Cost reduction of gymnasium equipment

THE DEVELOPMENT OF A COST REDUCTION FRAMEWORK THROUGH A CASE STUDY

PUBLIC VERSION

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NIJHA

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Preface

This thesis is the result of the project I executed for Nijha BV in order to obtain my Master of Science degree in Industrial Design Engineering at the University of Twente. The thesis comprises two main parts: the case study and the framework. The case study describes the project I did for Nijha, where I reduced the cost price of their Dorack climbing frame. The framework is based on the process followed during the case study and aims at applying the gained knowledge to other cost reduction projects.

Because the case study mentions several parts of the Dorack by name, and these may not mean much to the average reader, I included an exploded view of the product with all parts mentioned in this thesis on page 44.

All references to parts of the thesis, such as page numbers, chapters, sections, tables, figures and abbreviations, are hyperlinks that lead the user to the specific section upon clicking the link.

Certain confidential information is omitted in this public version of the thesis. The profit margin is omitted, as well as monetary values, process times, and names. These values are replaced by the letters X, Y or Z, or removed entirely. Therefore, certain diagrams miss axis labels and some tables have empty cells.

I would like to thank the employees of Nijha for helping me in this project and always making time to help me continue to the next step. I would especially like to thank Frank for his guidance, and Gert, Henry and Wouter for their hospitality at the engineering department.

I would also like to thank Sipke Hoekstra for his academic guidance from the University of Twente. Besides, I would like to thank Sebastian Thiede and Peter Chemweno for taking their time to read my thesis and being part of the graduation committee.

Lastly, I would like to thank my friends and family for their interest in my project. I would especially like to thank my parents for their support in the past 6 years of my student life, who have given me the opportunity to develop myself outside of the curriculum, by participating in the Solar Boat Twente team and studying at the Royal Institute of Technology in Stockholm.

I hope you enjoy reading my thesis.

Roman van den Broek

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List of abbreviations

Abbreviation	**Definition**
ATO	Assemble to order
BOM	Bill of Materials
CAD	Computer Aided Design
CODP	Customer Order Decoupling Point
DFA	Design for Assembly
DFM	Design for Manufacturing/Manufacturability
DFMA	Design for Manufacturing and Assembly
EOQ	Economic Order Quantity
EPQ	Economic Production Quantity
ERP	Enterprise Resource Planning.
ETO	Engineer to order
FEA	Finite Elements Analysis
JIT	Just in time
LUC	Least Unit Cost
MTO	Make to order
MTS	Make to stock
MRP	Materials Requirements Planning
RPA	Rapid Plant Assessment.
SMED	Single Minute Exchange of Dies
WIP	Work in Process/Progress

1 Introduction

To keep a healthy business, companies need to make a profit. The simplest way to calculate profit is to subtract all involved costs from the total revenue. On the level of a single product, this translates to the difference between the sales price and involved costs, known as the profit margin (Oxford University Press, 2010, p. 1213). Due to the dynamic nature of the economy, this margin changes continuously. This can pose challenges for small businesses or businesses with a low volume and high mix product portfolio. This thesis develops a framework for reducing the cost price of a single product of a low-volume, high-mix production company. The framework will be established through a case study and be based on literature about current state mapping, cost reduction, production process optimisation, sourcing decisions, and design for manufacturing and assembly.

1.1 Problem definition

The problem originates from a question of the client company to increase the profit margin of one of their products. The current profit margin is X% and they would like to increase this to Y or Z% without increasing the sales price. The approach taken to solve this problem is converted to a framework that can be applied to other products.

This thesis addresses the following problem:

> A low-volume, high-mix production company wants to increase the profit margin of one of its products by reducing the product's costs.

1.2 Research questions

The central research question in this thesis is:

> How can companies reduce the costs of individual products and how can this process be structured?

The case study aims at answering the following sub-questions:

1. How can the current state of a production facility be determined?
2. How can product costs be classified, and how can they be reduced?
3. How can production processes be improved?
4. How can be determined which parts must be made and which must be bought?
5. What guidelines exist for 'Design for Assembly' (DFA) and how can they be applied to this project?

Question 1 is partially answered through literature research of chapter 3, and partially answered during the orientation phase of chapter 4. Questions 2, 3, 4, and 5 are answered through literature research. The answers to these questions are used in the ideation phase of chapter 5 and the answer to the second half of question 2 forms the main structure of the cost reduction process.

In addition to the research questions described above, the following questions were defined for the ideation phase, which were a result of the orientation phase:

1. How can 'wasteful' operations in assembly (section 4.3) be eliminated or prevented?
2. How can powder coated parts be made cheaper, whilst not compromising functionality or aesthetics?
3. How can standard parts be purchased cheaper without compromising quality?
4. Which welded parts can be combined, to omit certain welding operations?

Because the case study developed a solution for one specific case, the question arose how this process can be applied to other cases. This is formulated as the following sub-question:

> How can the process followed in the case study be applied to other cost-reduction projects?

This question forms the basis for the framework of segment B.

1.3 Scope

The literature of chapter 3 describes various approaches to cost reduction, but no comprehensive approach exists for reducing products produced in a low-volume, high-mix production company. The scope of this thesis is:

> Developing a framework for reducing costs of mechanical (non-electronic) products by looking at how costs are built up and addressing cost reductions for various aspects of the costs.

The scope of the *case study* is formulated at the end of the orientation phase (chapter 4) as:

> The case study should reduce the cost price of the Dorack. This can be achieved by reconsidering the parts of, and processes used for, the product. The alterations cannot compromise the perceived quality, aesthetics, functionality, or safety of the product.

1.4 Method

To answer the research question and stay within the scope, the framework will be established through a case study at a playground and gymnasium equipment manufacturer. Based on findings of the literature research from chapter 3, the case study starts with an orientation phase that is aimed at creating an overview of the company, product and process. The combined findings of the literature research and orientation yield ideas for establishing a solid foundation of the product, several possibilities for major changes to the parts and processes and several minor changes to the parts of the product. After evaluating the ideas with stakeholders, the remaining ideas are concretised in the conceptualisation phase of chapter 6. Quotations are requested from suppliers, and those concepts that result in a lower cost price are ordered as parts of a prototype. This prototype is built, tested and evaluated to determine which concepts can be implemented in the company.

The process followed for the case study is combined with findings from literature to establish the framework. This framework aims at structuring the cost reduction process of mechanical products.

1.5 Structure of the thesis

The thesis consists of three segments. Segment A describes the case study. Segment B describes the framework and its development process. Segment C comprises an evaluation of the project and contains the overall conclusions, discussion, and recommendations. Each segment consists of several chapters, which consist of sections. Some sections are divided into even smaller paragraphs.

As described in section 1.4, the case study of segment A starts with literature research (chapter 3) and proceeds to the orientation phase (chapter 4). The findings of the research and orientation are combined to generate ideas, which are described in chapter 5. The ideas stakeholders consider feasible are developed further into concepts, which will be described in chapter 6. The expected cost reduction is calculated for each concept, which determines if the concept is prototyped. Chapter 7 describes the building and testing of the prototypes. Each concept is evaluated in chapter 8, where the total cost savings are calculated and necessary steps towards implementation are listed. Chapter 9 concludes the case study and the discussion on the case study is written in section 9.2.

Segment B describes the framework. Chapter 11 summarises the findings of each phase of the case study, and the takeaways for the framework. Chapter 12 describes the final framework. Section 12.3 describes the preparation necessary for using the framework. The first phase of the framework itself is orientation, which is described in section 12.4. This phase yields various opportunities for improvement, for which ideas are developed in the ideation phase (section 12.5). The ideas are then concretised during conceptualisation, which is described in section 12.6. The concepts developed here are subsequently brought to life in the realisation phase, which is described in section 12.7. To determine the applicability and feasibility of the concepts, they are verified in the verification phase (section 12.8). The final step of the framework is evaluation (section 12.9), after which the concepts can be implemented.

Segment C describes the final evaluation of the thesis as a whole. In this segment, the overall conclusions are drawn (chapter 13), the overall discussion is formulated, and recommendations are listed (chapter 14).

Segment A: Case study

In the scope of this thesis, the case study described in segment A functions as a method to develop the final framework of segment B. By executing a cost reduction project, the process for such a project becomes clear. Eventually, the findings from the case study are used in the framework.

The case study starts with literature research, followed by orientation, ideation, conceptualisation, prototyping, and evaluation.

2 Case study introduction

The case study was performed at Nijha B.V., which is a company specializing in indoor and outdoor sports- and playground equipment based in Lochem, the Netherlands. Their business can be divided into four main categories: sports- and play materials, playground installations, sports accommodations, and outdoor sports.

One of the products in the branch of play materials is the Dorack, a movable climbing installation that is developed for use in physical education of children aged 4 to 6. The Dorack has wheels so it can be rolled into position and has two climbing frames that can be positioned in various upright angles as well as sloped angles to create numerous configurations providing varying challenges to children.

After 15 years on the market and with a prospected increase in sales numbers, a need emerged to reconsider the product and its production process in terms of cost reduction. According to the company's decision-makers the current cost price is too high, which leads to a profit margin that is too narrow. The scope of this case study is to increase the profit margin by reducing the cost price.

The case study starts with literature research, which provides a theoretical basis for the rest of the case study and is described in chapter 3. Chapter 4 describes the orientation phase, which focuses on creating an impression of the company, product, and process. The combined findings from literature and orientation form the basis for the ideation phase of chapter 5.

The ideas are divided into three categories:

1. Ideas to create a solid foundation of the product.
2. Major changes to the design of the product and its parts, or to the process.
3. Minor changes to the product, concerning different suppliers and different purchased parts.

The ideas that proceeded to the conceptualisation phase described in chapter 6 amount to a theoretical cost saving of €X and a theoretical time saving of X minutes. These ideas are converted to CAD (Computer Aided Design) models and sent to suppliers for quotations. Certain parts are subjected to simulations to verify their strength. The quotations determine which parts are ordered for the prototype, whose building and testing processes are described in chapter 7.

Each concept is evaluated in chapter 8 and a final recommendation is formulated for each. The calculation of the total cost savings is also described in this chapter. The total cost savings amount to an interval between €X and €X, depending on calculation method. More details about this will be described in chapter 8.

Chapter 9 describes the conclusion and discussion of this case study.

3 Literature research

The research in this chapter serves as a theoretical basis for the case study and framework. Five research questions are formulated:

1. How can the current state of a production facility be determined?
2. How can product costs be classified, and how can they be reduced?
3. How can production processes be improved?
4. How can be determined which parts must be made and which must be bought?
5. What guidelines exist for 'Design for Assembly' (DFA) and how can they be applied to this project?

The first question is formulated to structure the orientation phase. It is answered in section 3.1, which explores factory layout, process flow, standardisation, and product portfolio as ways to determine the current state.

The other four questions are a result of the orientation phase and help in generating ideas during the ideation phase and structuring the framework of segment B. Question 2 is answered in section 3.2, which first describes the classification of costs and then discusses available techniques for cost reduction. Question 3 is answered in section 3.3, which describes methods to improve production processes using Lean methodology, automation, design for manufacturing, and assembly systems. Question 4 is answered in section 3.4 and question 5 is answered in section 3.5.

3.1 Current state

This section answers research question 1:

'How can the current state of a production facility be determined?'

The definition of 'current state' used here is the state of the production facility at the start of the cost reduction project, before anything has been changed. The current state can be determined by several factors: methods for characterising the *layout* of a factory will be described first in paragraph 3.1.1, followed by characteristics of the *process flow* (3.1.2), *standardisation* (3.1.3) and the *product portfolio* (3.1.4).

Torn and Vaneker (2021) studied various assessment tools for production systems and developed their own method consisting of four steps:

1. Product analysis, aimed at establishing a design space 'that provides insight into the extent to which the geometry of the product is allowed to change, while still meeting its functional requirements' (Torn & Vaneker, 2021, p. 142).
2. Process analysis, which consists of three steps: a walkthrough, detailed observation, and a functional decomposition.
3. Iterative automatization, aimed at reducing the complexity of process steps so off-the-shelf automatization solutions can be used.
4. Design output, where product and process come together.

This method is followed in the orientation phase of this project, but the third step is omitted because automation is not part of the scope of the project, as will be discussed in paragraph 3.3.2.

3.1.1 Factory layout

Koho (2010) compared various tools for assessing and improving production and production systems and developed his own: TUTKA. The TUTKA tool can be divided into three main parts:

1. Key characteristics of a well-performing production system, with decision area and production objectives.
2. An assessment scale that focuses on the correspondence between the characteristics of the assessed production system and the key characteristics of a well-performing production system.
3. Two assessment methods: a questionnaire and performance measures like potential process capability, changeover times, mean time between failures, mean down time, mean waiting time, and mean time to repair.

The scores for each characteristic are plotted on a radar chart to create an impression of the performance of the production system and indicate areas for improvement. The first part (key characteristics of a well-performing production system) will be used in the framework of segment B, and can be found in Appendix XVIII: Characteristics of a well-performing production system. The other two parts are considered too detailed for this project.

Several manufacturing structures exist in industry (Chryssolouris, 2006; Hayes & Wheelwright, 1979; Heragu, 1997; Nahmias, 1997; Wiendahl et al., 2015). An overview can be seen in Table 1 on the next page. Besides the options mentioned here, some companies adopt a hybrid layout that combines layout types (Heragu, 1997).

Goodson (2002) developed a method to establish a quick impression of a production facility, called the 'Rapid Plant Assessment' (RPA). The method aims at identifying where the plant performs well and where improvements are possible. It comprises two tools: a rating sheet and a questionnaire. The rating sheet asks users to rate the plant in eleven categories regarding 'Leanness' on a scale from 'poor' (1 point) to 'best in class' (11 points). The maximum score is therefore 121. The average score, based on experience of the author, is 55. The questionnaire asks the user 20 yes-or-no questions regarding best practices in Lean. On average, plants score seven yeses. The author stresses that the tool should be used in conjunction with due diligence. This method will be used in the orientation phase of chapter 4.

Kovács (2020) combined the theory of facility layout with Lean principles. He proposed using the Lean methods to aid in creating the proper facility layout. The combined method describes 13 steps, following a structure of determining scope (objectives and focus area), mapping and evaluating the current state, determining the objectives, creating alternatives, and narrowing these down until one ideal is selected, mapping the future state, and finally implementing the findings.

Stephens (2019, p. 3) suggested some simple questions that can be asked to be critical to the costs in a production facility: 'Ask why, who, what, where, when, and how for every operation, transportation, inspection, storage, and delay so we can eliminate, combine, change sequence, and simplify.' His work is mainly relevant for low-mix, high-volume factories, but some relevant takeaways for smaller facilities are: determine how each part will be produced, including as much data as possible about quantities, time standards, involved processes, and machines. Based on this, identify the most efficient flow through the facility and make amendments to the facility if needed. In the case of retrofitting an existing facility, constraints like building shape and permanent fixtures must be considered. If enough data is available, simulations can be used to determine and evaluate potential layouts of the factory. These questions have been incorporated into the framework of segment B in this thesis.

Table 1: Manufacturing structures

Name	Machines	Part types	Part-process relationship	Suitable for	Advantages	Disadvantages
Job shop/ process layout	General purpose, grouped by capability.	Large variety, low volume.	Part moves past processes, process oriented.	Small, dissimilar lot sizes (1-100) (Chryssolouris, 2006).	Adjustable to different products (Wiendahl et al., 2015). Good utilization of resources. (Nahmias, 1997; Wiendahl et al., 2015).	Long throughput times, high WIP (Wiendahl et al., 2015). Increased material-handling costs, complexity in planning and control, decreased productivity (Heragu, 1997).
Project shop/ site fabrication/ fixed position	Part-specific.	Big or heavy, low volume.	Part's position remains fixed, processes are moved to part.	Small lot sizes (1-10) (Chryssolouris, 2006).	Low part transportation costs (Heragu, 1997).	High tool transportation cost, low utilization (Heragu, 1997).
Cellular/ group technology	Grouped by process combination for a family of parts.	Medium variety, low-medium volume.	Part oriented.	Intermediate lot sizes (50-5000) with similarity (Chryssolouris, 2006).	Waiting times between work steps are avoided, short throughput times (Wiendahl et al., 2015).	Relies on part families with shared characteristics, duplicate machines (Nahmias, 1997).
Flow line/ product layout	Ordered by process sequence.	One or very similar type(s), large lot sizes.	Process specified to part.	Large lot sizes (500-10,000) of single part types (Chryssolouris, 2006).	Short throughput time (Heragu, 1997; Wiendahl et al., 2015).	Small disruptions can lead to a standstill of the whole system (Wiendahl et al., 2015). Changing products is laborious (Wiendahl et al., 2015).
Continuous systems	Ordered by process sequence.	Liquids, gases, powders.	Part oriented.	Continuous products.		

Wiendahl et al. (2015) described an elaborate process and an elaborate body of information on factory design. In general, they argue that synergy is important between the 'process view' (all the processes required to achieve the goals of the company) and the 'spatial view' (what is required from the building to enable these processes).

Although changing the layout of production facilities can have a major positive impact on cost reduction of products (Bernus et al., 2003; Heragu, 1997; Tompkins et al., 2010), this was considered to fall outside of the scope of the case study. The main reasons for this were:

1. The production mix of Nijha is high. This means its current process layout is suitable, as confirmed by Nahmias (1997, p. 570): 'Process layouts are most effective when there is a wide variation in the product mix.', as well as Hayes and Wheelwright (1979), and Ahmad and Schroeder (2002).
2. Other research subjects in this study have offered enough other opportunities for improving the Dorack.
3. Changing the facility layout would have a major impact on operations within the company, which would simply be too large for this project.

3.1.2 Process flow

Identifying the process flow in a facility is closely related to the layout of the facility, as the process flow is largely determined by the layout.

Liker (2004) described that the first step in approaching any process is mapping the value stream by following the path of material through the process. The information gathered can be summarised in a 'spaghetti map', which is essentially a floorplan of the facility with the physical path of the process flow drawn on top. At a later stage, a 'value stream map' can be drawn, that shows the processes, material flow, and information flow of a product in a more abstract way. Ideally, this current state map is followed by a future state map that shows the envisioned improved value stream.

Theisens (2016) also described spaghetti mapping and value stream mapping. He states that the objective of value stream mapping is to reduce lead time and eliminate waste. He calls it 'one of the most powerful Lean tools', because 'it links all activities together in one visual representation' (p.194). He states that a value stream map can help distinguish value adding, non-value adding and necessary activities in the process. Process mapping is seen as a part of value stream mapping, being supplemented with material and information flows, amount of work in process, cycle times, and waiting times.

Process time estimation

Part of quantifying the process flow is knowing how much time each process step takes. Cycle times are ideally measured while observing the process (Theisens, 2016) or based on historical data of the process. If exact process times cannot be determined by measurement or historical data, they should be estimated. Zandin (1980) described the Maynard Operation Sequence Technique (MOST) for determining process times. The technique breaks up every operation into a set of movements. Any operation can be classified as one or a combination of the following types:

- The General Move Sequence, where an object is moved freely through the air. This sequence consists of five components:
    - A: Action distance
    - B: Body motion

    - G: Gain control
    - P: Place
- The controlled move sequence, where an object is moved while remaining contact with a surface or is attached to another object during the movement. This sequence consists of three components:
    - M: Move controlled
    - X: Process time
    - I: Align
- The tool use sequence, which is used for common tool usage like cutting, cleaning, measuring, writing, inspecting, fastening and loosening.
- Equipment-handling, which in itself is broken into three:
    - Movement with a jib crane, consisting of six components:
        - T: Transport empty
        - K: Hook up and unhook
        - F: Free object
        - V: Vertical move
        - L: Loaded move
        - P: Place
    - Movement with a powered (bridge type) crane:
        - Same letters as above
    - Movement with a truck, consisting of three components:
        - S: Start and park
        - T: Transport
        - L: Load or unload

The components of each classification are defined in a table that assigns an index value to the specific movement (see Figure 1 and Figure 2). All index values of a movement are summed and multiplied by 10 to achieve the amount of time measurement units (TMU's). One TMU is equal to 0.036 seconds. This method will be illustrated with an example of screwing a fastener using a hand tool.

Example

The operation can be split up into four movements: grabbing the fastener, placing the fastener, using the tool, and returning to the starting position. Assuming the fastener is within reach, an index value of 1 is assigned to the action distance (see Figure 1). As the operator does not move his body, the body motion index value is 0. As the fastener is a light object, the index value for 'gain control' is 1. This yields a general move sequence of $A_1B_0G_1$. The other move sequences are mentioned in Table 2. Adding all indices yields 230 TMU's, which is equal to 8.28 seconds.

Using this method, theoretically any movement can be broken down, indexed and converted to a time standard.

Table 2: Move sequence for screwing a fastener using a hand tool

Getting fastener	Placing fastener	Using tool (9 turns)	Return to starting position	Total
$A_1B_0G_1$	$A_1B_0P_3$	F_{16}	A_1B_0	230 TMU = 8.28s

INDEX	A ACTION DISTANCE	B BODY MOTION	G GAIN CONTROL	P PLACE	INDEX
0	≤ 2 IN ≤ 5 CM			HOLD TOSS	0
1	WITHIN REACH		LIGHT OBJECT LIGHT OBJECTS SIMO	LAY ASIDE LOOSE FIT	1
3	1-2 STEPS	BEND AND ARISE 50% OCC	NON SIMO HEAVY OR BULKY BLIND OR OBSTRUCTED DISENGAGE INTERLOCKED COLLECT	ADJUSTMENTS LIGHT PRESSURE DOUBLE	3
6	3-4 STEPS	BEND AND ARISE		CARE OR PRECISION HEAVY PRESSURE BLIND OR OBSTRUCTED INTERMEDIATE MOVES	6
10	5-7 STEPS	SIT OR STAND			10
16	8-10 STEPS	THROUGH DOOR CLIMB ON OR OFF			16

ABGABPA — GENERAL MOVE

Figure 1: General move data card (Zandin, 1980, p. 19)

Table 4.1 Tool Use—Fasten/Loosen[a]

ABGABP ABPA — TOOL USE SEQUENCE — Fasten or Loosen

INDEX	FINGER ACTION FINGERS SCREW-DRIVER	WRIST ACTION — TURN HAND SCREW-DRIVER RATCHET	WRIST ACTION — REPOSITION WRENCH ALLEN KEY	WRIST ACTION — CRANK WRENCH ALLEN KEY RATCHET	WRIST ACTION — TAP HAND HAMMER	ARM ACTION — TURN RATCHET T-WRENCH	ARM ACTION — REPOSITION WRENCH ALLEN KEY	ARM ACTION — CRANK WRENCH ALLEY KEY RATCHET	ARM ACTION — STRIKE HAND HAMMER	POWER TOOL POWER WRENCH SCREW DIAMETER (MM)	INDEX
1	1				1						1
3		1	1	1	3		1		1	1/4'' (M6)	3
6	3	3	2	3	6	2		1	3	1'' (M24)	6
10	8	5	3	5	10	4	2	2	5		10
16	16	9	5	8	16	6	3	3	8		16
24	25	13	8	11	23	9	4	5	12		24
32	35	17	10	15	30	12	6	6	16		32
42	47	23	13	20	39	15	8	8	21		42
54	61	29	17	25	50	20	10	11	27		54

[a]Values are read "up to and including."

