. Instead, it causes ride comfort issues. Rollers use dust-protected bearings to combat environmental disturbances.
- Exact production processes are not yet defined, but at least welding, a process well known to alter material properties, is not used.

Utilizing correct design principles guides designers to make good decisions. Here is how different design principles were used in the final roller guide:

- Principle of flowlines of force: Design utilizes rounded corners to avoid stress concentration.
- Principle of direct and short force transmission path: The lengths of force transmission paths were tried to be minimized. Some suboptimal decisions had to be made in order to have clear and reachable interfaces and sufficient adjustability.
- Principle of matched deformations: The guide shoe is made mostly of same material, so the deformations should also be equal across parts. Those parts that deform differently are specifically designed to do so.
- Principle of division of tasks for distinct functions: In a roller guide, receiving forces is divided in three directions and there is a distinct roller for each direction. Also, each roller has its own adjustable damper giving more precise control of compression behaviour. A use case of this principal could be the proposition that a roller and a slider would share the responsibility of being the front contacting element. In normal ride the function of the roller would be providing smooth riding experience and under higher loads the slider would take the function of receiving forces.
- Principle of division of tasks for identical functions: This principle is already used regularly in elevators, most notably in hoisting ropes. Another interesting use case of this would be the idea of using multiple rollers as a single contacting element as proposed earlier in this thesis.
- Principle of self-protecting: The idea of using a roller and a slider together as presented in division of tasks is also self-protecting. The slider engaging at high

loads would extend the lifetime of the roller. Also, in dampers there are stoppers that limit the compression, which protects the polyurethane damping material and protects the rest of the elevator components from accidental contacts.

- Principle of stability: The stabilizing forces of the roller guide are higher the larger the compression is. Also, the rollers are in pretension against the guide rails which means that when disturbances happen the pretension lifts from the opposite side further driving the system towards the stable middle position. Furthermore, wheels are inherently stable, and their stability increases as their angular velocity increases [30].

With different design for X guidelines, designers can view the task on hand from the perspectives of different objectives. The different objectives chosen for this task were wear resistance, assembly and manufacturing. Design for wear resistance was considered in the following ways:

- The structure allows the rollers to be aligned with the guide rail.
- Minimal sliding motion occurs in coated rollers.
- Used materials and their properties are well known and proven to work in use.
- The bearings are dust protected.
- The design allows replacing smaller assemblies and some individual parts easily instead of needing to replace the whole guide shoe.
- The components most susceptible to fretting are the bearings. Not much can be done about it besides selecting the best bearings for the conditions.

Because assembly and mechanical installation are closely related, they are both considered here. Design for assembly was considered in the following ways:

- Tight spatial constraints meant that there is also very little space available for installation work. Therefore, positions of different interfaces were carefully considered.
- Minimal amount of assembly operations due to minimal part count.
- There is no need for tedious adjusting and measuring for each dimension because the roller guide is positioned with the temporary slider.
- There are only simple bolted connections with possibility to ease them further with press nuts and threaded holes.

- It is fairly self-explanatory how the parts attach to each other. Probability of mistakes is low.
- Clear and simple interfaces. Symmetric and consistent interfaces. Different interfaces are visually different and physically separated.
- Possibility to use same bolts in almost all interfaces.
- No stacked interfaces in the body which means that there is no possibility to stack parts in the wrong order.
- The interfaces that are needed in maintenance are easily accessible when the roller guide is attached to the sling.

Design for manufacturing was considered in the following ways:

- Because the roller guide is located with the temporary slider and it is adjustable, there is no need for tight tolerances.
- No need for tight tolerances means that the whole part can be cut before bending instead of alternating between them.
- Some bend radii are smaller than is generally advisable. However, the same radii are already used in current equivalent parts so this should not be a problem.
- The designed roller guide is closer to integral construction than differential construction because of tight spatial constraints and because low part count was preferred for cost saving reasons. Also, integral construction is particularly cost-effective with sheet metal because bending is fast and cheap when compared to welding [31].
- As said, the bended flanges of the roller guide are integral construction. Another way that integral construction was utilized was the integration of the safety throat into the body frame.

Providing good ride comfort is an important function of the roller guide. Determining the ride comfort would require comprehensive testing and measuring or complex simulations. Therefore, no definite results can be given at this point. However, ride comfort was kept in mind during the design process, and it was considered in the following ways:

- Fit as big as possible rollers to minimize vibrations and noise caused of high rotational speed.
- Damp vibrations as close as possible to the source to minimize the number of vibrating components.

- Avoid flanged rollers to avoid potentially noisy sliding contact.