Figure 2: Tool use (Zandin, 1980, p. 53)

Flow of goods

The exact path goods take through a process is determined by the interdependence of the processes. This can be illustrated using precedence charts, which can be useful for mapping possible changes in the order of processes (Tompkins et al., 2010) or determining the shortest makespan of a product (Theisens, 2016). A precedence chart shows every operation on a product, and which operation needs to occur before certain other operations. This can also be expanded to the interdependence between parts in an assembly (Hu et al., 2011).

The flow of goods in a process can roughly be characterised as following either a push or pull strategy (Kals et al., 2019; Nahmias, 1997; Wiendahl et al., 2015). In a push system, the production of goods is initiated by anticipation of future demand, whereas in a pull system production is initiated by current demand.

A common example of a push strategy is Materials Requirements Planning (MRP). The basic notion of MRP is that orders for the final product drive production. Production of all parts of the final product is planned ahead based on the Bill of Materials (BOM), current inventory levels of components, and lead times of components. In this way, the delivery date of the final product can be achieved. A weakness of MRP is that the production of final products must be frozen long in advance (Zijm & Regattieri, 2019).

A common example of a pull strategy is Just in Time (JIT), which relies on organizational changes on the shop floor instead of on planning procedures (Zijm & Regattieri, 2019). In short, the JIT system works with small inventories of parts at each workstation that are replenished as they are used. In this way, taking a finished product from the final stock triggers a chain reaction of production operations throughout the process. This only works if all processes can produce superb quality, and non-value adding activities are avoided.

Table 3 compares the advantages of push and pull strategies.

Table 3: Push versus pull

Advantages of push/MRP	**Advantages of pull/JIT**
Works well for varying production rates (Nahmias, 1997).	Early recognition of faults (Nahmias, 1997).
Can react quickly to changes in demand (Nahmias, 1997).	Less inventory means reduced holding costs (Kals et al., 2019; Nahmias, 1997).
Makes use of knowledge about demand patterns (Nahmias, 1997).	Short lead times (Kals et al., 2019; Zijm & Regattieri, 2019).
Facilitates sourcing from multiple suppliers (Nahmias, 1997).	Lower risk of overproduction (Theisens, 2016).
Enables producing larger batches in case of high setup costs (Nahmias, 1997).	
Facilitates larger number of variants (Wiendahl et al., 2015).	
Less reliant on delivery times (Wiendahl et al., 2015).	

Some production firms use a combination of push and pull principles (Olhager & Östlund, 1990). In these cases, the point where production becomes demand driven instead of forecast driven is known as the customer order decoupling point (CODP) (Olhager, 2012; Theisens, 2016; Wiendahl et al., 2015). Olhager (2010, p. 864) defined the CODP as: 'the point in the material flow where the product is tied to a specific customer order.' He identified the four main order fulfilment procedures the CODP creates as make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO), and engineer-to-order (ETO), each of which is associated with a different ability for customization and a different position of the CODP (Figure 3). He stated that an MTS approach is typical for firms producing high-volume standardized products, whereas MTO is more common for low-volume customized products.

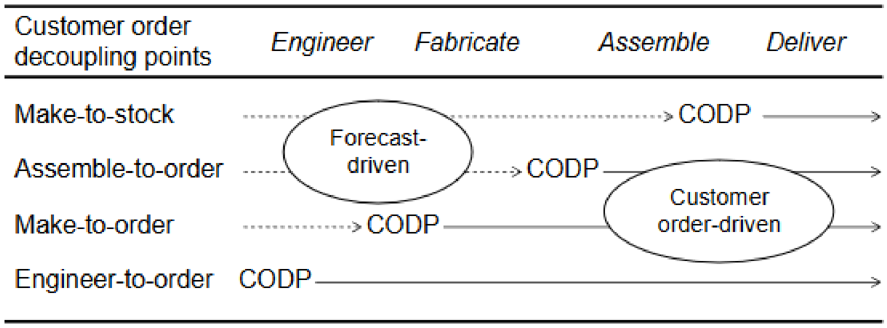


Figure 3: Position of CODP in different production strategies (Olhager, 2010, p. 864)

Wiendahl et al. (2015, p. 218) gave a concrete definition of these four variants:

- With an MTS approach, a product is produced and stored based on a forecast, without requiring an order. An advantage is shorter delivery times, a disadvantage is higher inventory costs.
- With ATO, assembly starts when a customer order is received, using prefinished standard components. An advantage is products can be tailored and delivery times are short. A disadvantage is that many standard components are needed in stock.
- With MTO, manufacturing starts after the customer order. Required materials are usually kept in stock based on forecasts.
- ETO occurs when a customer's specifications require a specific design process.

Kals et al. (2019) listed the CODP as one of the criteria upon which production systems can be classified. The others are the manufacturing type (mass, batch or single-piece production), place in the business sector (materials, semi-finished products, manufacturing system, or assembly system), and the arrangement of the manufacturing departments (line, departmental or cell structure).

Olhager (2010) described that the standard model for linking market characteristics to the design of the manufacturing planning and control system 'is concerned with three hierarchical planning levels: master planning (MTO, ATO, MTS), material planning (time-phased vs. rate-based), and shop floor control (MRP-type vs. JIT-type).' (p. 864).

In a later publication, Olhager (2012) linked the CODP to the value perception of the product by the customer. He argued that value is a function of quality, delivery, price, flexibility, and other aspects. According to him, in an MTS environment the price is typically dominant and acts as an order winner, whereas the quality and delivery are market qualifiers, and flexibility is not required. In an MTO environment on the other hand, the order winner is related to flexibility, and quality and delivery are market qualifiers. These differences need to be reflected in the value chain.

In order to have the right goods to perform all processes, all companies have some form of a supply chain. Smith and Lockamy (2000, p. 69) defined a supply chain as 'a network of operating entities through which an organization delivers products or services to a particular customer market'. It contains three core elements: suppliers, producers, and customers.

According to Fisher (1997), two types of supply chains exist. *Physically efficient* supply chains supply a predictable demand efficiently at the lowest possible cost, and *market-responsive* chains respond quickly to (unpredictable) demand. These classifications share similarities with push and pull principles. Fisher also argues two types of products exist. *Functional products* satisfy basic needs that do not change much over time and therefore have a predictable demand. *Innovative products* give customers an additional reason to buy the product and have an unpredictable demand. He then argued that only two combinations yield a match: functional products match with efficient supply chains, and innovative products match with responsive supply chains.

The movement of goods throughout a process is known as logistics. Logistics can be divided into four parts (Wiendahl et al., 2015):

- *Procurement* logistics make sure the right things are available at the right time at the right place.
- *Production* logistics concern transportation and storage of semi-finished goods between processes.
- *Distribution* logistics are responsible for supplying the final product to the customer.
- *Disposal* logistics concerns the end-of life logistics of the product.

Rushton et al. (2021) identified five main cost types in logistics: storage and warehousing, inventory-holding, information system, primary transport, and local delivery.

3.1.3 Standardisation

Another way to characterise a production firm is the degree of standardisation, which is generally correlated with production volume. Companies producing low volumes generally have low standardisation and companies producing large volumes generally have high standardisation (Hayes & Wheelwright, 1979).

Standardisation is one of the measures suggested by Design For Assembly (DFA), which will be discussed further in section 3.5.

Koho (2010) positioned standardisation as the opposite of customisation and defined five customisation (or standardisation) strategies, based on what part of the value chain is standardised and what part is customised (Figure 4).

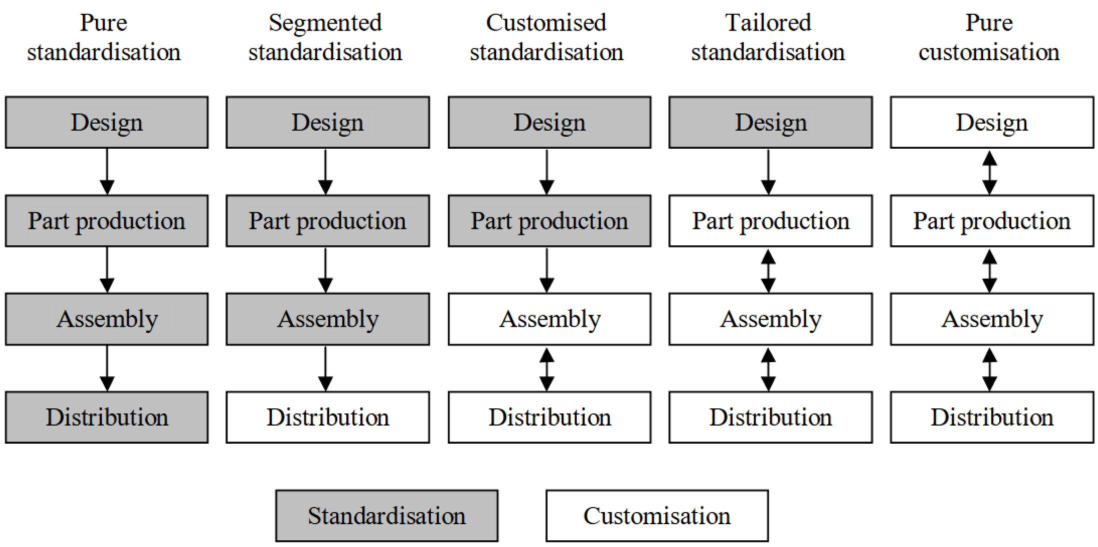


Figure 4: Customisation strategies (Koho, 2010, p. 25)

3.1.4 Product portfolio
Tompkins et al. (2010, p. 49) argued that the production facility of a firm should represent its product portfolio. Based on a volume-variety chart, which shows the production volume for each product, a distinction should be made between 'a mass production area for the 15% high-volume items and a job shop arrangement for the remaining 85%'.

3.1.5 Conclusion on current state
The current state of a production facility can be determined by looking at multiple aspects. The first aspect to determine the current state of a production facility is to look at the factory layout. Factories are generally laid out as a job shop, fixed position, cellular, flow line or continuous system. Each of these layouts is suitable for a different type of product mix in terms of volume and variety. Knowing the layout can help determine if that layout is the most suitable for the product mix.

The second aspect is determining the flow of the process. Goods generally follow either a pull principle, where production is initiated by current demand, or a push principle, where production is initiated by anticipation of future demand. A common example of a pull system is JIT, and a common example of a push system is MRP. The point where a process is tied to a specific customer order is known as the customer order decoupling point (CODP). The position of this point in the process determines if the process is make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO), or engineer-to-order (ETO). Again, knowing about the flow can help determine if the company uses the correct strategy for their products.

The third aspect is the degree of standardisation used in the firm, which is generally correlated with the production volume. Companies producing low volumes generally have low standardisation and companies producing large volumes generally have high standardisation.

The fourth and last aspect is the product portfolio. A production facility should represent the company's product portfolio. This can be quantified by creating a volume-variety chart that shows how many copies of each product are produced in a given time.

3.2 Cost reduction
This section answers research question 2:

'How can product costs be classified, and how can they be reduced?'

Paragraph 3.2.1 first describes how costs can be classified. Paragraph 3.2.2 then describes various techniques to reduce the costs of a product. Paragraph 3.2.3 finally describes how cost reduction is applied to this project.

3.2.1 Classification of costs
Ulrich et al. (2020) divided the cost of goods into various elements, as can be seen in Figure 5. They also suggested methods to estimate the costs of standard components (either by comparing to a similar part or by soliciting quotations from suppliers) and custom components (by soliciting quotations from suppliers or adding costs for raw materials, processes, and tooling) in early stages of the development process.

Bralla (1999) split labour costs into direct labour (determined by manufacturing processes, part design, and productivity) and indirect labour ('setup, inspection, material handling, tool sharpening and repairing, and machine and equipment maintenance labor' (p.1.10)). Additionally, he split equipment and tooling costs into special tooling (fixtures, jigs, dies, moulds, patterns, gauges, test equipment), perishable tools and supplies (bits, cutters, grinders, files, drills, taps, reamers), and invested capital.

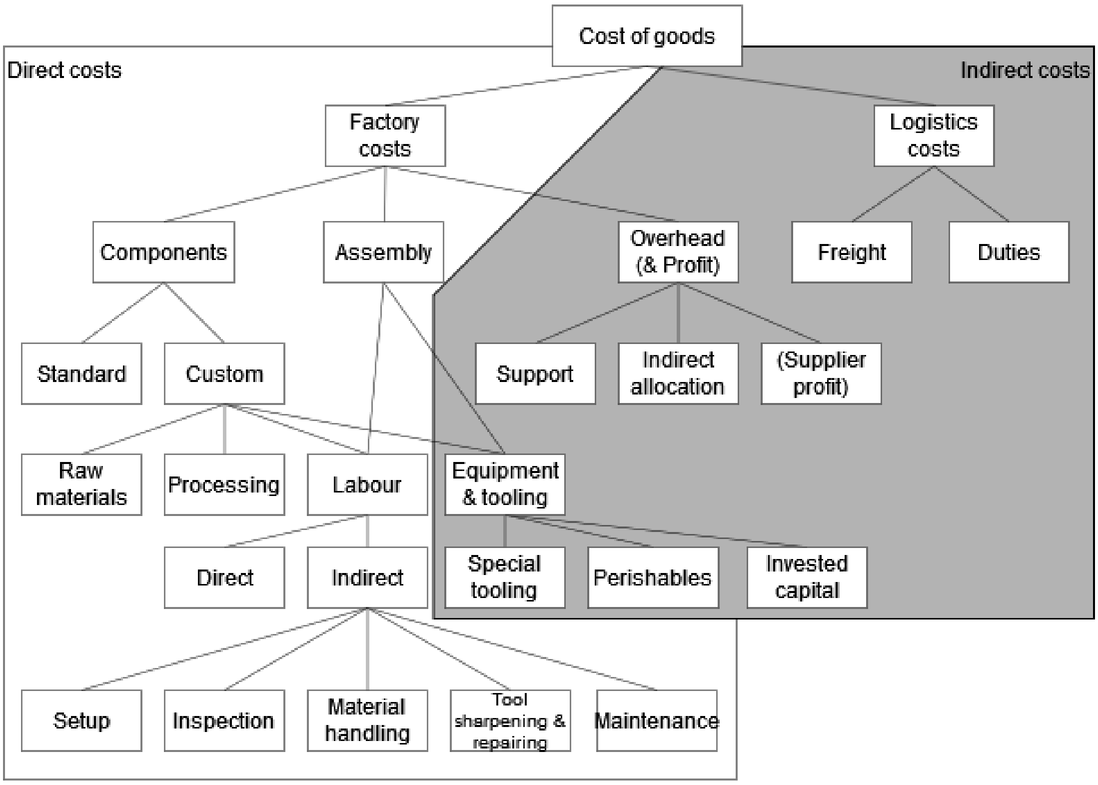


Figure 5: Elements of the cost of goods (Bralla, 1999; ten Brinke, 2002; Ulrich et al., 2020, p. 267)

Ullman (1997), Stephens (2019), and ten Brinke (2002) categorised costs as being either direct (associated with the component, assembly, or product and usually in the form of labour or material) or indirect (all other costs). Besides, ten Brinke (2002) divided manufacturing costs into variable (dependent on production volume) and fixed (independent from production volume).

Kals et al. (2019) followed a similar logic and gave a clear overview of the costs associated with producing a part: they divided the production cost price into execution costs, costs of repeat orders, preparation costs, and indirect costs. The same categories hold for assembly costs.

In short, costs can be classified as direct or indirect. Direct costs are associated with specific attributes of the part or process, and indirect costs are costs associated with more general attributes of the process. By classifying costs, the biggest contributors to a product's cost price can be identified and targeted for a cost reduction project. Several cost reduction techniques will be described in the following paragraph.

3.2.2 Cost reduction techniques

Bralla (1999, p. 9.9) suggested prioritizing savings in a design for low quantities as follows: 1. Tooling, 2. Overhead, 3. Labour, 4. Materials. For high quantities, direct labour and materials costs are more important. Because tooling was already developed in this case study, and overhead was incorporated in the cost of parts, the focus was on labour and materials.

Ulrich et al. (2020) suggested various techniques to reduce the costs of components:

- Understanding the constraints and cost drivers in the process.
- Redesigning components to eliminate processing steps.

- Choosing the appropriate process and associated economic scale for each part.
- Standardizing components.

Meeker and McWilliams (2004); (2003) defined a few main approaches to achieve cost reduction:

- Redesigning (parts of) a product.
- Reducing existing component costs, either by renegotiation or sourcing through a different vendor.
    - One method for renegotiation is that of Bernstein and Kök (2009). This method distinguishes between cost-contingent contracts where the purchasing price is adjusted in response to earlier cost improvements, and target-price contracts where a path of cost reduction is agreed upon in advance. An important side note here is that order quantities must be of sufficient volume for a supplier to consider a specific pricing scheme.
- Changing components for alternatives with lower costs, lower performance, lower tolerance, or lesser quality and still achieve the product requirements without sacrificing quality control.
- De-featuring - offering only the features that make economic sense.

Berk (2010) added considering make/buy decisions (see also section 3.4), improving the process, and optimizing workflow.

Mascitelli (2011) added some more considerations for being critical to cost: some DFA measures (see section 3.5), reducing the cost of testing, eliminating unique parts, simplifying the supply chain, eliminating exotic raw materials, reducing capital intensive or low-yielding process steps, maximizing compatibility with existing flow lines or work cells, and optimizing the cost of packaging and shipping.

Kals et al. (2019) suggested looking for the break-even point in the number of workpieces, relative to the sum of production costs. One can then choose the method that has the lowest cost for the number of workpieces or adjust the number of workpieces to the method.

Weustink et al. (2000) argued that four main product characteristics drive costs: geometry, material, production processes, and production planning. They then suggested breaking down the costs from the assembly level to the component level. This is essentially what is described in paragraph 4.2.5.

3.2.3 Application of cost reduction to this project

A combination of the strategies described above is used in this project:

- The product costs are broken down to the component level (Weustink et al., 2000).
- Components are redesigned, as suggested by Ulrich et al. (2020) and Meeker and McWilliams (2004); (2003), in some cases by applying DFA measures (Mascitelli, 2011).
- For parts not produced in-house, the strategies of renegotiation, re-evaluation of suppliers and changing components for cheaper alternatives are used (Meeker & McWilliams, 2004; Meeker & McWilliams, 2003), or these parts are changed for standardised components (Ulrich et al., 2020) or alternatives of lower cost.
- Make/buy decisions are considered (Berk, 2010), see also section 3.4.

These strategies are used because they are concrete and can be implemented directly.

Changing the way costs are calculated is not considered part of the scope. The existing cost calculation system of Nijha represents reality and is therefore taken as the status quo. In addition to this, cost reductions can be calculated more accurately if the same calculation method is used for the new cost price and old cost price.

3.3 Production process optimisation

This section answers research question 3:

'How can production processes be improved?'

This section first describes how production processes can be optimised by applying Lean methodology, making automation considerations, using Design for Manufacturing, and using certain assembly systems. Paragraph 3.3.5 finally describes how these findings are applied to this project.

3.3.1 Lean methodology

Lean methodology is a widespread process improvement methodology originating from the Toyota motor company (Liker, 2004). It focuses on process stability and the elimination of waste (Theisens, 2016). Lean provides numerous tools to improve the production process (Kovács, 2020; Theisens, 2016). Many of these tools, like takt-time analysis, line balancing, and overall equipment effectiveness, do not apply to this case study because they are mainly useful for repetitive processes with large quantities. Therefore, this paragraph will only describe the Lean takeaways that are used in this thesis.

The Lean philosophy identifies eight types of 'waste' (Liker, 2004, p. 29; Theisens, 2016, p. 203) that need to be minimised:

1. *Overproduction*. Producing more items than necessary.
2. *Waiting* for other processes to finish, equipment to be repaired or other instances where time is not used effectively.
3. *Transport* of materials or products.
4. *Overprocessing*. Taking unnecessary steps to process parts.
5. *Inventory*. Unnecessary supplies or stock waiting to be processed, leading to longer lead times, obsolescence, damaged goods, and holding costs.
6. *Movement* of employees searching for parts, walking to other locations, or handling parts.
7. *Defects*. Also includes rework or repair, scrap, replacement production, and inspection.
8. *Unused expertise* of employees. Not using the full potential of all employees.

Any production system holds some form of inventory. The four main types are raw materials, components (subassemblies), WIP (inventory waiting for processing or being processed), and finished goods (Nahmias, 1997, pp. 212-213). Although inventory is seen as a type of waste, Nahmias (1997, pp. 213-215) lists seven motivations for holding inventory:

1. Economies of scale. Each production run requires set-up costs. Production numbers must be high enough to justify these. In case the set-up costs can be reduced, the lot sizes can become smaller.
2. Uncertainties. Inventory provides a buffer against the uncertainty of external demand.
3. Speculation. If the value of an item is expected to increase, it can be economical to purchase it in a larger quantity.
4. Transportation. Relevant for in-transit or pipeline inventories.

5. Smoothing. Compensating for varying demand.
6. Logistics. Other reasons such as constraints in purchasing, production, distribution.
7. Control costs. Sometimes it is simply cheaper to keep inventory than to keep detailed records for these items.

Herron and Braiden (2006) described three steps to address manufacturing problems using Lean tools. They suggested starting with a Productivity Needs Analysis, which gives an overview of the current manufacturing condition and forms the basis for a detailed study of production efficiency. After that, they proceed to a Manufacturing Needs Analysis, which is aimed at ascertaining the current level of adoption of Lean tools. The third step is assessing the level of understanding and application of Lean tools by the workforce.

Some Lean principles have already been applied at Nijha, as will be described in paragraph 4.3.1. Sections 4.1 and 4.3 essentially describe a form of current state mapping and show that the process is already optimized to a large extent. In addition to this, several ideas described in chapter 5 reduce certain types of waste.

3.3.2 Automation

The possibility of automating the assembly of a product depends on factors such as design, production volume, number of variants, product life cycle, and the size and degree of difficulty of the assembly operations (Kals et al., 2019).

Although automation may seem like an obvious cost reduction strategy, manual assembly is still the most suitable option for processes with low quantity, low productivity, high diversity, and high flexibility (Lotter & Wiendahl, 2009).

Torn and Vaneker (2021) stated: 'Due to the complexity of assembly, for many operations, human workers are still the most efficient solution.' (p.141), where they referred to Hu et al. (2011).

A summary of the advantages and disadvantages of manual assembly are mentioned in Table 4. For this case study, the advantages outweigh the disadvantages as batches are small, products are relatively complex in relation to the batch size, and variation is high. The disadvantages of size, weight and harsh environments do not play an influential role.

Lotter and Wiendahl (2009) described the advantage of fewer tool changes in a 'set-wise assembly flow', where products are produced in sets (or batches), step by step, just like the Dorack.

Table 4: Advantages versus disadvantages of manual assembly

Advantages of manual assembly	Disadvantages of manual assembly
Flexibility (product types, variants, component variation, faulty components, unforeseen assembly problems) (Andreasen et al., 1983, p. 83; Nof et al., 1997; Swift & Booker, 2013)	Certain skill level required (Swift & Booker, 2013)
Low equipment investment (Andreasen et al., 1983, p. 83; Swift & Booker, 2013)	Size and weight must be considered for handling safety (Swift & Booker, 2013)
Greater job satisfaction (Andreasen et al., 1983, p. 83)	Operator fatigue, health and relaxation time must be considered (Swift & Booker, 2013)
Simpler and less costly hand tools (Nof et al., 1997)	Assembly errors increase if components/sub-assemblies are complex, difficult to align,

Advantages of manual assembly	Disadvantages of manual assembly
	insert, or if there is restricted access for insertion (1% error rate possible for some manual operations). (Swift & Booker, 2013)
Greater variation in part dimensions (Nof et al., 1997)	Repeatable accuracy of component alignment is low to moderate depending on part complexity, typically ±0.5 mm (Swift & Booker, 2013)
Quick detection of defective components (Nof et al., 1997)	Not suitable for harsh environments (Swift & Booker, 2013)
Unexpected problems are solved by judgement (Nof et al., 1997)	
(Relatively) constant costs (Nof et al., 1997)	
Economical for low to moderate production rates (Swift & Booker, 2013)	
Short lead time (Swift & Booker, 2013)	

3.3.3 Design for manufacturing

Bralla (1999) listed several principles to aid in designing products that are cheap to manufacture: simplicity, using standard materials and components, standardizing the design of the product itself, using liberal tolerances, using processible materials, collaborating with manufacturing personnel, avoiding secondary operations, designing according to the expected production quantity, utilizing the specific process characteristics, and avoiding project restrictiveness.

Ulrich et al. (2020) described a structured method for design for manufacturing (DFM):

1. ‘Consider the strategic sourcing decisions.
2. Estimate the manufacturing costs.
3. Reduce the costs of components.
4. Reduce the costs of assembly.
5. Reduce the costs of supporting production.
6. Reduce the costs of logistics.
7. Consider the impact of DFM decisions on other factors.’ (p.263)

3.3.4 Assembly systems

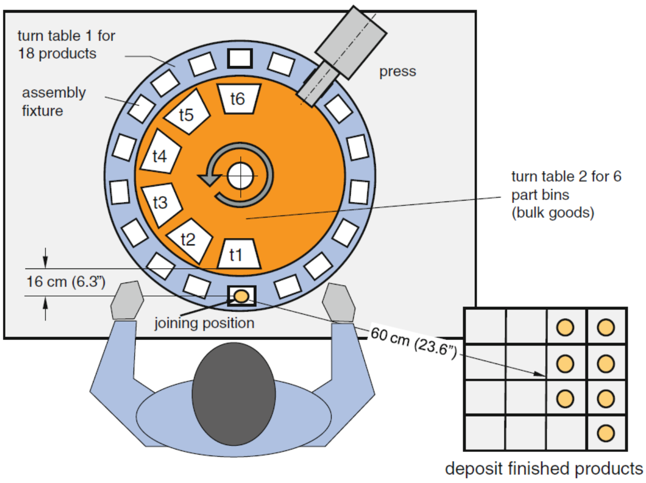


Figure 6: Assembly table for batch-wise assembly (Wiendahl et al., 2015, p. 152)

Lotter and Wiendahl (2009) and Wiendahl et al. (2015, pp. 149-158) described the layout of assembly systems. Various systems can be classified based on the output rate and complexity of the products (number of parts or operations). Two systems that are useful for small quantities are two types of assembly tables.

The first type is suitable for batch-wise assembly and consists of two turning tables (Figure 6). The outer ring holds a maximum of 18 copies of the product being assembled and the inner ring holds bins containing components. The same component is added to all copies of the product, and this process is repeated until all components are added to all copies of the product and the finished products are deposited in the bin on the right.

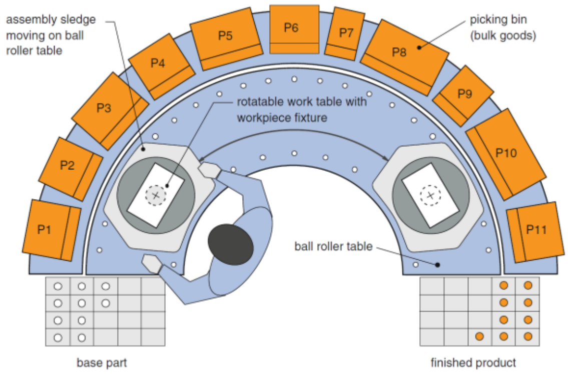


Figure 7: Assembly table for one-piece-flow (Wiendahl et al., 2015, p. 152)

The second type is suitable for one-piece flow and can be seen in Figure 7, where the employee uses a 'sledge' for the workpiece. All components are placed in bins on a semi-circle around the workplace and the worker adds the components to the workpiece as he passes the bins. At the end, the workpiece is finished and put in a bin with the other finished products.

3.3.5 Application of process optimization to this project

The layout of the production facility of Nijha will not be investigated further, because the focus lies on just one product and not the facility as a whole. For the same reason, Lean methodology will not be implemented as the be-all and end-all solution, but rather as a set of tools that can be used to improve specific parts the process. Different waste types are identified during process observation and current state mapping is used to create an overview of the company and process.

The various sources mentioned above have confirmed that the choice to keep all assembly processes manual is reasonable for the case study. Therefore, options for automation will not be considered in the case study. The considerations for automation will be part of the final framework of segment B.

The various principles of design for manufacturing are included in the overview of Appendix VII: Assembly, manufacturing, and cost-reduction guidelines.

A precedence chart is created during ideation (paragraph 5.2.3), to generate insight into the interdependencies of the production process. The need for this overview became apparent in the semi-structured interviews (see Appendix IV: Semi-structured interview transcripts).

The assembly table of Lotter and Wiendahl (2009) was proposed as an idea but discontinued because it was not considered beneficial for the batch sizes. The assembly systems are also included in the framework of segment B.

3.4 Make-buy decisions/outsourcing

This section answers research question 4:

'How can be determined which parts must be made and which must be bought?'

Probert (1997) considered the company strategy and customer requirements as part of the decision-making process. He prescribed an elaborate process to determine a make-or-buy strategy. This process roughly consists of four phases: assessment of the firm's purpose and direction, analysis of the firm compared to competitors, generation and evaluation of the strategic options, and lastly choosing the optimal strategy. Factors to take into consideration include: strategic importance of the part, available capacity, and competitive role of the part.

Tompkins et al. (2010) simplified the decision-making process into a set of primary questions supported by secondary questions. The primary questions are:

1. 'Can the item be purchased? If no, make the part, if yes, continue to question 2.
2. Can we make the item? If no, buy the part, if yes, continue to question 3.
3. Is it cheaper for us to make than to buy? If no, buy the part, if yes, continue to question 4.
4. Is the capital available allowing us to make? If no, buy the part, if yes, make the part.' (Tompkins et al., 2010, p. 37)

In case making and buying are both possible, the decision should be based on fixed, variable, and investment costs, as well as liability issues and availability of capital.

Berk (2010) stated: 'Make-versus-buy decisions should be driven by the two factors of cost and risk.' (p. 90) He suggested first identifying which areas induce high costs or problems and determining which parts become 'candidates' for switching. Then, identify associated risks and determine the 'present value' of these parts. Based on this, decide which candidates should indeed switch.

Parmigiani (2007) researched a hybrid solution, called 'concurrent sourcing', where a company both makes and buys a certain good. She concluded that 'Firms will be more likely to produce goods which they can produce efficiently and effectively' and 'find suppliers that have skills unlike their own' (p. 298). Also, 'Greater performance uncertainty will motivate firms to choose making over concurrent sourcing and making over buying.' (p. 303). This supports the view of Berk (2010) that sourcing decisions are driven by cost and risk.

Nahmias (1997) phrased the break-even point between making and buying as a simple equation:

$$K + c_2 x = c_1 x \quad (1)$$

Where K is the investment of the company for in-house production, c_2 is the internal production price, x is the number of units produced, and c_1 is the purchase price at the external supplier. In case either side of the equation is smaller, that strategy should be used. He also emphasized the shortcomings of this equation. It only describes a static situation, giving a rough approximation and ignores factors like learning effects, changes in demand, and the time value of money.

In the simplest form, the decision to make or buy a part comes down to the following: considering all involved costs (such as materials, operations, human resources, and overhead) and risks (such as successful making of the part, availability of skills and labour, delivery time and quantity, meeting of requirements, and increase in price), is it cheaper to make the part in-house or outsource it to an external supplier? Whichever option is cheapest is generally the better choice. Kals et al. (2019) warned for drawing incorrect conclusions when comparing in-house production and outsourcing, which can happen when factors like order costs, transport costs, and overhead costs are insufficiently considered in the comparison.

3.4.1 Application of make-buy decisions to this project

In the case of Nijha, the choice to make or buy only concerns those parts that are made using processes that can also be performed in-house. This mainly concerns metalworking, coating, and assembly. Thoroughly investigating and potentially altering the company strategy, as suggested by Probert (1997), falls outside the scope. Identifying candidates for outsourcing, as suggested by Berk (2010), is a suitable choice and is used for several ideas in paragraph 5.2.3.

3.5 Design for Assembly

This section answers research question 5:

'What guidelines exist for "Design for Assembly" (DFA) and how can they be applied to this project?'

Various approaches to DFA are described below and paragraph 3.5.1 finally describes how these approaches are applied in this project.

Boothroyd and Dewhurst (1994; 1992; 2002) divided manual assembly into two areas: 'handling' and 'insertion & fastening'. Swift and Booker (2013) elaborated on this by adding the process of feeding at the start, and checking and transfer at the end of the operation. Andreasen et al. (1983) divided assembly into three functions: handling, composing, and checking. Ullman (1997) divided it into retrieving, handling, and mating or inserting. A comparison of these views can be found in Table 5.

Table 5: Assembly sections

Handling → Insertion & fastening	Boothroyd and Dewhurst (1994; 1992; 2002)
Feeding → Handling → Insertion & fastening → Checking → Transfer	Swift and Booker (2013)
Handling → Composing → Checking	Andreasen et al. (1983)
Retrieving → Handling → Mating/inserting	Ullman (1997)

Kals et al. (2019) divided the assembly process into primary and secondary operations. Primary operations are value adding, such as handling, joining, tuning, inspection, and testing. Secondary operations are all other necessary actions, such as storage, transport, cleaning, and packaging. The authors also distinguished three ways parts can be supplied to the assembly station: unordered - where parts lay in bins and are taken out separately -, ordered - where orientation is no longer necessary -, and partially ordered – where final orientation takes place during assembly.

In general, three main approaches exist for DFA: that of Boothroyd and Dewhurst, Hitachi, and Lucas.

Boothroyd and Dewhurst (1994; 1992; 2002) followed two basic principles: 1. Reduce the number of assembly operations by reducing the number of parts. 2. Make the assembly operations easier to perform. To determine which parts must be separate, each part is examined against three criteria:

1. Does the part move relative to all the other parts in the assembly?
2. Must the part be of a different material than the other parts?
3. Must this part be separate to facilitate the assembly of other parts?

Only if a part fulfils one of the criteria, it must be a separate part. The criteria cannot be applied to purchased subassemblies, and separate fasteners by definition do not meet the criteria.

Barnes et al. (1997) divided the criteria for the assembly sequence into hard constraints, dealing with the geometric feasibility (consistent geometry, feasible trajectory, feasible joining processes, stability), and soft constraints, dealing with 'best practices' for assembly (compatible materials, compatible joining processes, compatible with joint characteristics).

The *Hitachi* assemblability evaluation method (AEM) uses two indices to evaluate designs: the assembly evaluation score E, which indicates design quality or ease of assembly, and the assembly-cost ratio K, which is used to project assembly costs relative to current assembly costs (Boothroyd, 1994; Corbett, 1991; Miles, 1989; Nof et al., 1997; Syan & Swift, 1994; Warnecke & Bäßler, 1988).

The *Lucas* method follows three steps (Boothroyd, 1994; Miles, 1989; Mital et al., 2014; Syan & Swift, 1994):

- In the *functional* analysis, parts are categorized into A parts (demanded by the design specification), and B parts (required by that particular design solution). A target is set for design efficiency (A/(A+B)), expressed as a percentage. The objective is to exceed an arbitrary 60% target value by the elimination of category B parts through redesign.
- In the *handling and feeding analysis*, parts are scored based on three areas: size and weight, handling difficulties, and orientation. The score is summed to give the total score for the part, and a handling/feeding ratio is calculated which is the total score divided by the number of A parts. A target of 2.5 is recommended.
- In the *fitting analysis* each part is scored based on whether it requires holding in a fixture, the assembly direction, alignment problems, restricted vision, and the required insertion force. The total score is divided by the number of A parts to give the fitting ratio. Again, it is recommended that this ratio should approach 2.5 for an acceptable design.

Samy and ElMaraghy (2010) proposed a numerical approach to 'measure products assembly complexity'. To do this, they suggested assessing each individual part in terms of structural and functional complexity to achieve an index. By aggregating these indices, the total complexity of the product should become apparent.

The works of Boothroyd et al. (2002), Andreasen et al. (1983), Miles (1989), Barnes et al. (1997), Corbett (1991), Syan and Swift (1994), and Edwards (2002) have suggested a long list of guidelines and design principles concerning design for (ease of) assembly, often overlapping. An overview of these guidelines can be found in Appendix VII: Assembly, manufacturing, and cost-reduction guidelines. Many of these guidelines are used throughout the case study. The qualitative guidelines can be categorized as concerning part count, manual processes, compatibility, tolerances, insertion and fastening, sub-assemblies, and the assembly system as a whole.

Bralla (1999) prioritised the reduction of part count over all other changes in design but nuances the aim of reducing parts later: 'Occasionally, it pays to *add* parts to an assembly if doing so allows more liberal tolerances in the component parts. (p. 7.17)' He also mentioned the three criteria of Boothroyd and Dewhurst and paid some attention to the application of DFM on low-quantity production. In this light, he emphasised standardisation and making use of available manufacturing techniques.

Langeveld (2009) identified three disadvantages of the existing DFA methods:

- The high amount of detailed data needed.
- The evaluative character of the existing methods.
- The existing methods are focused on the reduction of parts and handling operations.

As a response, he proposed an alternative approach to DFA, called 'Design *with* Assembly'. This approach follows seven steps:

1. Analysis of company characteristics (internal).
2. Analysis of competitive products (external).
3. From principal solution to product architecture.
4. Make a suitable joint choice.
5. Detail the parts.
6. Calculate the lead time.
7. Calculate the costs.

3.5.1 Application of DFA to this project

Although some of the methods described in this section partially consist of quantitative measures, only qualitative measures will be used in this project. The reason for this is that the quantitative parts of the methods are based on estimates and experimental evidence, and the authors themselves mention the theoretical assembly times differ from the actual times ('For any particular operation, these average times can be considerably higher or lower than the actual times' (Boothroyd et al., 2002, p. 128)). This shortcoming is also supported by Langeveld (2009).

Concretely, the three principles of DFA will be used in chapter 5 to determine which parts of the Dorack can be combined and the guidelines listed in Appendix VII: Assembly, manufacturing, and cost-reduction guidelines are used to generate ideas.

3.6 Conclusion on literature research

This chapter answered five research questions. They will be repeated below, along with a brief summary of the findings in this chapter:

1. How can the current state of a production facility be determined?

The current state of a production facility can be determined by looking at the layout of the factory, the flow of the process, the degree of standardisation and the product portfolio. All these factors were discussed in section 3.1. These findings are used to structure the orientation phase described in chapter 4, which describes the factory layout, process flow, and product variety. Information about the current state of a production facility can identify areas for improvement.

2. How can product costs be classified, and how can they be reduced?

Product costs can be classified as being either direct or indirect. Direct costs are associated with specific attributes of the part or process like materials, processing, and labour costs. Indirect costs are costs associated with more general attributes of the process like overhead, logistics and equipment costs. Paragraph 3.2.1 described the classification in further detail. This thesis will mainly focus on direct costs. Paragraph 4.2.5 of the next chapter will investigate the cost buildup of the product.

Product costs can be reduced by a variety of techniques. The techniques that will be used in this case study originate from several approaches. In short, components can be redesigned, costs can be reduced (by renegotiation, re-evaluation of suppliers and changing components for cheaper alternatives), make/buy decisions can be reconsidered, and costs can be broken down to the component level to find their sources.

3. How can production processes be improved?

The improvement methods found in this literature study comprise the Lean methodology, considering automation options, applying DFM measures, and using specific assembly systems. These measures were described in section 3.3. The case study will mainly focus on identifying 'waste' types of Lean, and applying DFM measures. The findings of paragraph 3.3.2 substantiate the choice to use manual processes instead of automated processes.

4. How can be determined which parts must be made and which must be bought?

Several approaches exist to determine which parts must be made and which must be bought. The core of all is to determine the cost of producing a part internally and externally, and compare these. The considerations were described in section 3.4. These findings will be used to determine the sourcing decisions described in paragraph 5.2.3.

5. What guidelines exist for 'Design for Assembly' (DFA) and how can they be applied to this project?

Three main approaches exist for DFA: that of Boothroyd and Dewhurst, Hitachi, and Lucas. Boothroyd and Dewhurst suggest reducing the number of parts and making assembly operations easier to perform. They formulated three criteria parts must fulfil to remain separate. The Hitachi method is a more quantitative method that uses various scores to rate a part's design quality and ease of assembly. The Lucas method follows a functional analysis, handling and feeding analysis and fitting analysis to determine the assemblability of a product. The approach of Boothroyd and Dewhurst is followed in this case study, along with a number of guidelines mentioned in Appendix VII: Assembly, manufacturing, and cost-reduction guidelines. These three main approaches, along with some lesser-known approaches were described in section 3.5.

The findings of research question 1 are used to structure the orientation process described in chapter 4. The findings of the other four research questions are used in the generation of ideas in chapter 5 and to structure the framework of segment B.

4 Orientation

The orientation phase is aimed at establishing the current state of the company, product, and process to ultimately determine the scope of the case study. This chapter is divided into four sections. Section 4.1 describes the company in terms of product portfolio and factory layout. Section 4.2 describes the history, functionality, structure, cost build-up and sales figures of the product, as well as the characteristics of its competitors and how it differs from those. Section 4.3 describes the production process of the product and which considerations have already been made to streamline it. Section 4.4 summarizes this chapter, formulates four questions to be answered in ideation and phrases the scope of the case study.

4.1 Company

Besides the general information about the company described in the introduction of this thesis, the characteristics of the product portfolio and production facility establish an impression of the company. The sales figures of each product characterise the product portfolio, as will be described in paragraph 4.1.1. The Rapid Plant Assessment (RPA) of Goodson (2002) assesses the state of the production facility of the company. In addition to this, findings from the works of Chryssolouris (2006) and Nahmias (1997) help identify the layout of the factory. This is described in paragraph 4.1.2.

4.1.1 Product portfolio

The business of Nijha can be divided into four main categories: sports- and play materials, playground installations, sports accommodations, and outdoor sports. Most products Nijha sells classify as retail, meaning they are bought and sold without any modification. Only about 5% of the products sold are produced at the facility.

The volume-variety chart of Figure 8 helps in assessing the production mix of the company and subsequently determining an appropriate layout, as suggested by Tompkins et al. (2010, p. 49). The figure follows a Pareto distribution, which means that a small proportion of the portfolio is responsible for a large proportion of the sales. Knowing this can help determine which products to focus on for improvement projects, as products with large sales numbers can have a larger impact.