The purpose of this master's thesis was to explore different options of fitting a roller guide into the tight spatial constraints of the space-efficient sling, and design a concept based on the findings. The proposed solution fulfils the requirements that could be reviewed in the scope of the project. It also complies with all the introduced design rules, principles and guidelines in numerous ways. Based on these, it can be stated that the thesis was successful. Also, since a relatively unexperienced designer was able to go through the process independently, and the results of the process seem positive, it is reasonable to say that this thesis further confirms the validity of Pahl and Beitz's design process model as a practical framework for mechanical product development.

Even though objectivity was the goal during the evaluations and the review of the results, there is a possibility of some subjectivity being present, because the evaluations and the review were done by a single person alone who also was the designer. Another way that the results could have been skewed was the fact that the review considered only the perspectives of the introduced design principles and guidelines. In the perspectives of other principles and guidelines the results may have been different. However, the introduced principles and guidelines were chosen because they were seen as the most important and relevant.

6. CONCLUSIONS

Pahl and Beitz's design process model worked well. The model was structured enough to guide a relatively unexperienced designer through the different phases of the process, and yet it was not so strict that it would have hindered creativity. The model does well with emphasizing that even though the process seems to be laid out as a linear list of steps with methods assigned to specific steps, the actual process does not have to follow the model strictly. For example, the evaluation procedure was introduced at conceptual design phase but in this design case, there was not enough information at that point to perform a numerical evaluation. Different design rules, principles and guidelines helped greatly with considering all aspects of the product and different objectives. Sensible compromises were able to be done by combining all the different perspectives.

The final result of the design process seems promising. It fulfils the most important goal of the project: to fit a roller guide into the very tight spatial constraints. It also fulfils all of the requirements to the extent that they could be assessed in the scope of the project. Based on the results of this thesis it seems possible to fit a requirements-fulfilling roller guide inside the specified space in a space-efficient sling.

There were some limitations due to the limited scope of the project. Because the time frame for executing the project and the overall scope of the master's thesis were limited, structural analysis could not be performed, and relatively subjective estimations had to be used instead. Another limitation was that the manufacturing costs were based on very rough calculations. These limitations may have influenced the results of the evaluations and so also the results of the design process. Limited time frame also prevented the process to proceed to a point where the results could have been validated by creating and testing a prototype.

The design still needs some further work. Firstly, new axles for the rollers should be designed in order for them to work with the elastic damping assembly. The old axles are designed for a spring suspension. Secondly, the 60 mm roller used in this roller guide is just a visualization model modified from an 80 mm roller. It may have to be designed from the ground up. Thirdly, structural analysis should be made to ensure adequate strength and appropriate material thicknesses and bolt sizes should be chosen based on the results. The results of the calculation may also bring up a need to modify the structure. Lastly, testing should be done with both options, a 60 mm roller and a slider, as the front contacting element to find out their ride comfort properties. Also, a lifetime cost analysis should be done for both options if they pass the testing.

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APPENDIX A: FINAL REQUIREMENTS LIST

Kone	Requirements list for Sling integrated roller guide		Issued on: 08/03/2022
Changes	Source	D/W	Requirements
			Loads
	SO-07.07.004	D	Must withstand max roller force of 2000 N
			Performance
		D	Nominal speed 1 m/s
		W	Nominal speed 1.75 m/s
			Assembly, Installation and Maintenance
	1365359D01	D	Assembly and maintenance must be able to be done with standard tools
	1365359D01	W	The number of different bolt types and sizes and required tools must be minimized
	1365359D01	W	As little as possible assembling and adjusting must be left to do on site
	1365359D01	D	Assembly work should be as easy and as fast as possible (consider positioning, click-in mechanisms, visibility, ergonomics, usability)
17/12/21	1349800D01	D	Rollers must be aligned vertically or have possibility to adjust it (misalignment reduces ride comfort / may cause excessive axial load to bearings)
	1349800D01	D	Enough space to perform installation and maintenance
	1365359D01	D	Adjustment work should be easy
	1349800D01	D	Guides must be adjustable to compensate tolerances
14/2/22	1349800D01	D	Proper interfaces that facilitate installation and maintenance
14/2/22	1365359D01	D	Parts should be accessible for inspection for condition monitoring (inspection criteria needed)
17/12/21	SO-07.07.004	D	There should be possibility to use a temporary slider for accurately locating the roller guide in relation to guide rail (during installation or maintenance)
17/12/21	SO-07.07.004	D	When using temporary slider, there should be a way to release the compression force of the rollers (for example, removable claps for springs)
	1365359D01	W	Safety gear should not interfere with maintanence of guide shoes

Figure 26. *Requirements list part A*

			Clearances and General Structure
	1365359D01	W	Use existing parts where possible
	1365359D01	D	Sheet metal parts must comply with KONE sheet metal guideline
	1349800D01	W	Interface between guide shoe and basic frame that enables use of different guide shoes
		W	Use D70 or D80 roller wheels
	1365359D01	W	Use as large diameter rollers as possible for noise and vibration reduction and longer lifetime
	SO-07.07.004	D	Must be compatible with guide rail nose widths from 9 mm to 16 mm
	EN 81-20	D	The combination of deflections of guide rails and deflections of brackets, play in the guide shoes and straightness of the guide rails shall be accounted for
	SO-07.07.004	D	Clearance between guide rail and guide shoe safety throat should be max. 5mm to every direction
	ASME A17.1-2019		- Additionally, any failure or wear of guide shoe must not allow more than 13 mm displacement from normal running position
8/3/22	ASME A17.1-2019	D	Clearance on any side between a safety gear's gripping face and the guide rail must not be less than 1.5 mm when guide shoe is fully compressed
	1365359D01	D	Maximum of 2 mm displacement allowed during use
	1365359D01	D	Design must incorporate sufficient damping
	1365359D01	D	Wear resistance must be sufficient for life time of whole assembly
	1365359D01	D	Roller bearings must be protected from dust. RS or ZZ type bearings recommended.
		D	Must fit inside the space constraints (specified in figure 12 and appendix B)
			Materials and Production
	1365359D01	D	Use commonly used materials and manufacturing methods (to enable free manufacturer selection)
	1365359D01	W	Use standard tolerances
	1349800D01	D	Rollers must have sufficient friction
	1349800D01	D	Rollers must be wear resistant
17/12/21	1365359D01	D	Components must be manufacturable/purchasable by at least two different suppliers (2nd source)
	1365359D01	D	Design must withstand shaft's environmental conditions
	ASME A17.1-2019	D	Cast iron must not be used