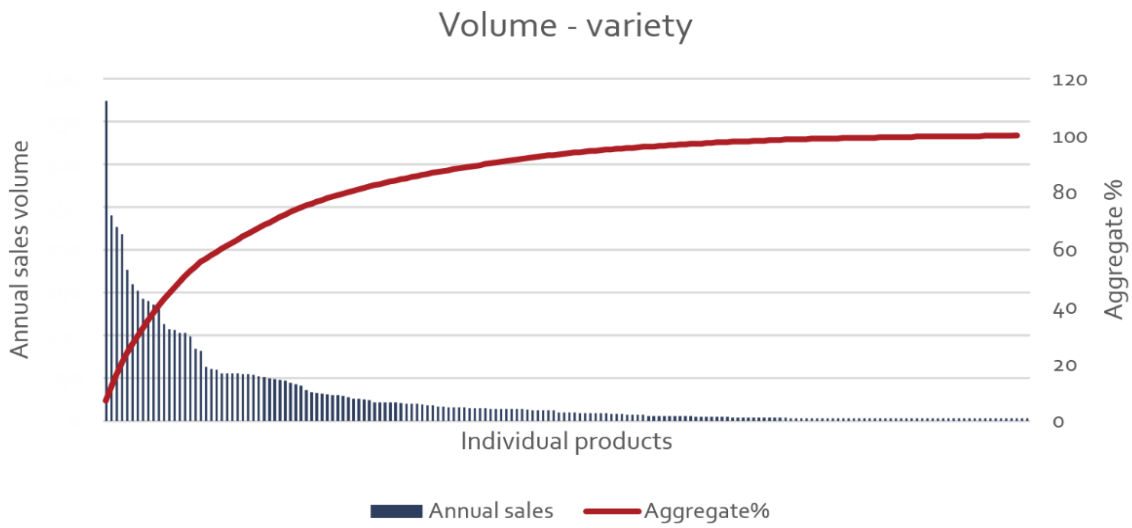


Figure 8: Volume-variety chart products produced in-house

However, as Figure 8 shows only the sales volume of each product and tells nothing about required production capacity it can give a distorted view of which products are dominant. Figure 9 therefore shows the capacity distribution chart. The chart shows what fraction of the total annual production capacity is used for each of the products. To calculate the capacity used per product, the annual sales number is multiplied by the cost price of the product. This is done only for the products produced in-house with at least one item sold annually. Although this chart, just like the volume-variety chart of Figure 8, also follows a Pareto distribution, the positions of individual products differ. The Dorack takes the 23rd place in the volume-variety chart, whereas it finishes first in the capacity distribution chart, being attributed the largest annual capacity. This substantiates the choice for the Dorack as subject of this case study.

Because most products of Nijha are produced at a low volume, a make-to-order (MTO) or assemble-to-order (ATO) approach (Koho, 2010, p. 6; Wiendahl et al., 2015) is applicable (Olhager, 2010). Because the Dorack is sold in relatively large quantities, a make-to-stock (MTS) approach is used for this product. In terms of standardization, Nijha falls under 'segmented standardization' (Koho, 2010, p. 25), because its portfolio is largely fixated, but some room is left for specialized adjustments for individual clients. Incidentally, 'specials' are developed for specific clients. These are products based on (a combination of) existing products, but with some form of alteration. This falls under the category of 'customized standardization'. The Dorack is 'pure standardization', because no variation exists between individual Doracks.

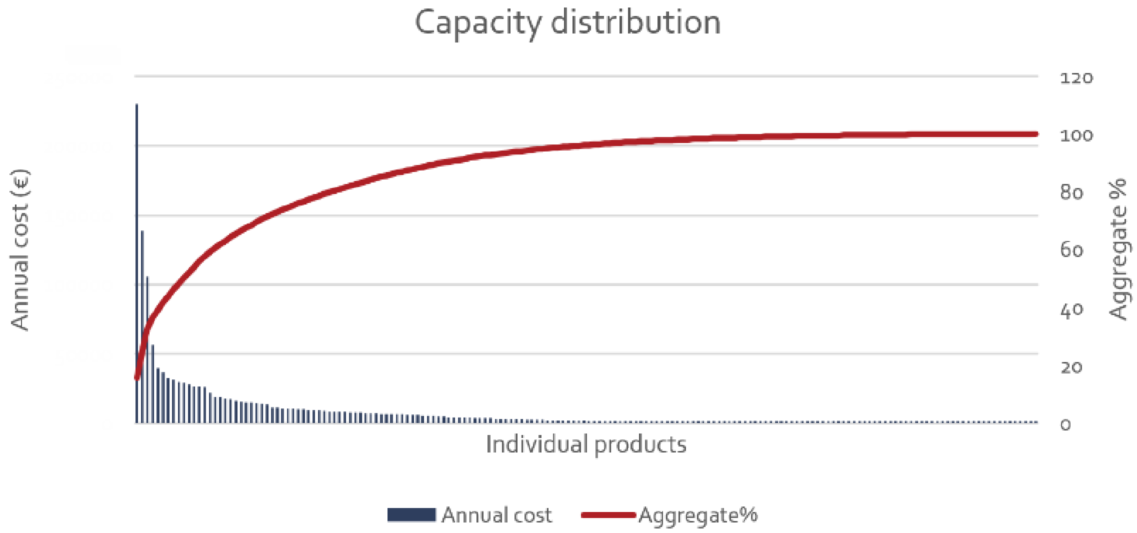


Figure 9: Capacity distribution products produced in-house

4.1.2 Factory layout

The RPA of Goodson (2002), as described in paragraph 3.1.1, is a method that helps in creating a quick impression of a manufacturing plant by focusing on 11 categories. It shows that the shopfloor of Nijha scores 78 out of 121 points in the categories associated with Lean principles and 12 out of 20 questions regarding 'leanness' are answered with a 'yes'. Both are higher than the average of 50 points and seven 'yeses' (Goodson, 2002). Some more attention can be given to involving customer satisfaction throughout the process and integrating suppliers in the process. Also, some communication in terms of operational goals, customer satisfaction, productivity, and maintenance can be included. For the full RPA, see Appendix III: RPA.

Figure 10 shows a floorplan of the factory. This layout was established to enable a smooth trajectory through the factory, considering logistics to minimise unnecessary movements. The machines in the workshop are general purpose and each have a dedicated working area. The workpieces are transported to the machine and treated in batches. These are all characteristics of a job shop (Chryssolouris, 2006; Hayes & Wheelwright, 1979; Wiendahl et al., 2015) and a process layout (Heragu, 1997; Nahmias, 1997), which is suitable for small lot sizes (1-100 parts) (Chryssolouris, 2006).

Further details regarding the processes and the flow between them will be discussed in section 4.3.

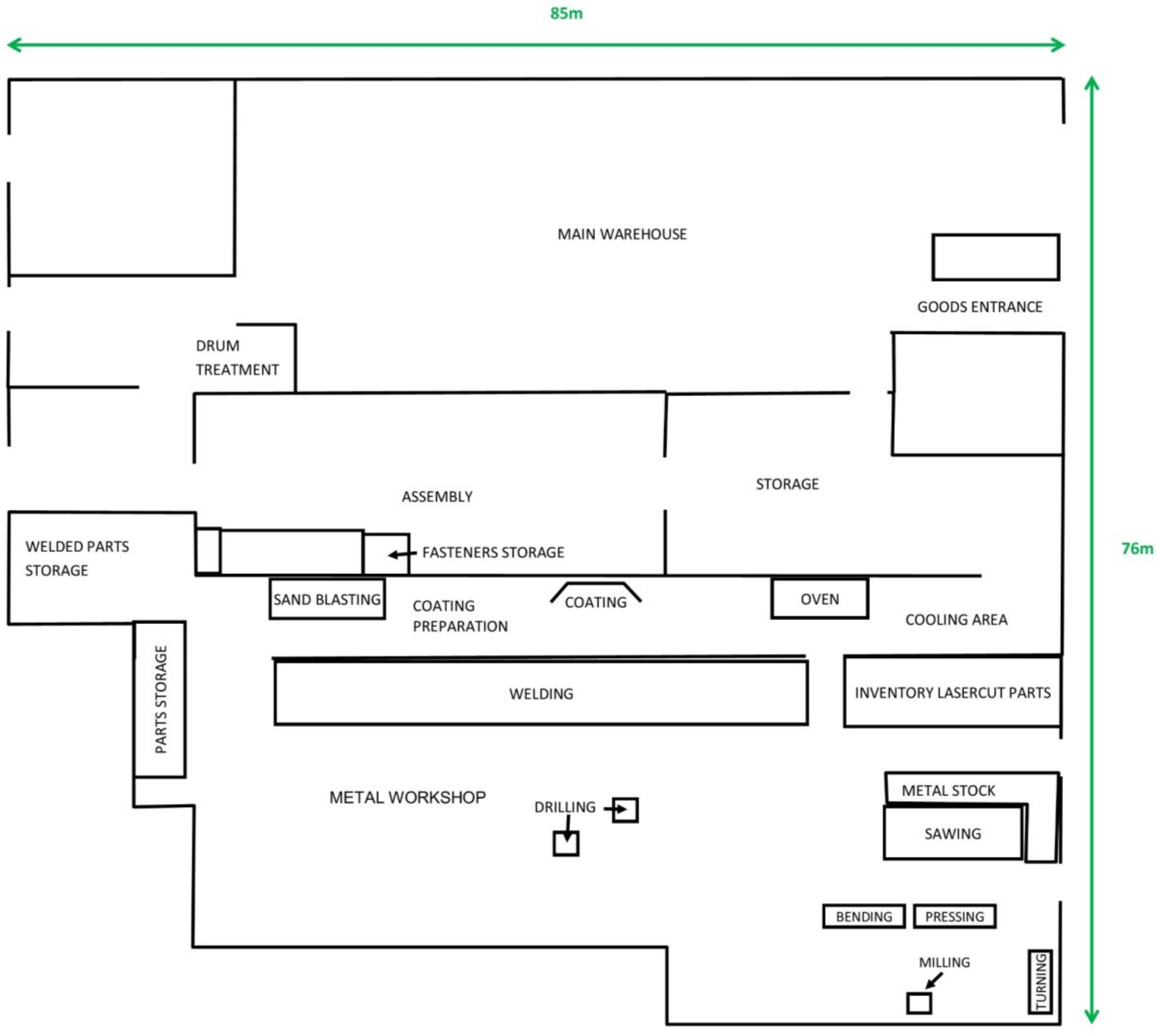


Figure 10: Factory layout

4.2 Product

This section describes the product in terms of its history, functionality, hierarchy, competitive position, costs, and sales figures. This helps in understanding the product, the build-up of its costs, and determining the boundaries of the case study.

Available documentation on the development of the product, along with several semi-structured interviews with involved employees gave insight into how the product was developed (paragraph 4.2.1) and how it works (paragraph 4.2.2).

In addition to this, BOM and the CAD models of the product as a whole, and those of most subassemblies and other parts, show that the product has a clear structure of assemblies (paragraph 4.2.3). An exploded view of the product with the parts mentioned throughout this thesis can be found in Figure 30 on page 44.

A competitor analysis determines the market position of the product compared to its competitors (paragraph 4.2.3). It shows that two main categories of competing products exist, each with less functionality than the Dorack but also offered for a lower price.

Lastly, the buildup of costs (paragraph 4.2.5) and the product's sales figures (paragraph 4.2.6) show that 67% of costs come from material costs and 33% are production costs. The material costs follow a Pareto distribution. The sales figures show that the distribution of orders follows the school year, with most orders being placed before the summer break (June and July) or the end of the calendar year (November and December) and most deliveries taking place at the start of the school year (August and September).

4.2.1 History of the Dorack

This paragraph describes the history of the product and is based on the available documentation and several semi-structured interviews. For the full transcript of these interviews, see Appendix IV: Semi-structured interview transcripts. The history shows what considerations have previously been made, so options that have already been proven unfeasible will not be considered again.

The development process of the Dorack started as a reaction to a need for more flexibility in primary school gymnasiums, which generally had a wall-mounted climbing frame that occupied precious space, looked boring, and had limited functionality. The core requirements for the product were that it needed to:

- Be movable;
- Be lightweight;
- Be colourful;
- Be multi-functional;
- Require minimal maintenance;
- Offer a range of challenges to children with varying motoric competence.

Early in the development process, the idea arose to make a frame consisting of one central, rollable frame with two hinging frames attached to it. These attached frames also needed to be variable in angle, see Figure 11. This formed the basis of the Dorack's functionality.

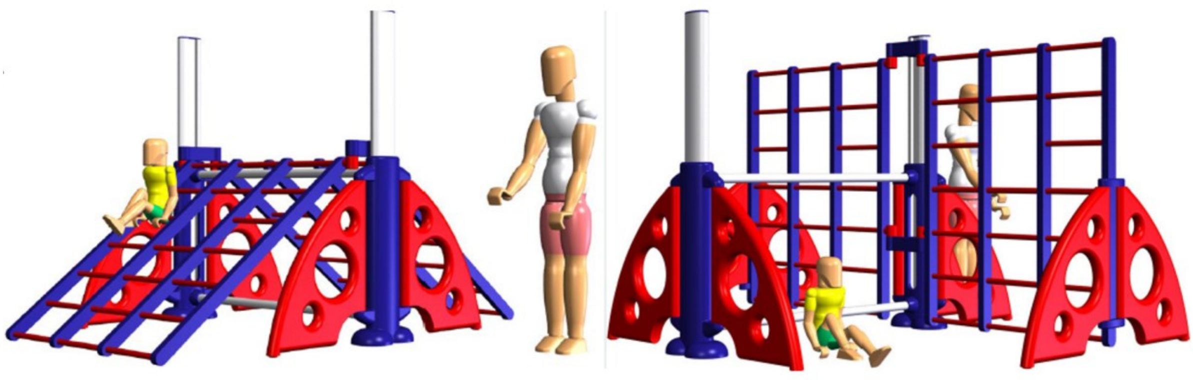


Figure 11: Concept models Dorack

The product was launched to the market in 2007 after a process of detailing (in which many choices regarding stability, weight, and appearance were made), prototyping, and testing. Since then, some changes have been made concerning the gears, support legs, and the frame support plate. Also, some earlier efforts have been made in reducing the cost price. This led to a simplification of various parts and a cost price reduction of X%.

The dimensions of the Dorack are mainly driven by physical dimensional constraints. The height is determined by the height of standard doors and the wheelbase is determined by an optimum between stability and a minimum footprint.

4.2.2 Product functionality

The product as it is currently sold can be seen in Figure 12. It can be used in three main configurations: the collapsed, upright position (Figure 12), the 'roof' position, where the two racks are lowered to form an angled plane (Figure 13), and the expanded position, where the racks are decoupled and turned outwards (Figure 14). Any angle between the collapsed position and the expanded position is possible. This also holds for the roof position. In the collapsed position, the wheels of the product (under the domed red covers at the bottom) can be extended. This lifts the product off the ground by 2 cm and facilitates rolling it to another location. The central column in each of the racks has one rung less than the other columns, to facilitate slides and other attachments to be mounted to the rack and enable children to climb through the gap. Nijha also sells additional frames that are compatible with the Dorack, which can be used to create several other configurations, like the one in Figure 15.

Figure 12: Dorack with dimensions in collapsed, upright position

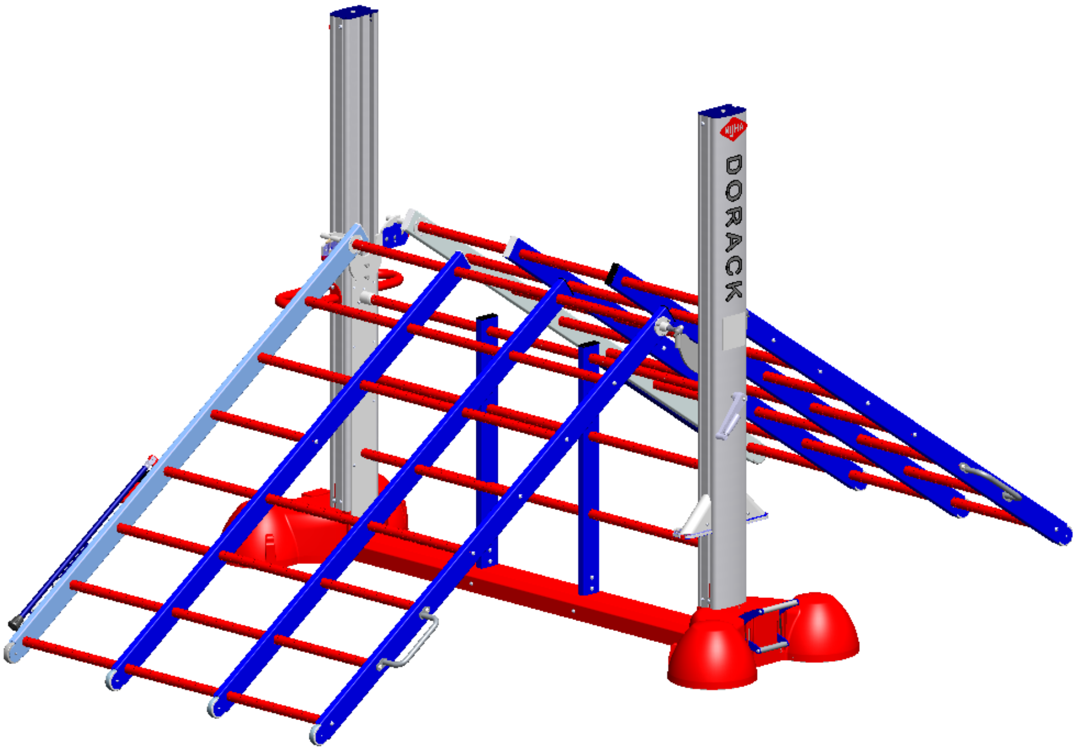


Figure 13: Dorack in 'roof' position

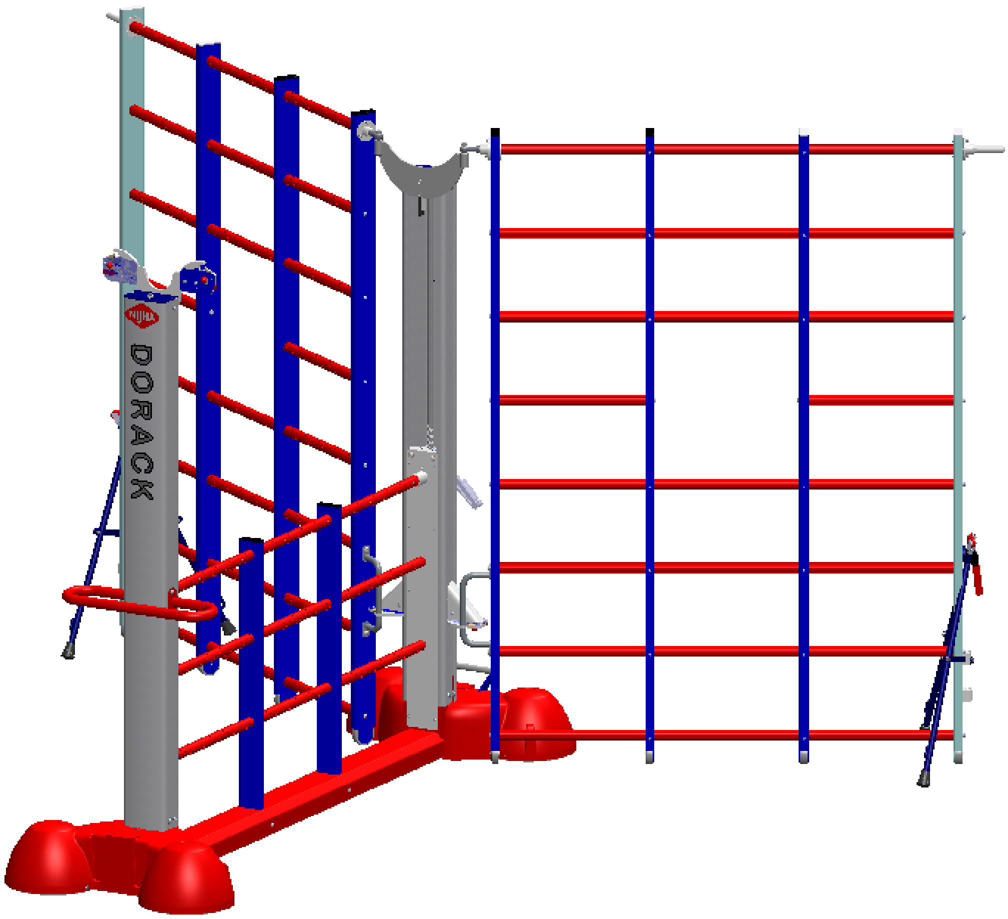


Figure 14: Dorack with expanded racks

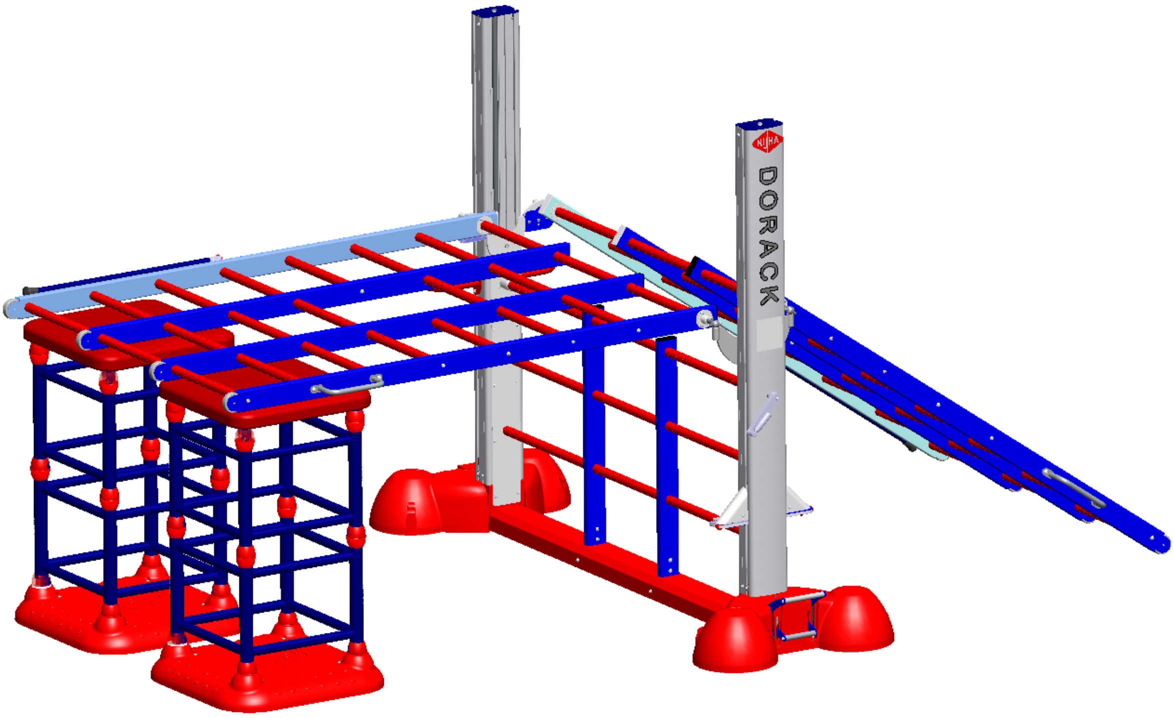


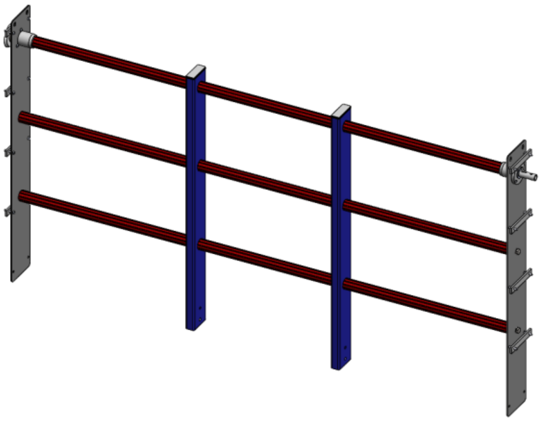
Figure 15: Dorack with compatible frames

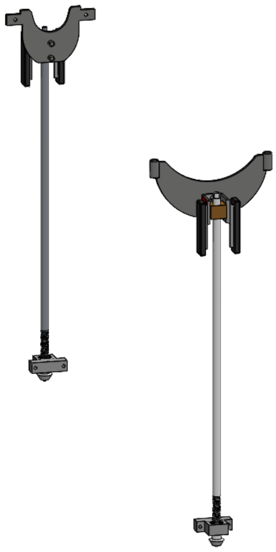
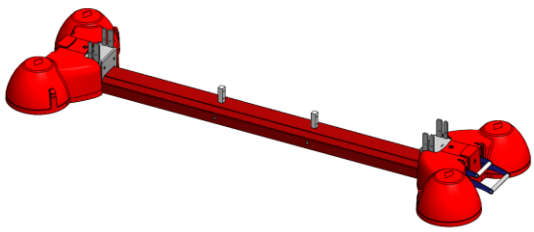
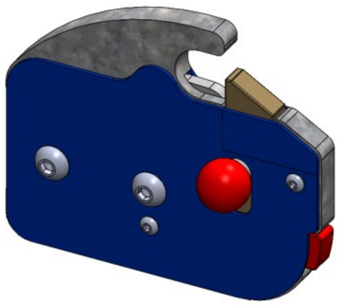
4.2.3 Product structure

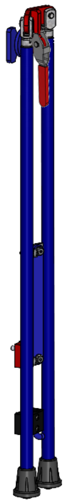
An expanded BOM, containing information from the CAD model, the BOM and the enterprise resource planning (ERP) system, creates an overview of the product's structure. This expanded BOM lists each of the parts, their quantity, to which subassembly they belong, which processes are used to produce them, what they cost and how this cost is built up. A condensed version of this BOM can be found in Appendix II: Assembly tree. The main assemblies are described briefly in Table 6 below.

Because this thesis mentions many parts by name, and most will likely not mean much to the reader, an exploded view of the product with all parts mentioned in this thesis can be found in Figure 30 at the end of this chapter (page 44).

Table 6: Main assemblies

Assembly name	Description	Image
Climbing frame	Each Dorack has two climbing frames comprising three columns of eight rungs.	 *Figure 16: Climbing frame*
Middle frame	The middle frame differs from the other two frames in that it is lower (only three rungs), it is fixed to the rolling base, and the shaft for the height adjustment mechanism passes through the upper rung.	 *Figure 17: Middle frame*

Assembly name	Description	Image
Height adjustment	The height adjustment mechanism comprises two spindles to which a frame support is mounted at the top. The frame supports hold the climbing frames. As the spindles are rotated, the frame supports move up and down.	 *Figure 18: Height adjustment mechanism with frame supports*
Rolling base	The rolling base is the lower part of the product that holds the wheels and their lowering mechanism. The middle frame and uprights are mounted to the rolling base.	 *Figure 19: Rolling base*
Latch	Each Dorack has four latches to lock the climbing frames to the uprights: two at the top of the height adjustment mechanism and two at the bottom of the upright.	 *Figure 20: Latch*

Assembly name	Description	Image
Legs	The legs are mounted to one side post of each of the climbing frames. When the frames are put in their expanded position, the legs are expanded to provide stability.	 *Figure 21: Legs*

4.2.4 Competitors

All competitors of Nijha have one or several products that share similarities with the Dorack. Each of these products is analysed in Appendix V: Competitor analysis. In summary, the products of the competitors are all quite similar to each other and can be divided into two categories: movable climbing frames and wall-mounted climbing frames. All have wooden rungs and aluminium or steel posts painted in grey. None have the extra functionality of altering the angle of the climbing frame, as the Dorack has in its 'roof' position. The competitors are also cheaper: the wall-mounted frames cost around €3500, and the movable frames are priced around €5900, as opposed to the Dorack's sales price of €X. The mechanisms used for putting the frames on wheels are simpler than the mechanism used in the Dorack.

In short, the Dorack differentiates itself from the competition by using aluminium rungs, being colourful, having a 'roof' configuration, and having a more advanced wheel mechanism. This is represented in a higher sales price.

4.2.5 Costs

Data from the ERP system unveils the roots of the costs of the Dorack. The total cost of one Dorack is €X, of which €X are material costs and €X are production costs (Figure 22). The production costs are split up further into the individual operations (Figure 23). Coating contributes most to the costs, followed by final assembly, and welding. Figure 24 shows 25% of parts contribute to 80% of the costs, meaning the material costs follow a Pareto distribution. The largest portion of these costs lies in parts that have been produced specifically for the Dorack.

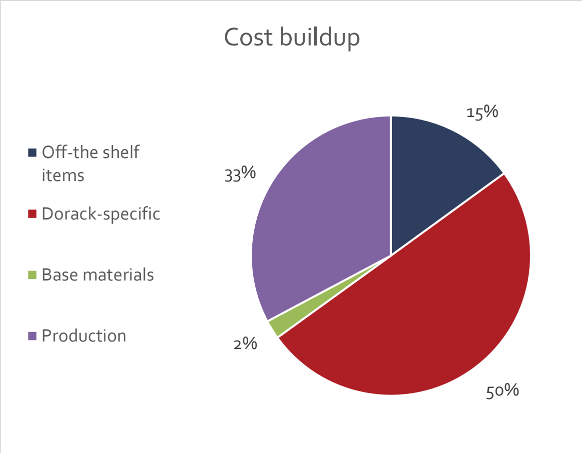


Figure 22: Cost build-up

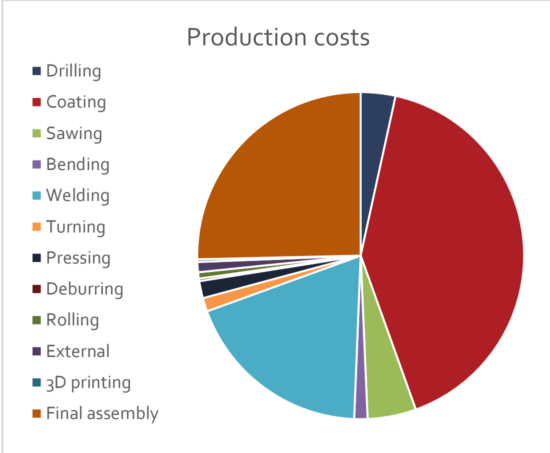


Figure 23: Production cost build-up

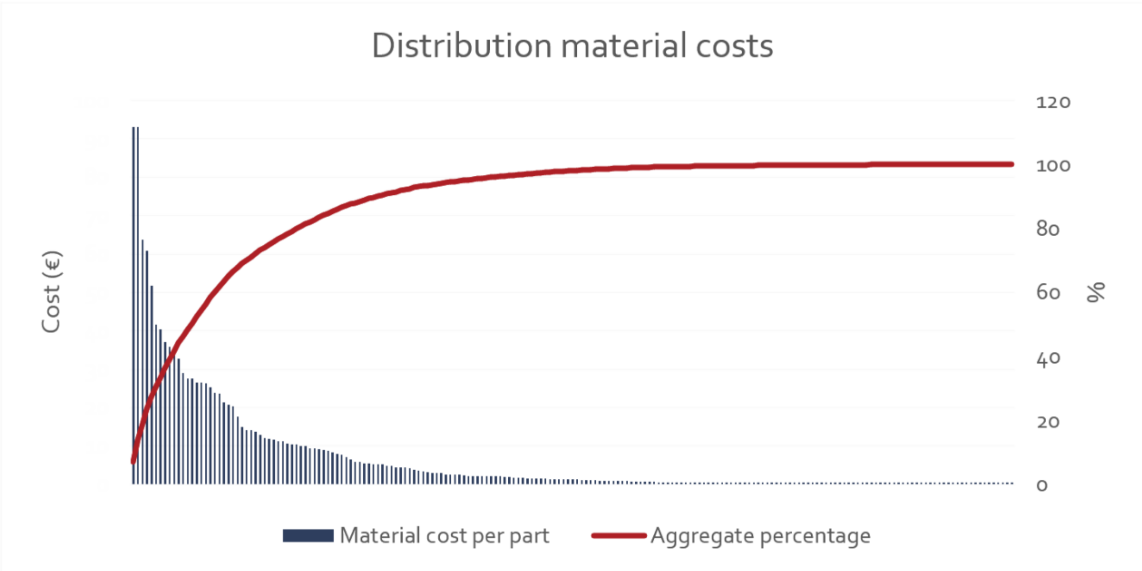


Figure 24: Distribution material costs

4.2.6 Sales figures

Since the launch of the Dorack in 2007, a total of X have been sold (as of January 2024). Two bar charts (Figure 25 and Figure 26) visualise the number of Doracks ordered and shipped monthly, over the past 17 years. The sales follow a pattern that somewhat represents the school year. Many Doracks are ordered just before the summer break (June and July), to be delivered at the start of the next school year (August and September). Another pattern is that orders increase towards the end of the calendar year, potentially because many schools and other institutions need to spend their budget for sports equipment in that fiscal year. On average, the difference between the number of Doracks shipped between the busiest month (September) and the quietest month (April) is a factor 2.2. In practice, this means that a series of X Doracks is produced either twice a month or once a month, and this does not have a large influence on the capacity of the factory. The demand is expected to increase to around X annually in the near future, meaning a monthly demand of X.

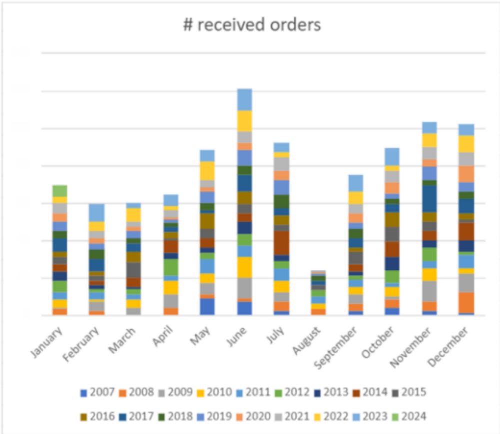


Figure 25: Distribution of orders

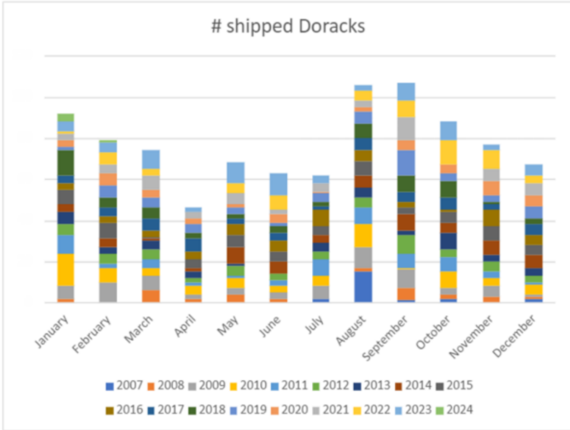


Figure 26: Distribution of deliveries

Looking at the sales figures of all other products produced at Nijha (Figure 27), Dorack falls within the top 10%. Products with larger sales figures are generally much simpler. The only other 'complex' products with higher sales numbers are benches, jump boxes, and an adjustment mechanism for gymnastics rings. Certain accessories for the Dorack are also sold a lot.

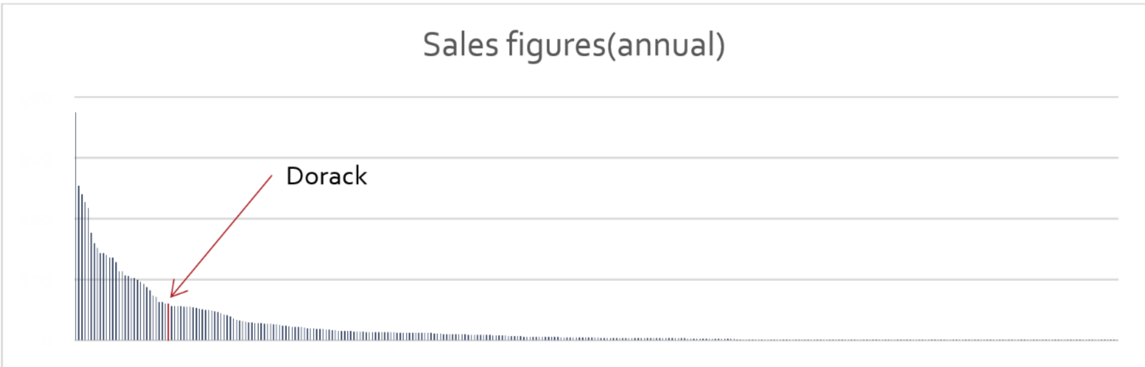


Figure 27: Sales figures production parts

4.3 Process

This section will first describe the processes involved in producing the Dorack, the standard flow of goods through the factory, and how this flow is accommodated for by the layout of the factory and the procurement strategy. Next, further attention will be given to the efficiency of the process, first describing what measures are already in place and which opportunities still exist.

To create an overview of the processes involved in producing the Dorack, Appendix II: Assembly tree is augmented with the processes required for each part. The typical production process of a Dorack is described below. The numbers between parentheses correspond to the numbers in Figure 28, which illustrates a typical flow of goods through the factory.

- Sales orders for each product enter the ERP system through the sales department.
- When a new sales order comes in, it is put at the bottom of the list of sales orders. In cases where the product is already in stock, it can be shipped, and a production order is created to replenish the stock. The lead time for the Dorack is approximately X to X weeks.
- When the stock of Doracks is at 1, a new production order is sent out.
- Based on historical data from previous sales, other data like current stock level, and the expertise of the employees, a forecast is made for the sales of Doracks in the upcoming months. This is essentially an MRP system (Kals et al., 2019; Nahmias, 1997).

- A combination of the forecasted and true demand is used by the production planning department to plan when Doracks should be produced. The typical production quantity is one series of X Doracks per one or two weeks.
- All incoming goods enter the factory through one door (1) and are split based on their destinations.
    - All parts that need any manufacturing operation are sent to production (3).
    - Laser-cut parts are drum treated (2) to remove sharp edges. Only the joints[1] remain.
    - Standard parts used in assembly are stored in storage (8).
    - All retail items are sent to the warehouse (10).
- Production materials are divided into raw steel and aluminium stock (3a), and externally produced (usually laser-cut) parts (3b).
- Raw steel and aluminium stock are sawed to the correct length based on the production order (4).
- After sawing, the parts are either welded to form subassemblies (5a) or first machined further through milling, bending, pressing, turning, or drilling (5b). Employees of the welding department have their own workplace because an earlier project has shown they are more efficient when they work with the same equipment every time.
- The welded subassemblies are stored in a dedicated storage area (6) to wait for further processing.
- Metal parts generally receive one of two surface treatments: powder coating (7) or zinc plating, which is outsourced.
- After cooling down from powder coating, coated parts are stored in the storage area (8), where zinc plated parts are also stored after they return from the plating partner.
- The assembly of all products takes place in the assembly area (9).
    - A weekly planning is made for the assembly department as a whole, individual assembly tasks are not assigned to specific employees.
    - When assembling the Dorack, the rolling base is assembled first. From there, all other parts are assembled and mounted to the rolling base. First the middle frame and uprights, then the climbing frames. This order is not set in stone, but simply the preference of the employee.
- After assembly, all products are stored in the warehouse (10) until they are transported to the customer.

[1] Laser joints are the start and end point of a laser's path and are visible as a small notch on the product.

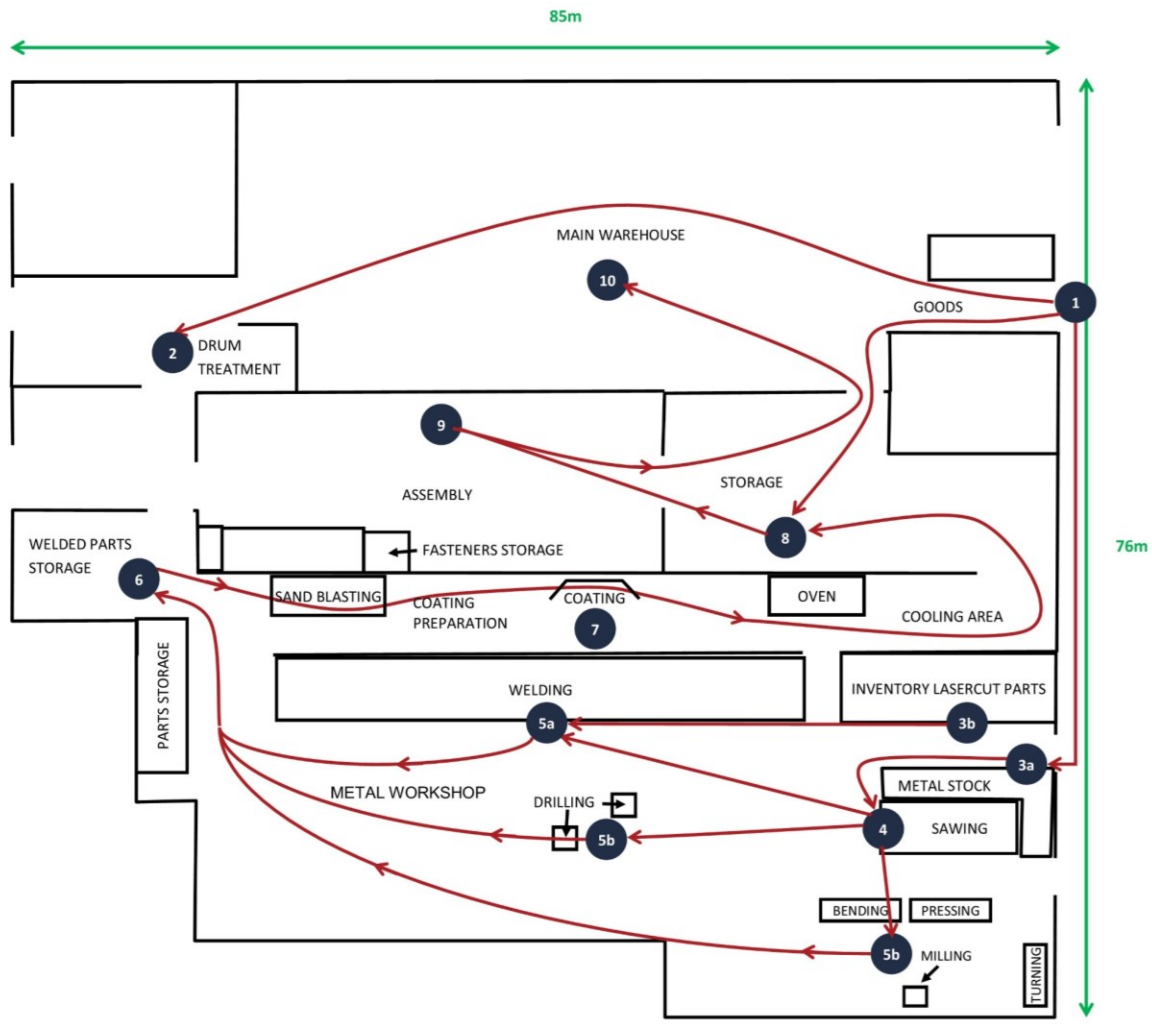


Figure 28: Production flow

A combination of procurement strategies is used at Nijha:

- The Dorack follows a 'push' strategy, similar to MRP (Nahmias, 1997), because production is initiated in anticipation of forecasted demand.
- Raw materials and subassemblies of other products generally follow a 'pull' strategy. These are taken from stock when needed and when the stock level reaches a certain point, the stock is replenished.
- Looking at the characteristics mentioned by Freeland (1991) (as quoted by Nahmias (1997, p. 19)), Nijha shows more characteristics of conventional purchasing (4/6) than JIT purchasing (2/6). See Table 7.

Table 7: Conventional vs JIT purchasing

Conventional Purchasing	JIT Purchasing
Large, infrequent deliveries	Small, frequent deliveries
Multiple suppliers for each part	Few suppliers, single sourcing
Short-term purchasing agreements	**Long-term agreements**
Minimal exchange of information	Frequent information exchange
Prices established by suppliers	Prices negotiated
Geographical proximity unimportant	**Geographical proximity important**.