Replaces issue of 15/12/2021

Figure 27. *Requirements list part B*

APPENDIX B: SPACE RESERVATION

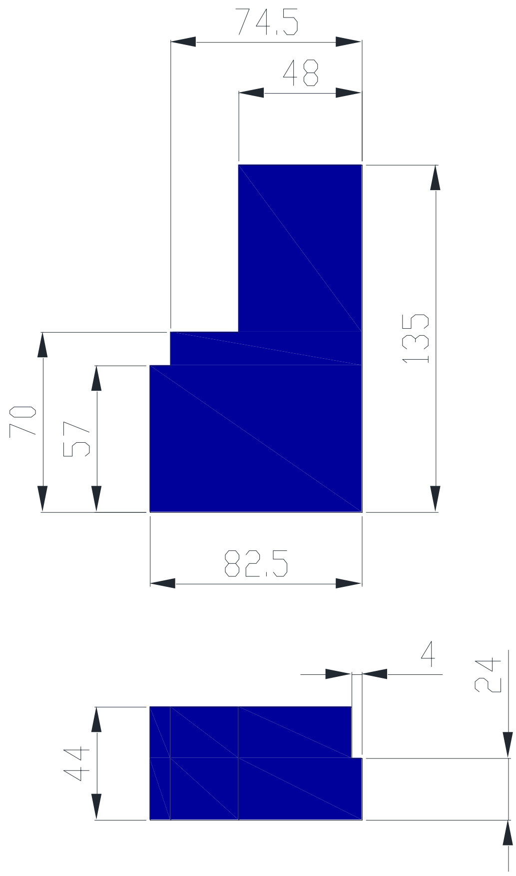

Figure 28. *Front space reservation*

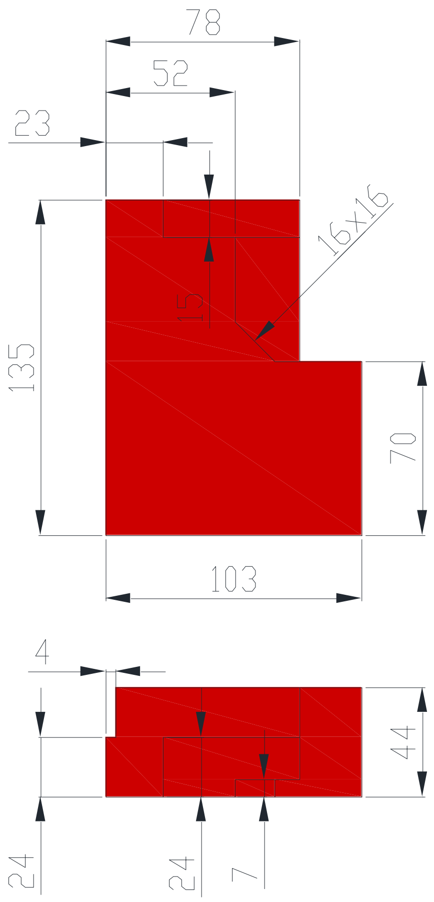

Figure 29. *Back space reservation*

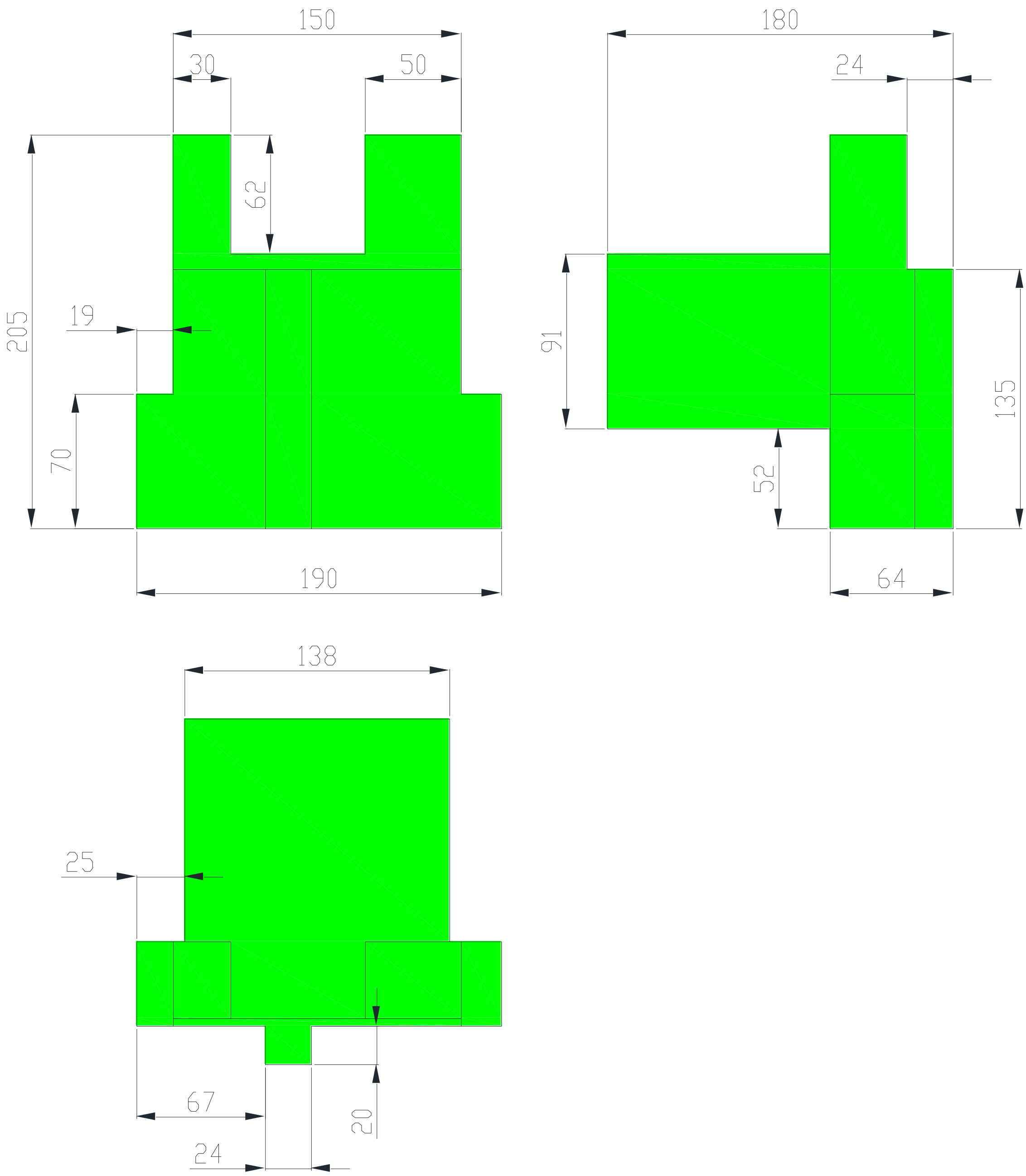

Figure 30. *Side space reservation*