4.3.1 Process efficiency

Observations of the production process showed which considerations have already been made to maximise efficiency and which opportunities still exist for improvement.

Existing considerations

Many efficiency-increasing measures are already in place at Nijha in general and for the Dorack specifically. The measures that apply to producing the Dorack will be described below.

Parts that share similarities are treated in the same batch where possible. For example, parts that need the same colour of powder coating are coated simultaneously, regardless of whether they belong to the same product.

The metal workshop uses templates for practically all welding and drilling operations to increase accuracy and reduce set-up time. The same holds for certain assembly operations like assembling the climbing frames. Besides this, tools required for specific operations are stored near the machine. For example, all drill bits are placed on a cart close to the drill press, with a designated hole for each drill diameter. In terms of machine utilization, the rule of thumb is followed that each part should be produced approximately once per month to optimize set-up costs in preparatory processes. The quantity of the batch is then based on the forecasted internal demand.

Parts that belong to the same product are placed close together in the warehouse to facilitate efficient picking. In addition to this, the exact storage area where a part is placed is determined by what processes it needs to go through. Raw materials are placed near the metal workshop, parts waiting for powder coating are stored near the coating street and purchased parts are stored near the assembly area. To minimize the chance of confusing similar parts, these are stored in distinct positions in the same area. For example, the rungs of the Dorack have different lengths and therefore one type is stored at the entrance of the storage area, another type is stored on the left side, another on the right side, et cetera.

The batch size of X Doracks in assembly is partially based on spatial considerations, as the available space does not allow more products to be assembled simultaneously. The other reason is capacity. The number of assembly employees is limited and assembling one Dorack takes approximately X hours. Increasing the batch size would mean one of the employees would be busy with just assembling Doracks for more than X days. As the monthly demand varies between X and X, potentially growing to X, the current batch size suffices.

The three most common products are assigned their own section in the assembly area. This holds for the Dorack, height adjustment systems for gymnastics rings, and benches. Each section has multiple drawers and containers that hold smaller (up to approximately 50*50*20 cm) purchased parts. Larger parts are gathered on rolling carts.

Figure 29: Cart with powder coated Dorack parts

For example, all powder coated and larger purchased parts of the Dorack are gathered on a rolling cart (Figure 29) that fits exactly the parts for X Doracks. In this way, the distance travelled by the assembly employee for gathering parts is minimized, which reduces the 'transportation' and 'motion' types of waste (Liker, 2003; Theisens, 2016).

The product is assembled in one continuous session, and not in separate subassemblies like the product structure described in paragraph 4.2.3 might suggest. One reason for this is logistics. Using subassemblies would mean storing these somewhere and thus occupying space, requiring logistics, and requiring extra handling. Another reason is financial: each subassembly becomes an internal production order, which has a starting overhead fee of €X. The last reason is that one person always assembles the product. First letting this person create subassemblies and subsequently combining these subassemblies at another moment would have no added benefit.

Some principles of Lean, like visual management, have already been implemented. Employees who are responsible for the shopfloor understand the benefits of Lean, but struggle with maintaining the principles because other employees simply do not follow all the 'rules'.

In short, the first 3 to 4 S's (Sort, Straighten, Shine, Standardize) of the 5S method (Liker, 2003, p. 150) are followed. Only the last S (Sustain) is difficult to maintain.

Opportunities

As the breakdown of the product costs described in paragraph 4.2.5 showed that coating and assembly contributed most to the production costs, these processes are given extra attention to determine opportunities for improvement. This is done by observation of the coating and assembly operations, and consulting the coordinator of the metal workshop. For the full documentation of the observations, see Appendix VI: Process observations.

The observation of the coating operation shows that sand blasting the parts is the bottleneck of the process, and some parts are coated without having any aesthetic function. This last point is the most suitable opportunity for the case study, as the other would require a more detailed analysis of the operation that is not considered necessary by the involved employees.

The observation of the assembly process shows that it contains several types of 'waste', (Liker, 2003, p. 28). Thirteen instances of 'overprocessing', two instances of 'movement', and three instances of 'transport' are identified. An important sidenote is that the 'transport' instances are necessary from an ergonomic perspective as they relate to moving the product from the trestles to the floor to facilitate easy reaching of the top parts of the product. Especially 'overprocessing' is dominant, as it accounts for X minutes of extra work for each Dorack. Many of these operations have their roots in earlier process steps but only become apparent during assembly. Some of these points are:

- Extra reaming, drilling, and tapping operations are required to remove the coating from many holes.
- Some parts are more complex than may be necessary.
- Some parts are relatively expensive and may be replaced by cheaper alternatives.
- Some parts can be made from alternative materials.
- The variation in required tools may be reduced.

4.4 Conclusion on orientation phase

The orientation phase aimed at creating an impression of the company, product, and process. The impression of the company showed that only 5% of the products are produced in-house. Of these products, the Dorack is attributed the largest portion of the annual production capacity. A make-to-order (MTO) or assemble-to-order (ATO) approach is used for most products, and a make-to-stock (MTS) approach is used for the Dorack. The factory layout facilitates a smooth trajectory of goods past all required operations.

The impression of the product showed that the product has three main configurations and consists of several main subassemblies. An exploded view of the most relevant parts can be found in Figure 30 on page 44.

The competitor analysis showed that competitors sell either wall-mounted climbing frames for around €3500 or movable climbing frames for around €5900. The Dorack differs from its competition in having an additional 'roof' configuration, using aluminium rungs, and being more colourful.

The cost breakdown showed 67% of costs come from material and 33% are production costs with coating, welding and assembly being the biggest contributors. Lastly, the sales figures analysis identified a pattern where most orders are received before the summer break and end of the year. The distribution of shipping dates showed a difference factor of 2.2 between the busiest month (September) and the quietest month (April).

The process analysis described the typical flow of goods through the factory and identified current efficiency measures as well as opportunities for additional efficiency measures.

Based on the orientation phase, the focus for the rest of the case study is determined as reducing the cost of individual parts and process steps. The following questions are formulated for the ideation phase:

1. How can 'wasteful' operations in assembly (section 4.3) be eliminated or prevented?
2. How can powder coated parts be made cheaper, whilst not compromising functionality or aesthetics?
3. How can standard parts be purchased cheaper without compromising quality?
4. Which welded parts can be combined, to omit certain welding operations?

These questions are partially answered through literature research (sections 3.2, 3.3, 3.4 and 3.5) and developed further during Ideation.

4.4.1 Scope of case study

The orientation phase yielded a more concrete scope for the case study:

> The case study should reduce the cost price of the Dorack. This can be achieved by reconsidering the parts of, and processes used for, the product. The alterations cannot compromise the perceived quality, aesthetics, functionality, or safety of the product.

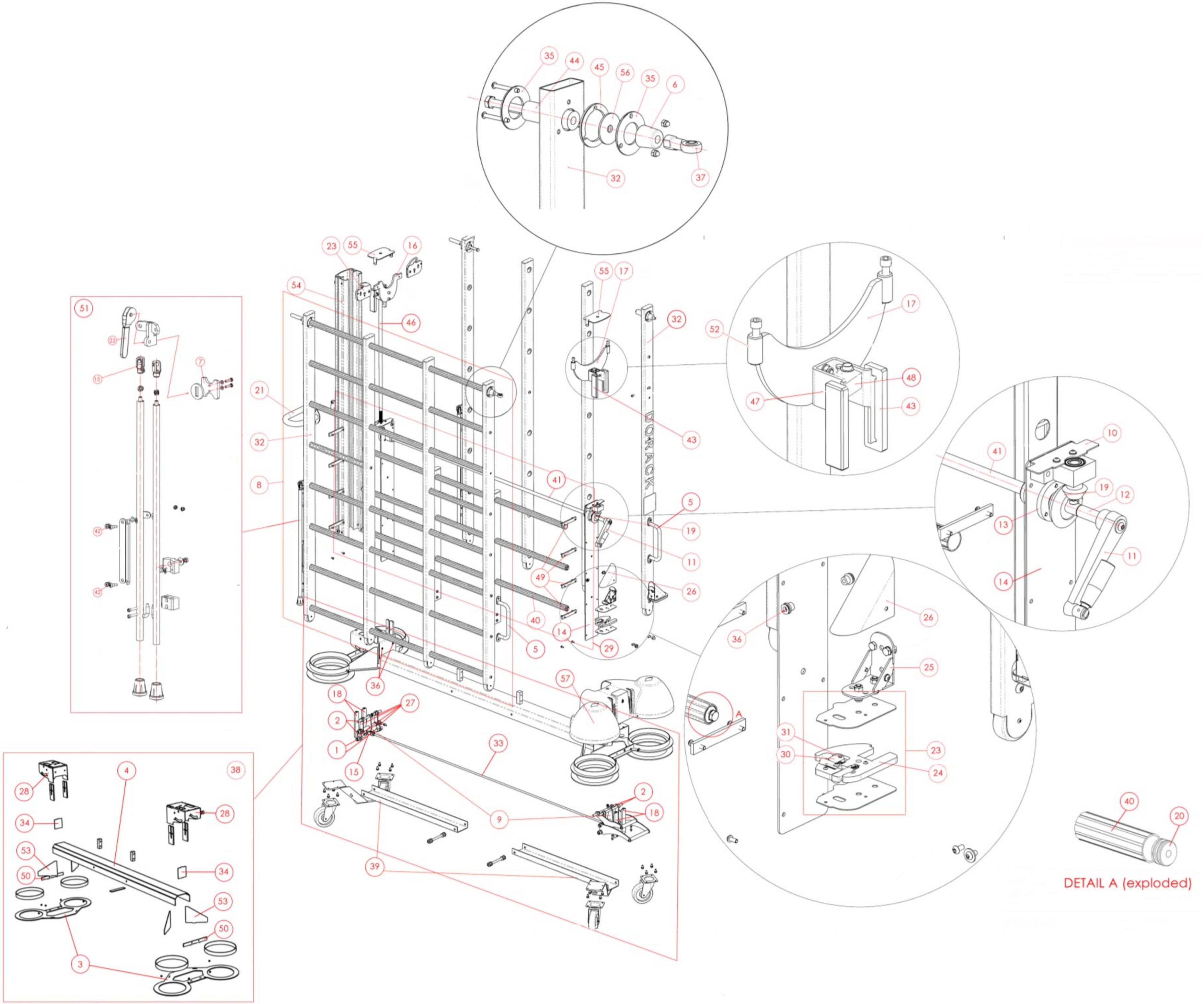


Figure 30: Exploded view

Table 8: Parts list exploded view

Drawing number	Part number	Part name (Dutch)	Part name (English) ↓A-Z
1	544431	As verrol	(Short) Axle 75mm
2	544430	As 215 verrol	(Long) Axle 215mm
3	553052	Bodemplaat verrol	Base plate
4	534007	Tussenbalk verrol	Beam rolling base
5	603142	Beugel	Bracket
6	553175	Bus	(Conical) Bushing
7	551046	Klemplaat	Clamping plate
8	741238	Klimrek	Climbing frame
9	603148	Koppelhefboom	Coupling lever
10	553184	Afdekplaat tbv klimrek Dorack	Cover plate
11	358106	Handgreep/slinger	Crank
12	544175	Koppelstuk Dorack	Crank-shaft connector
13	553169	Flens tbv tussenframe Dorack	Flange
14	553166	Flensplaat	Flange plate
15	368112	(Stel)Gaffel	Fork joint
16	553181	Reksteun tbv klimrek Dorack	Frame support (without bushing)
17	603176	Reksteun klimrek Dorack	Frame support with bushing
18	553065	Voorplaat verrol	Front plate rolling base
19		Tandwielen	Gears
20	553167	Groefmoer	Grooved nut
21	600480	Handgreep Dorack	Handgrip
22	358105	Handgreep	(Clamping) handle
23	726123	Grendel	Latch
24	553157	Grendelhuis	Latch housing
25	603149	Grendelsteun	Latch support
26	553077	Kap Dorack	Latch support cover
27	553062, 553064	Schalmen	Links
28	603145	Huis bedienings mechanisme	Mechanism housing
29	783998	Tussenframe	Middle frame
30	553070	Houdpal	Pawl
31	312612	Parallel pen ISO 8734-6m6x10	Pin
32		Stijl	Post
33	544432	Stang verrol	Push-pull rod
34	553056	Verstevigingsplaat	Reinforcement plate
35	551050	Montagering	(Mounting) ring
36	312345	Blindklinkmoer	Riveting nut
37	361416	Stangkop	Rod end
38	787329	Verrol	Rolling base
39	603147	Draagarm verrol	Rolling base arm
40		Sport	Rung
41	544173	As Dorack	Shaft
42	343106	Pasbout	Shoulder screw
43	553163	Glijblok/glijstuk	Sliding block
44	553173	Glijlager	Sliding rod
45	553174	Tussenring	Spacer ring
46	544161, 544178	Spindelas	Spindle
47	553162	Geleidingsplaat	Spindle guide plate
48	553160, 553161	(Spindel) Moer	Spindle nut
49	553051	Moerplaat	Strip
50	553057	Strip verrol	Strip rolling base
51	765902	Schoren	Supporting legs
52	135202	Draadbus reksteun	Threaded bushing frame support

Drawing number	Part number	Part name (Dutch)	Part name (English) ↓A-Z
53	553054	Schoorplaat verrol	Triangular plate
54	568067 & 568068	Staander	Upright
55	553183	Afdekkap tbv klimrek Dorack	Upright cover
56	553177	Sluitring	Washer/closure ring
57	575110 & 575109	Verrolkap	Wheel cover

5 Ideation

The orientation phase ended with four questions (section 4.4):

1. How can 'wasteful' operations in assembly (section 4.3) be eliminated or prevented?
2. How can powder coated parts be made cheaper, whilst not compromising functionality or aesthetics?
3. How can standard parts be purchased cheaper without compromising quality?
4. Which welded parts can be combined, to omit certain welding operations?

These questions are answered by ideas grouped in three categories. The first question is partially answered by the first category of ideas: establishing a solid foundation of the product by improving tolerances and altering technical drawings (section 5.1). The rest of the answer lies in redesigning and combining certain parts. These are both part of the second category of ideas: making major changes to parts of the product and process (section 5.2).

The second question is answered in paragraph 5.2.3: making changes to process operations. In addition to this, section 5.2 describes a few ideas for using cheaper or stronger materials for certain parts.

Question 3 is answered in section 5.3: by considering different suppliers and different (varieties) of parts. These belong to the third category of ideas: making minor changes to parts of the product and process.

Question 4 is answered in paragraph 5.2.2.

All ideas that are continued to the next phase will be listed for each category in this chapter. The problem, envisioned solution, and estimated win per Dorack are stated for each idea. In cases where the win is expressed as a unit of time these estimations are based on the observation of the assembly process described in section 4.3, or the work of Zandin (1980). In cases where the win is expressed as a cost reduction, the estimates are based on data from the ERP system for Dorack-specific parts and alternative prices of suppliers for purchased parts.

Only the ideas that were developed further in the project are described in this chapter. The decisions to proceed with or discontinue ideas were made during an interactive session with representatives of the engineering, production, and assembly department. The main criteria for the ideas were feasibility, realism, and the expected benefit of the idea. The discontinued ideas can be found in Appendix X: Discontinued ideas.

Readers note: most ideas are illustrated with a figure, but be reminded that Figure 30 on page 44 can be used to see where in the product certain parts can be found.

5.1 Solid foundation

Most ideas for establishing a solid, flawless foundation for the product relate to improving the fit of joining parts. In these instances, the parts do not fit well in practice, despite their dimensions suggesting they should.

The seven ideas described below are proceeded from a total of 17 ideas. The other ideas are discontinued because they either turned out not to be as prevalent as thought, the current process would not allow these changes, or the parts were intentionally designed to have a loose or narrow fit. The discontinued ideas can be found in Appendix X: Discontinued ideas.

5.1.1 Altering technical drawings

As Edwards (2002, p. 654) suggested, the use of tolerances should be minimized and tolerances should only be as tight as required. This advice can be applied to several parts of the Dorack.

Crank-shaft connector

The part that connects the crank to the shaft of the middle frame (Figure 31) often needs to be sanded during assembly because it does not fit in the shaft. This qualifies as 'overprocessing' (Liker, 2004, p. 29) and can be avoided by improving the pairing of the tolerances[2] of the connector and shaft. Because the connector is fixated with a screw, the looser fit should not lead to a looser connection.

Estimated win per Dorack: X minutes.

Holes for riveting nuts

The holes for the riveting nuts in the mechanism housing (Figure 32) are a fraction too narrow[3]. This means that they need to drilled out during assembly, which qualifies as 'overprocessing' (Liker, 2004, p. 29). This can be avoided by increasing the specified diameter of the holes on the technical drawings.

Estimated win per Dorack: X minutes.

Rivet hole in flange

The hole for the rivet that is part of the flange is positioned straight above the rung below it (Figure 33). This means the riveting gun does not fit in between the rungs and therefore has to be disassembled, which qualifies as 'overprocessing' (Liker, 2004, p. 29). Repositioning the hole would solve this problem. Another solution would be to use a different (for example manual) riveting gun.

Estimated win per Dorack: X min.

Holes in latches

The holes for the pins in the latch housings (Figure 34) are designed as a transition fit (6mm H7/m6). In practice, the holes need to be drilled out as a result of the zinc plating of the latches narrowing the holes, which qualifies as 'overprocessing' (Liker, 2004, p. 29). Enlarging the dimension of the hole on the drawing can omit this step. Another option is to integrate the pin with the latch housing while milling the pocket. This idea will be further described on page 51. A third option is to use a spring-type pin, which is less sensitive to small variations in diameter. All three options are prototyped.

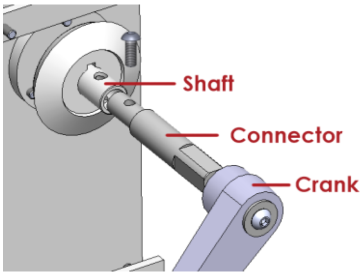


Figure 31: Crank-shaft connector

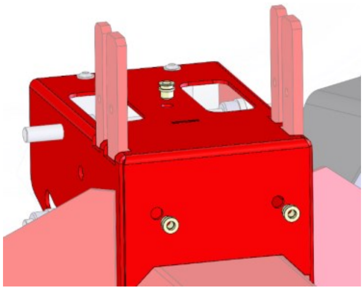


Figure 32: Mechanism housing and riveting nuts

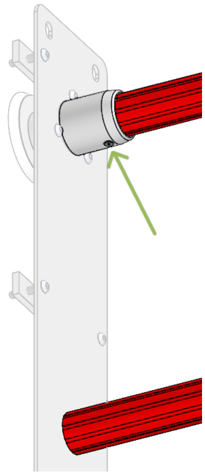


Figure 33: Flange rivet above rung

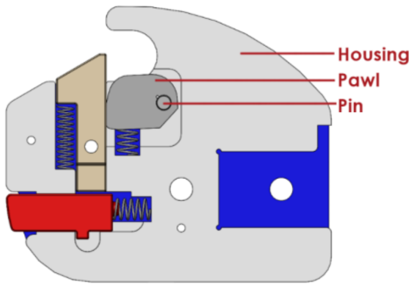


Figure 34: Latch

[2] The connector currently has a 15h7 tolerance, meaning 0, -0.02mm and is zinc plated (10 ±2 µm) afterwards. The shaft has a tolerance of 15 (0, +0.1) mm. Thus, the fit can be anywhere between 12 µm too tight and 0.128mm too wide.

[3] The holes are currently dimensioned as 10 (0, +0.2) mm, to which a layer of powder coating (2*0.08mm) is added. The riveting nuts require a hole of 10 (0, +0.15) mm. Thus, the fit can be 0.16mm too narrow.

Estimated win per Dorack: X minutes.

Hole in pawl 553070

The laser-cutting process leaves some molten metal spatters on the pawl in the latch (Figure 34). These must be filed away, which qualifies as 'overprocessing' (Liker, 2004, p. 29). To avoid this, either the supplier will need to remove the spatters, the part needs to be drum treated, or a chamfer needs to be added to the part.

Estimated win per Dorack: X minutes.

Laser joints

Spacer ring 553174 and washer 553177 (Figure 35) both have a laser joint on the contact area, which collide when the parts rotate. To prevent this, the parts are filed during assembly, which qualifies as 'overprocessing' (Liker, 2004, p. 29). This can be avoided by either enlarging the internal diameter of the ring, reducing the external diameter of the washer, or repositioning the joints. The prior option was chosen.

Figure 35: Conflicting laser joints on ring and washer

Estimated win per Dorack: X minutes.

The same holds for pawl 553070 (indicated in Figure 34), which also has a laser joint on the contact area that can be repositioned.

Estimated win per Dorack: X minutes.

5.2 Major changes

A total of 43 ideas emerged in a response to the findings of the DFA, costs, and process analyses (paragraphs 3.5.1, 4.2.5 and 4.3). The 25 ideas described in the following paragraphs are proceeded and can be categorised as: redesigns of parts, combinations of parts, changes to process operations, and robustness. The main reasons for discontinuing the other ideas are that these changes would be too large to allow other ideas to be developed, the changes would inhibit repairs or maintenance, the problem was less prevalent than thought, the change would require investments that are not worth the win, the change would lead to insufficient strength, or the change would be too complex. The discontinued ideas can be found in Appendix X: Discontinued ideas.

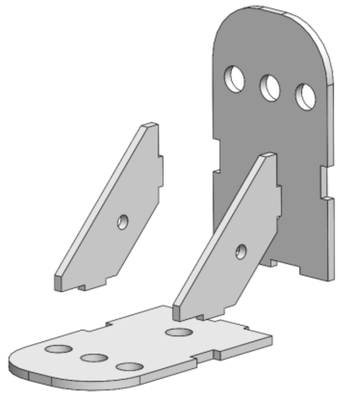


Figure 36: Latch support exploded

5.2.1 Redesigns of parts

Latch support

The latch supports (Figure 36) consist of four welded parts each, costing a total of €X for the parts and €X for welding. Subsequently, they are powder coated for €X in total. Alternatively, this part can be produced by bending from one piece, following the DFA guideline of reducing the number of parts. The part can then also be zinc plated at the supplier, saving another €X.

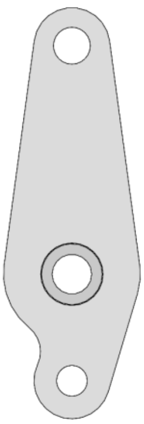


Figure 37: Asymmetrical coupling lever

Estimated win per Dorack: €X for bending instead of welding and €X for zinc plating instead of coating.

Coupling lever
The coupling lever (Figure 37) is asymmetrical, which could lead to incorrect assembly. Following the DFA guideline of using symmetry where possible (Boothroyd et al., 2002), the part should be symmetrical. This also is an example of 'poka yoke' from the Lean methodology (Theisens, 2016).

Estimated win per Dorack: easier and more error-proof assembly.

Latch housing
To prevent jamming and tangling of the springs in the latch housing (Figure 34, page 48), a chamfer can be added (Boothroyd et al., 2002).

Estimated win per Dorack: easier assembly (Xs), higher reliability.

The latch housing (Figure 34, page 48) is produced by laser-cutting the main shape and subsequently milling out the pockets. This is a relatively expensive method, as the four latches cost €X each. Producing the part by joining three laser-cut plates can reduce the cost significantly.

Estimated win per Dorack: 4*(X-X) ≈ €X.

Front plate
The rolling base contains four front plates (Figure 38). Each has one tapped hole at the front of the plate and one at the top of the plate. Applying the DFM guidelines yields the following ideas:

- The four plates can be exchanged for two wide plates. This would remove two sawing operations. **Estimated win per Dorack:** X/2 = €X
- The hole at the top can be exchanged for another hole in the front of the part. This makes the part symmetrical and easier to tap, as it does not have to be repositioned in the drill press. **Estimated win per Dorack:** X*0.25 = €X
- Instead of tapped holes for assembly using bolts, rivets can be used which require a regular (untapped) hole that can be made by punching. **Estimated win per Dorack:** X*0.75 = €X

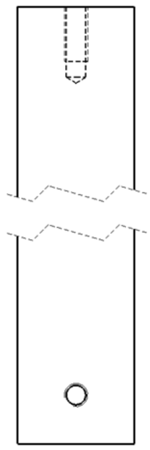


Figure 38: Front plate

The largest cost reduction can be achieved by using fewer and thinner plates, as well as positioning holes on the same surface and using untapped holes. Using rivets for mounting the plates would enable all these options. Therefore, this idea was proceeded.

Two quotations were requested: one for adding an extra strip to the mechanism housing so the front plates can be made with just holes in the front, and one for replacing the front plates with a bent plate so the existing holes in the mechanism housing can remain in the same location.

5.2.2 Combining parts
All 269 individual parts of the Dorack are evaluated against the three principles of DFA. See Appendix VIII: DFA criteria. This shows that the product could theoretically consist of 122 individual parts. The improvement potential formula of Ulrich et al. (2020) yields the following potential:

$$Potential = \frac{actual\ number\ of\ components - theoretical\ number\ of\ components}{actual\ number\ of\ components}$$

$$= \frac{269 - 122}{269} = 55\%$$

This means the improvement potential is 'fair'. However, as Boothroyd et al. (2002) already stated, in practice the product will consist of more separate parts than this number. Each extra part needs to be justified. In the case of Dorack, many parts are justified because of:

1. Safety: the product needs to adhere to safety standards concerning risk of injury.
2. Production cost: theoretically, many non-moving parts could be combined. However, this would mean creating specific parts that are difficult to produce. For example, the upright could theoretically have an integrated handgrip and latch support. However, this would mean those parts cannot be made with extrusion, but with an even more specific production method.
3. Reliability: combining certain parts would make the new part more prone to failure.
4. Standardization: some parts, like the upper latches, can be integrated with the frame supports. However, because they have the same functionality as the lower latches, it is more feasible to standardize them.

The remaining opportunities will be described below. The full DFA investigation can be found in Appendix VIII: DFA criteria.

Pin and latch housing

Because the latch housing (Figure 34, page 48) is machined, the pin can be machined as a part of it, eliminating the need for an additional pin.

Estimated win per Dorack: €X and X minutes.

Reinforcement plate and rolling base frame beam

The reinforcement plate can be made part of the beam of the rolling base frame (Figure 39).

Estimated win per Dorack: two fewer welding operations.

Triangular plate and base plate rolling base frame

The triangular plate of the rolling base frame (Figure 39) can be combined with the base plate.

Estimated win per Dorack: four fewer welding operations.

Triangular plate and mechanism housing

An alternative to the option above is combining the triangular plate with the housing of the mechanism.

Estimated win per Dorack: four fewer welding operations.

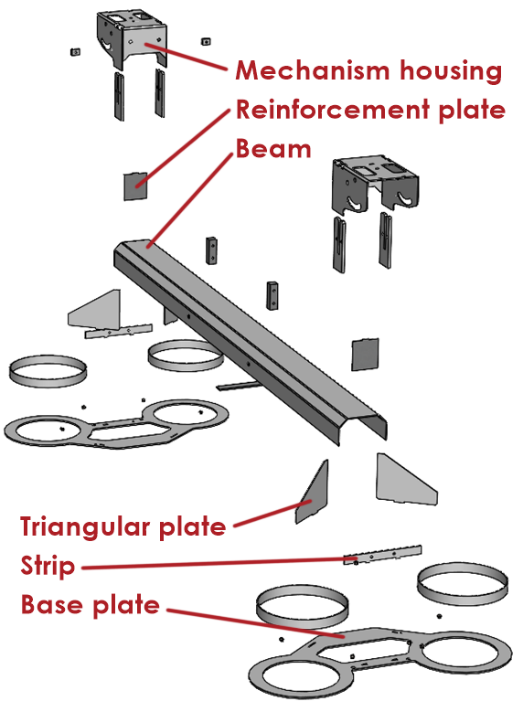


Figure 39: Exploded view rolling base frame

Base plate rolling base frame and strip

When making a single bend in the base plate of the rolling frame (Figure 39), the strip can be omitted.

Estimated win per Dorack: fewer welding operations.

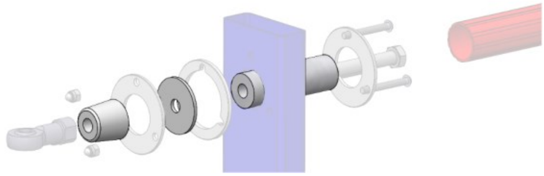


Figure 40: Bushing, washer and sliding rod

Conical bushing, washer, and sliding rod

The conical bushing, washer and sliding rod at the top of the climbing frame (Figure 40) can be combined. This makes assembly easier and could impact material cost.

Estimated win per Dorack: fewer parts, easier assembly. (4*X=Xs).

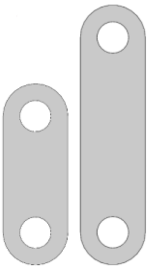


Figure 41: Short and long link

Links

For the sake of standardisation, the short and long links used in the rolling base (Figure 41) can be replaced by one universal link.

5.2.3 Changes to process operations

Various changes can be made to the operations in the process. Several powder coated parts can be zinc plated, the assembly sections can be structured, and several production steps can be outsourced. All will be described in the paragraph below.

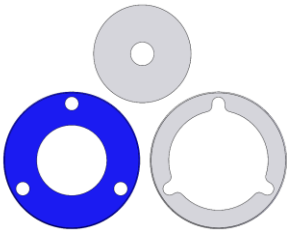


Figure 42: Rings 551050 (left), 553174 (right) and 553177 (top)

Zinc plating instead of powder coating.

Ring 551050 (Figure 42) is powder coated, but only for aesthetic reasons. Rings 553177 and 553174 are of comparable size, and are zinc plated. These cost €X and €X per piece respectively, whereas 551050 costs €X per piece. In case it will be zinc plated, it can be produced at the same supplier as the other two.

Estimated win per Dorack: 8*(X-X) = €X.

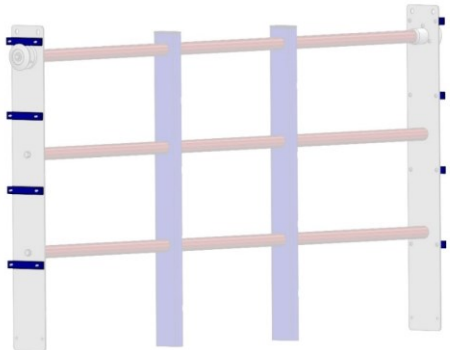


Figure 43: Middle frame strips

Strips 553051 (Figure 43) of the middle frame are coated. They are not visible on the outside, so aesthetics are not a factor. Coating costs €X and the holes need to be re-tapped to remove the coating from the threads. Zinc plating would be a cheaper alternative and would not require re-tapping.

Estimated win per Dorack: €X and X minutes of tapping.

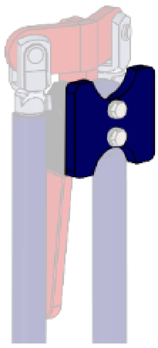


Figure 44: Clamping plate

Clamping plate 551046 (Figure 44) is coated but is not visible from the outside. Zinc plating or not treating this part would save costs in coating.

Estimated win per Dorack: €X.

Cover plate 553184 (Figure 45) is laser-cut at an external supplier and then coated grey at Nijha. Zinc plating would again be a cheaper option, and the aesthetics would be comparable. One potential hazard is that zinc plating may leave a sharp edge on the part. This will be tested in the prototype.

Estimated win per Dorack: €X.

Latch support cover 553077 (Figure 46) is formed externally but coated grey in-house. Again, zinc plating would be cheaper and have comparable aesthetic value.

Estimated win per Dorack: €X.

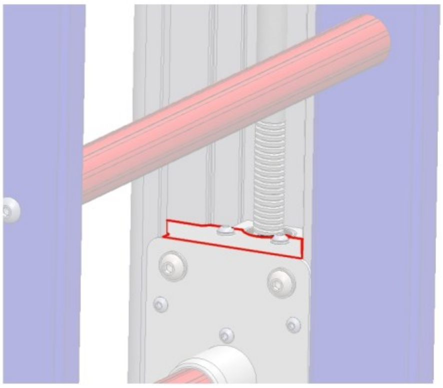


Figure 45: Cover plate 553184

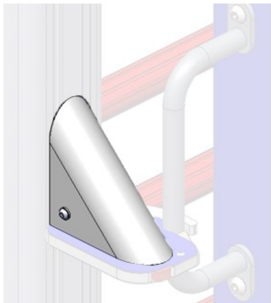


Figure 46: Latch support cover

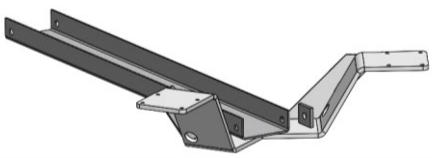


Figure 47: Rolling base arm

Structuring production sections

Certain steps of producing the Dorack can be performed independently of each other. It is currently not documented which steps are interdependent. Creating a precedence map or dependency map may help in clarifying what can be done when, to counteract delays resulting from supply issues (Hu et al., 2011; Langeveld, 2009; Tompkins et al., 2010).

Outsourcing

Some operations are performed in-house but can also be outsourced, especially when parts needed in that operation are produced at a supplier that can also perform the next step.

The *rolling base arm* (Figure 47) is welded at Nijha, after which it is sent to an external company for zinc plating. It then has to come back again to Nijha for assembly in the Dorack. Outsourcing the welding operation to the zinc plating partner saves transportation.

Estimated win per Dorack: 2*X=€X.

Front plate 553065 (Figure 38, page 50) is sawed and tapped in-house and zinc plated externally. Outsourcing the machining operations to the zinc plating partner saves transportation.

Estimated win per Dorack: €X.

Coupling lever 603148 (Figure 37, page 49) consists of an externally laser-cut part and a tube that is sawed in-house. These are then welded in-house, after which they are zinc plated externally. Outsourcing the laser-cutting, welding, and zinc plating to the same company will save logistics.

Estimated win per Dorack: €X, but likely more.

Axle 544431 is produced internally, whereas axle 544430, which is only longer but otherwise identical, is produced externally. Either in- or outsourcing both axles would be more logical. Quotations are requested for both options.

Estimated win per Dorack: 4*(X-X) =€X.

5.2.4 Alternative materials for parts

Reconsidering the materials used for parts can contribute to cost reduction (Berk, 2010; Bralla, 1999; Edwards, 2002; Mascitelli, 2011; Weustink et al., 2000).

Stainless to zinc plated steel

Pawl 553070 (as seen in Figure 34 on page 48) is made of stainless steel. The initial reason for using stainless steel was that it is easier to keep to the tolerances, as it gets no surface treatment. Changing to zinc plated steel can save costs.

Estimated win per Dorack: 4*X – 4*X = €X.

Bushing 553175

The bushing that spaces the rod end and the climbing frame (Figure 40, page 52) is made of zinc plated steel. Making it of a different material, for example plastic, could make it cheaper. A quotation was requested to verify this.

Estimated win per Dorack: 4*(X-X) = €X.

Rungs

The rungs are responsible for 10% of the total costs of a Dorack. The largest part of this cost comes from coating (38%) and the grooved nuts (31%). Both factors can be omitted by making the rungs of wood.

Estimated win per Dorack: X-X = €X.

5.2.5 Robustness

Gears

The gears are the part of the Dorack that must be repaired most often (X times in 2023). A gear repair set has already been assembled that contains two sets of gears, keys and set screws. This problem can be solved in two ways:

1. Changing the material of the gears from polyacetal to polyketone. Polyketone gears are 5% stronger (torque ratings of 2.20 and 4.39 Nm instead of 2.09 and 4.18 Nm) (Mädler GmbH, 2024). **Estimated win:** better reliability, fewer repairs.
2. Include a detection mechanism for when to stop turning the crank. An auditive click is prototyped, but a bell or a tactile clue like a torque limiter might also work. **Estimated win**: better reliability, fewer repairs.

5.3 Minor changes

Several parts can be reduced in cost through minor changes. Paragraph 5.3.1 applies the suggestion of Meeker and McWilliams (2004); (2003) to achieve cost reduction by sourcing through a different vendor. Paragraph 5.3.2 identifies candidates for '[changing] components for alternatives with lower costs, lower performance, lower tolerance, or lesser quality', whilst 'still achiev[ing] the product requirements without sacrificing quality control' (Meeker & McWilliams, 2004, p. 32). The latter part of the advice, referring to still achieving requirements and not sacrificing quality, is tested in the prototype as will be described in sections 7.2 and 7.3.

The following eight ideas are proceeded from a total of 19. The main reasons for discontinuing the other ideas are unavailability of suppliers, inhibiting maintenance or reparations, inferior wear resistance, and requiring changes to other parts. The discontinued ideas can be found in Appendix X: Discontinued ideas.

5.3.1 Different suppliers

The shoulder screws (343106) in the legs cost €X per piece and are bought at a different supplier than all other fasteners. Other suppliers sell them for €X to €X per piece.

Estimated win per Dorack: 8*(X-X) =€X.

The suppliers for each standard part are reconsidered, to determine if cheaper alternatives are available. The results are described in paragraph 6.4.3.

5.3.2 Different (varieties of) parts

Bolts

The Dorack contains a total of 461 fasteners, costing €X in total. 247 of these are metric bolts or screws, which cost €X and comprise 31 variations. Limiting the variety of fasteners and subsequently required tool changes can decrease the assembly time (Corbett, 1991).

Estimated win per Dorack: smoother assembly.

Where possible, some bolts may be replaced by rivets as these are a cheaper alternative (Boothroyd, 1994). The wheels are attached to the rolling base arm using bolts (Figure 48). This takes time and requires tapping the holes in the arms twice (during production as well as assembly), which qualifies as 'overprocessing' (Liker, 2004, p. 29). Instead, rivets could be used to attach the wheels. This would omit the tapping and screwing operation.

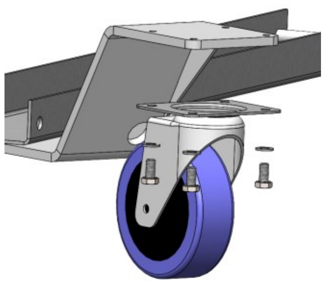


Figure 48: Wheel attachment

Estimated win per Dorack no tapping (X min) and bolt screwing (16*X=Xs), only riveting 16 times (16*X=Xs). Time saved: X+X-X=Xs. The price difference between bolts and rivets is negligible. One bolt and washer cost €0.05 and €0.01 respectively, a rivet costs €0.058.

Rod end

The rod ends (Figure 49) that connect the climbing frames to the height adjustment mechanism cost €X each, while a cheaper version (X-X€) is also available. The cheaper version is tested in the prototype.

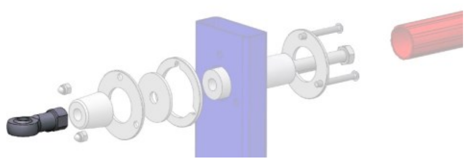


Figure 49: Rod end

Estimated win per Dorack: 2*(X-X) =€X.

Push-pull rod rolling base

The push-pull rod of the rolling base is produced in-house. Using a standard threaded rod for this would be cheaper. These range in price from €X to €X, depending on the material.

Estimated win per Dorack: X – X = €X, no sawing, no turning.

Clamping handle

The clamping handles that fixate the supporting legs (Figure 50) cost €X each. Finding a cheaper option for these can save a significant amount. Nijha already uses a different clamping handle for other products, which might also be used for this application.

Estimated win per Dorack: 2*X=€X.

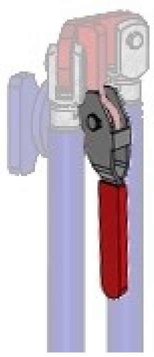


Figure 50: Handle

Rung screws

The rungs are attached to the outer posts by bolts, requiring grooved nuts inside the rungs (Figure 51). In the middle posts, however, they are attached using screws (Figure 52). Using these screws for the outer posts as well removes the need for the grooved nuts and bolts. This idea is prototyped to test its rigidity (see sections 7.2 and 7.3), along with one rack containing wooden rungs (as described on page 54)

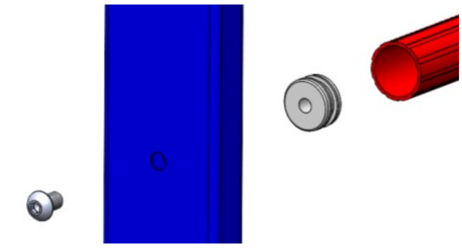


Figure 51: Screw, post, grooved nut and rung

Estimated win per Dorack: 32*(X+X+X-X) = €X.

Threaded bushing frame support

The bushings on the frame supports (Figure 53) are custom made and cost €X per piece. They can be replaced by hexagonal nuts that cost €X per piece.

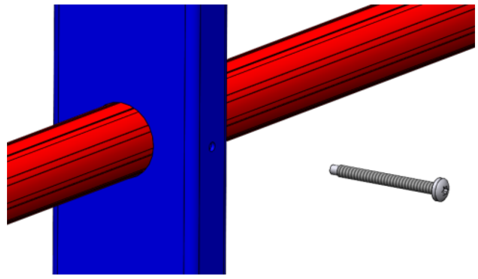


Figure 52: Screw attachment

Estimated win per Dorack: 2*(X-X) =€X.

5.4 Conclusion on ideation

The questions formulated at the end of the orientation phase (chapter 4) were answered with a total of 83 ideas as follows:

1. How can 'wasteful' operations in assembly (section 4.3) be eliminated or prevented?

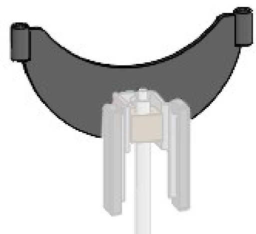


Figure 53: Frame support

Several instances of 'overprocessing' (Liker, 2004, p. 29) can be avoided by making changes to the technical drawings or changing to a rivet connection.

2. How can powder coated parts be made cheaper, whilst not compromising functionality or aesthetics?

Zinc plating is generally cheaper than powder coating. In cases where parts are not visible, or coated in grey, an alternative was proposed to zinc plate these parts. The effects on safety, functionality and aesthetics are tested in the prototype (sections 7.2 and 7.3).

3. How can standard parts be purchased cheaper without compromising quality?

Many alternatives are available for standard parts. Paragraph 5.3.2 indicated various candidates, and a complete overview of options can be found in paragraph 6.4.3.

4. Which welded parts can be combined, to omit certain welding operations?

Several welded parts were indicated as candidates for combination. CAD models are developed during conceptualisation, and quotations are requested from suppliers. The results can be found in Table 9 on page 63.

In addition, the guidelines of DFA and DFM, and make/buy considerations yielded several extra ideas.

The ideas were categorised as contributing to establishing a solid foundation for the product, encompassing major changes, or encompassing minor changes. All ideas generated would yield a roughly estimated cost saving of €X and a time saving of X minutes in total. These ideas are condensed into a more structured list of ideas to proceed with, in correspondence with representatives of the engineering, production, assembly, and maintenance departments. The remaining ideas theoretically add up to cost savings of €X and time savings of X minutes, and are developed further in the next phase, so quotations can be requested from suppliers.

6 Conceptualisation

All ideas considered worthwhile for proceeding during ideation are concretised during conceptualisation. The goal of the conceptualisation phase is to develop the ideas of the ideation phase to such a level of detail that they can be sent to suppliers for quotations and can be implemented in a prototype.

Following the idea from paragraph 5.2.3 to structure the production steps, a precedence map is created in section 6.1.

For ideas involving (re)designs of parts, CAD models are created along with their accompanying technical drawings. This is briefly described in section 6.2. The strength of certain redesigned parts is simulated to determine if they still fulfil the strength requirements after redesigning. This can be read in section 6.3.

The CAD files, technical drawings and order quantities (see paragraph 6.4.1) of redesigned parts and parts to be outsourced are sent to suppliers for quotations. The quotations show that a cost reduction of approximately €X can be achieved by these concepts. In addition to this, the product catalogues of standard part suppliers are studied to compare alternatives, and the variation of fasteners is reduced. These findings are described in section 6.4. The alternative sourcing of off-the-shelf parts has a potential cost reduction of €X and the variation of fasteners is reduced from 26 to 19 distinct types.

Based on the quotations, decisions are made regarding which parts should be produced for the prototype. The development of the prototype is described in chapter 7.

6.1 Precedence map

A precedence map is created to generate an overview of the interdependencies of the production processes (Figure 54). The map can be used in two ways:

1. In case a certain part is delayed, it can be looked up in the graph to determine which processes and other parts are delayed as a result. Simultaneously, parts that are not influenced by the delay can be processed earlier than normally.
2. In case a process is unavailable, all parts that need to undergo that process can be identified. Simultaneously, processes and parts not influenced by the unavailability of the process can proceed and potentially be performed earlier.

6.2 Modelling

The ideas from the previous chapter referring to (re)designing parts are all converted to complete CAD models and their accompanying technical drawings. The tolerances specified on the technical drawings are copied from the existing parts on which the new parts are based where possible. By doing this, the specification of the new part resembles that of the old part as closely as possible, minimising the risk of not complying with the original requirements. The remaining tolerances are determined in consultation with the engineers of Nijha. An overview of the CAD models that are developed can be found in Appendix XI: CAD models.

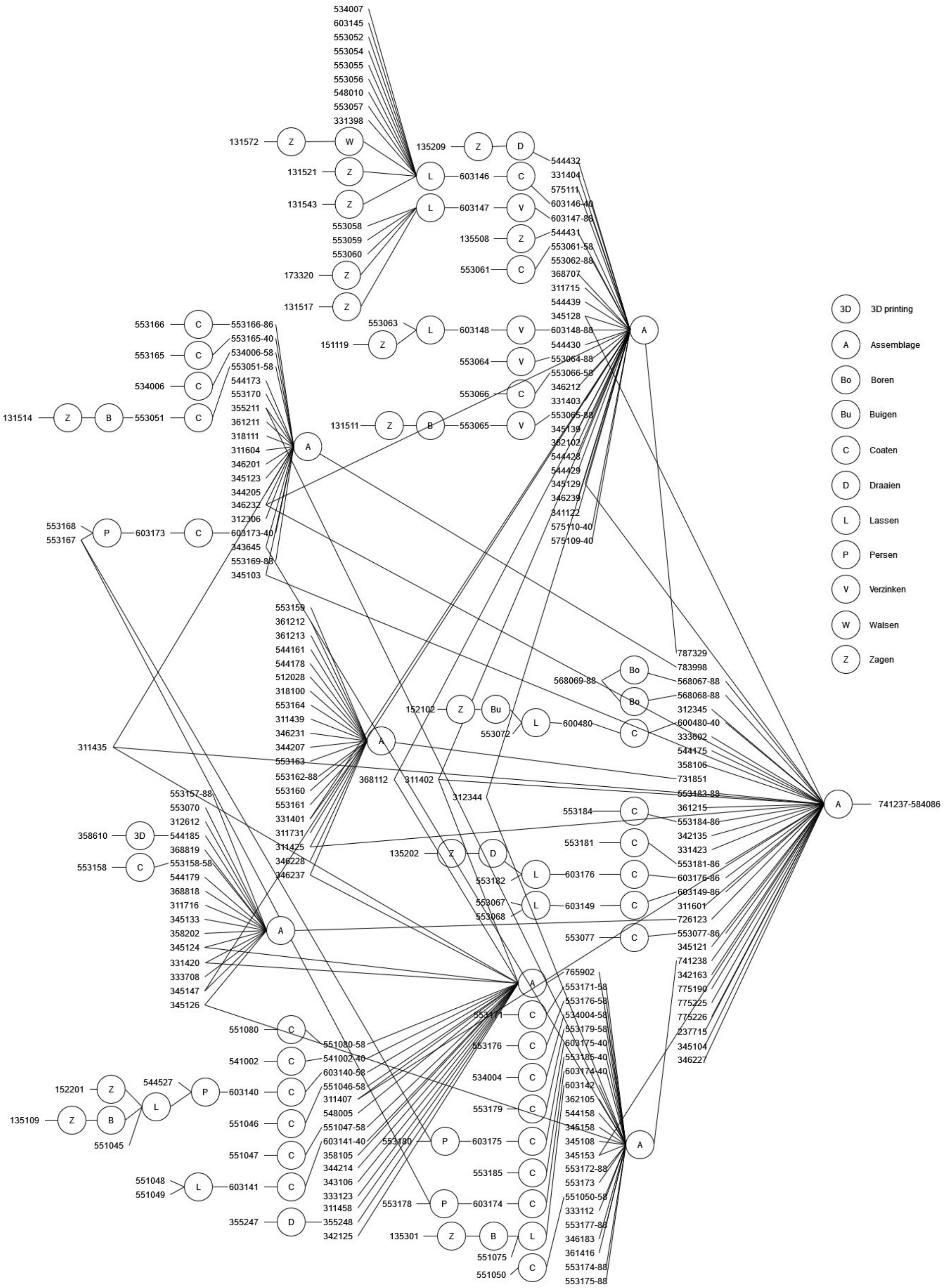


Figure 54: Precedence map

6.3 Strength calculation

In cases where the redesign might impact a part's strength, Finite Elements Analyses (FEAs) are performed. This includes the coupling lever, latch supports, bushings, latch consisting of plates, and the bracket attachment. All results can be found in Appendix XII: Simulation results and will be briefly discussed in the following section.

6.3.1 Coupling lever

Because the coupling lever of the rolling frame is made symmetrical, some material is removed (Figure 55). To determine the effect on the strength of the part, a series of FEAs is performed in SolidWorks Simulation. For both the old and new design, the force is determined where they would reach their yield strength in a static situation. This shows that the original part would reach its yield strength at a force of 5.40 kN and the new part at 4.08 kN under the same conditions.

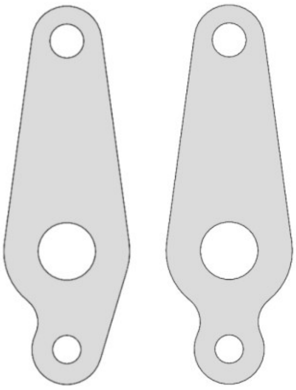


Figure 55: Old (left) and new (right) coupling lever

Despite a strength reduction of 25%, the part is still considered strong enough and therefore no further investigation is required.

6.3.2 Latch supports

As described in paragraph 5.2.1, the latch supports will be produced from one bent piece of steel. Two variants are designed: one 'cis' symmetrical and one 'trans' symmetrical (Figure 56).

Three simulations are performed: one with the 'trans' piece attached to the latch, one with the 'cis' piece attached to the latch with the openings towards the horizontal plate, and one with the 'cis' piece attached to the latch with the openings towards the vertical plate.

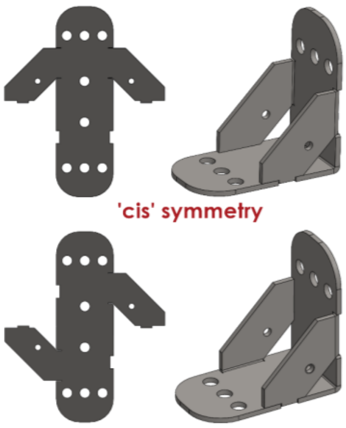


Figure 56: Cis vs trans symmetry

In all simulations, the boundary conditions are kept identical. A force of 1332N[4] is exerted on the part that remains exposed from the latch cover when in use.

All simulations have comparable results. The displacements are only 0.5mm and the stresses in the latch supports stay below the yield strength. In the simulation, some peak stresses (also known as stress singularities, hot spots, or red spots) occur in the bent edge of the support. Testing of the prototype will determine whether the real behaviour of the parts corresponds with the theoretical displacements and stresses.

The simulations show no notable differences between the configurations of the latch supports. If the practical test also shows no significant differences, the alternative that has the best nesting opportunities should be chosen to maximize material utilisation and minimise costs.

[4] This value is the result of factors found in European standard NEN-EN 913:2018+A1:2021 (European Committee For Standardization, 2021). Mass = 74kg, dynamic factor = 1.5, safety factor = 1.2.

6.3.3 Straight bushing

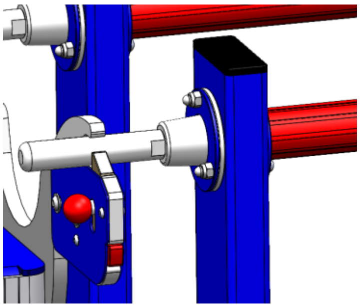


Figure 57: Frame supported by latch

To determine whether the change in geometry of the frame bushing (from conical to straight) will not result in insufficient strength, an FEA is conducted on the assembly of the existing nylon rod, steel ring, steel rod, and bolt, combined with the new straight steel bushing. A force of 1926N is exerted on the section of the metal rod that is supported by the latch. Figure 57 shows how the frame is supported by the latch. The force used for the simulation is calculated as follows:

The user manual of the Dorack states a maximum load bearing capacity of 388kg per frame. The weight of the frame (40kg) is added to this and then multiplied by the dynamic factor 1.5 and safety factor 1.2, as can be found in European standard NEN-EN 913:2018+A1:2021 (European Committee For Standardization, 2021), after which it is divided by 4, as the weight is supported at the bottom and two points at the top. This yields:

$F_{sim} = (388+40) * 10 * 1.5 * 1.2 * 0.25 = 1926\text{N}$

The simulation shows that the maximum stress is 1.1MPa above the yield stress of steel S235 and is not a result of stress singularities. It only occurs in a small area of the part but is still too large. The calculated displacement is a maximum of 0.22mm, which is reasonable.

6.3.4 Combined bushing, ring, and rod

For the simulation of the combined bushing, ring, and rod, made from type 6 nylon, the same force of 1926N is used. This simulation shows that the maximum stress in the nylon part does not exceed the yield stress of the part. However, the maximum stress in the steel part does exceed the yield stress of type S235JR steel by 691MPa. A further investigation into potential stress singularities proves that the peak stresses are no stress singularities, and the result is therefore reliable. The calculated displacement is 2 mm, which is ten times as large as that of the straight bushing made of steel. Physical testing should reveal whether the part can withstand the forces exerted on it in a real use case.

6.3.5 Current bushing, ring, and rod

Because both new designs for the bushing exceed the yield stress of the material, the question arises if the current design would turn out strong enough in the same simulation. Therefore, the current assembly is subjected to the same simulation. This shows that it exceeds its yield strength by 8.1MPa. Because the part has never failed in a real use case, the origin of the high simulation results may lie in incorrect factors in the simulation. Physical testing of the prototype should reveal whether the parts can withstand the forces exerted on them in a real use case.

6.3.6 Latch consisting of plates

The newly designed assembly of plates, which could be an alternative to the latch housing, is also subjected to simulation. The same force is used as for the other parts.

The maximum stress found in the assembly is 143 MPa, which is below the yield strength of 275 MPa of S235JR steel. The maximum displacement is only 8 micrometres, so the part is considered strong enough.

6.3.7 Bracket

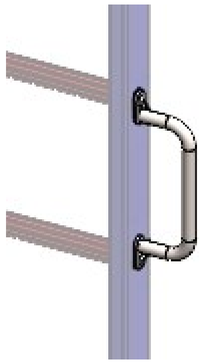


Figure 58: Bracket on side post

Because one of the concepts is using screws to attach the rungs to the outer posts (see page 56), this means also the stainless steel bracket on the side of the post (Figure 58) will be fixated in a different way (using riveting nuts instead of a nut pressed inside the rungs). A simulation is conducted to determine the effect of this new attachment method on the strength of the construction. Because the exact force the bracket will have to withstand is unknown, the simulation is aimed at finding the force at which the material of either the bracket or post reaches its yield strength and then determine if that would be sufficient.

The simulation shows that the post would be the first to reach its yield strength, when a force of 700N is exerted on the bracket. Although this seems like a small force, the engineers expect the bracket will not be exerted to these forces while in use, and in reality, the part may be stronger. This will be verified during testing.

For comparison, a simulation is also conducted of the existing post and bracket. This shows that in the current design the bracket reaches its yield strength first, at a force of 1230N. This means that theoretically, the change to riveting nuts moves the point of failure from the bracket to the post and reduces the strength with 43%, which is significant.

6.4 Quotations

The CAD models of the new parts and candidates for outsourcing are sent to suppliers to obtain quotations. These quotations are then compared to the current price of the parts, to determine the cost difference. Following the warning of Kals et al. (2019) to be aware of drawing incorrect conclusions when comparing in-house production and outsourcing, special attention is given to order costs, transport costs and overhead costs. The cost price stated in the ERP system is representative of the true price of a part and no direct overhead or inventory costs are allocated to individual parts. For externally produced parts, the order and transport costs are not incorporated in the cost price of the part but fall under the general overhead of the company. The suppliers used for the quotations in this case study do not charge any order or transport fee, so these are no factor in this study. The order quantities used for the quotations represent true order quantities (see also paragraph 6.4.1). Altogether, this means that a quoted price and internal cost price can be compared fairly.

A noteworthy aspect of the quotations is zinc plating. See also paragraph 7.1.1. Some suppliers offer this service, but outsource it themselves, yielding a higher added cost than if Nijha would order untreated parts and then ship them to the plating partner. Therefore, the quotations are requested for untreated parts and subsequently all parts are ordered untreated. After delivery, these parts are collected and shipped to the zinc plating partner in one batch.

6.4.1 Order quantity

To get a reliable quotation, the correct order quantity should be investigated. The heuristic used currently at Nijha is:

$$Order\ quantity = Yearly\ demand/6 \tag{2}$$

This value is then rounded up to the production quantity. The reason for this formula is liquidity. Nijha does not want to have too much capital stuck in inventory.

This heuristic is used for the quotations because of two reasons:

1. Alternative order quantity methods like the EOQ, Silver-Meal Heuristic or Least Unit Cost (LUC) rely on factors like set-up cost, proportional order cost, and holding cost (Nahmias, 1997, p. 225). These factors are not currently used at Nijha, meaning they would have to be assumed, and the final order quantity would therefore be based on a combination of assumptions.
2. Using a different method for calculating the order quantity can yield a different optimal quantity than the existing heuristic would. This can subsequently influence the quoted price. In that scenario, it cannot be said for certain whether the price difference is caused by the order quantity or the alteration of the part. By keeping to the existing heuristic, this factor is ruled out.

6.4.2 Evaluation of quotations

Table 9 compares the current price and quoted price for each of the new parts. The current price is the total price of the part(s) that the new parts replace. The table also mentions the decision made based on the quotation. In most cases, the concept was continued if the price difference was positive (quoted price lower than current price) and discontinued if the price difference was negative. Appendix XI: CAD models shows the CAD models for the parts.

The parts that replace welded parts of the rolling base frame are not allowed to be much more expensive than their welded counterparts. The reason for this is that the actual welding contributes only for a small part to the costs made during the welding operation. Handling is a larger part and will remain to assemble the frame before welding it all together.

Table 9: Quotations of new parts

Part	Current price (€)	Quoted price (€)	Difference (€)	Win per Dorack (€)	Decision
Front plate bent					Discontinue[5].
Front plate straight					Prototype two.
Combination bushing, ring, rod					Prototype two.
Straight bushing metal					Prototype two.
Straight bushing nylon					Discontinue.
Universal link					Discontinue.
Latch housing with integrated pin and chamfer					Prototype one.
Latch housing plates					Prototype one.
Middle frame strips					Discontinue.
Wheel support					Prototype (part of arm rolling base).
Arm rolling base					Prototype two.
Short axle					Discontinue.

[5] The current mechanism housing and a bent front plate would cost X+X=€X. Adding a strip to the mechanism housing and using a straight front plate would cost X+X=€X, thus this is a cheaper option.

Part	Current price (€)	Quoted price (€)	Difference (€)	Win per Dorack (€)	Decision
Locking pawl zinc plated					Prototype.
Clamping handle bent					On-hold in favour of 'clamping handle two plates'.
Clamping handle two plates					Prototype one.
Leg hinge					Prototype one.
Mechanism housing with strip front plate					Prototype two[5].
Rolling base frame beam and reinforcement plate					Prototype one.
Mechanism housing with triangular plates					Discontinue.
Base plate with strip + triangular plates					Prototype two.
Latch support trans symmetry					Prototype one.
Latch support cis symmetry					Prototype one.
Coupling lever symmetrical plate					Prototype two.
Coupling lever total (cutting, welding)					Discontinue.

6.4.3 Off-the-shelf parts

Besides custom parts, the Dorack also contains many standard, off-the-shelf parts. Because these parts can be bought at various suppliers, these suppliers are compared to investigate whether cheaper options are available. The suitability of each option is determined according to the following factors: price of the current part, specifications of the current part, required specifications, specifications of the alternative, and price of the alternative. An overview can be found in Table 10 below. The findings are discussed with relevant stakeholders to decide which parts should be ordered for the prototype. In general, the decision is based on the trade-off between cost reduction and performance uncertainty.

Polyketone is investigated as an alternative material for the gears. Gears made of this material can withstand a torque that is 5% larger than polyacetal, the current material, can (Mädler GmbH, 2024, p. 317).

Table 10: Alternatives for off-the-shelf items

Part	Factors considered	Current price (€)	Alternative price (€)	Win per Dorack (€)	Number of alternatives considered	Decision
Rod end	Material, dimensions, static axial and radial load capacity, dynamic axial and radial load capacity				26	Order alternative.
Rivets	Dimensions, tensile strength, shear strength				21	Order alternative.
Threaded rod	Material, strength class, surface treatment, dimensions				6	Order alternative.
Shoulder screws	Dimensions, material, head type, supplier				16	Order alternative.
Threaded bushing frame support	Dimensions, shape, material, surface treatment				13	Order alternative.
T-nuts	Dimensions, supplier				6	Available alternatives differ too little from existing price. Therefore, keep current part.
Crank	Dimensions, torque rating, material, supplier				7	Available suppliers do not have cheaper options. Therefore, keep the current part.
Thrust bearing	Dimensions, dynamic load rating, static load rating, reference speed, suppliers				3	Order alternative
Radial ball bearing	Dimensions, seal, dynamic and static load rating, reference speed, suppliers				3	Price difference is too small, keep current part.
Clevis joints	Dimensions, pin type				7	Order alternative.

Part	Factors considered	Current price (€)	Alternative price (€)	Win per Dorack (€)	Number of alternatives considered	Decision
Large wheels	Dimensions, load capacity				4	Price difference is too small, keep current part.
Gears	Module, ratio, material,				4	Order alternative.

Reducing variation of fasteners

As mentioned in paragraph 5.3.2, the variation of fasteners used in the Dorack is reduced. 26 distinct types of bolts are used in the current design. The approach described by Matthews (1998) is used to structure this process:

1. The first step in this process is to determine for each location of the fasteners what the acceptable diameters and lengths are, essentially determining the tolerances per fastener.
2. The next step is to determine which fasteners are currently used most in the Dorack.
3. Based on this information, combined with the tolerances, various alternatives are determined for each fastener.

This analysis shows that the number of variants could theoretically be reduced from 26 to 13. However, this would lead to a price increase of €X, which is X%, for the fasteners. A list of 19 bolts was determined to be tested in the prototype.

6.5 Conclusion on conceptualisation

The conceptualisation phase aimed at specifying the ideas of the ideation phase to such a level of detail that quotations can be requested from suppliers. These quotations formed the basis for deciding which concepts should be prototyped and tested. Several FEAs were conducted for parts where the change in design can have an effect on the part's strength. Most were not conclusive and therefore physical testing is considered useful.

Based on the quotations, the total cost reduction resulting from all concepts amounts to approximately €X. The alternative sourcing of off-the-shelf parts amounts to a cost reduction of €X. The number of fastener types was reduced from 26 to 19. All concepts considered worthwhile were proceeded to prototyping.

7 Prototyping

The processes involved in production of the prototype parts are described in section 7.1. This section also describes the calculation of the cost of zinc plating previously coated parts. This calculation is used to determine the cost reduction of plating instead of coating.

The process of building the final prototype is described in section 7.2 and the tests this prototype is subjected to are described in section 7.3. The prototype and its new components are tested in four categories: producibility, assemblability, functionality, and aesthetics. The producibility test is essentially the phase of producing the parts of the prototype, as described in section 7.1. The assemblability test comprised building the prototype (section 7.2). Section 7.3 describes the functionality and aesthetics tests.

7.1 Parts production

The decisions regarding which concepts to proceed with (as stated in Table 9 and Table 10) are followed. Parts are produced either internally or externally and off-the-shelf parts are ordered at alternative suppliers. An overview of the required production steps for each part can be found in Figure 59 on page 68. The externally produced parts are inspected for compliance with the specified dimensions upon delivery. The parts are then sorted into three categories: those that need to go to the zinc plating partner, those that are needed for the welding operations and those that can go directly to storage to wait for assembly.

During the production phase, special attention is given to the alterations that are made and the envisioned improvements they should create. In that way, the production of the prototype is already part of the verification process. To structure this, several evaluation questions are phrased based to the following standard questions:

- Does part X fit together correctly with other parts?
- Does part X adhere to specifications?
- How much time does it take to assemble/produce part X?
- Can a change in strength be noticed for part X?

All questions and their answers can be found in Appendix XVI: Evaluation questions. In general, no major flaws became apparent. Some externally produced parts had to be modified slightly in order to fit in the assembly, but in all these cases the cause was that no tolerance was specified on the technical drawing of the part. Although the alterations to (parts of) the rolling base frame should theoretically lead to a reduction in welding time, the welding time for the prototype was exactly the same as the existing welding time. The general reactions to the alterations were positive. Any points for improvement are mentioned in chapter 8.

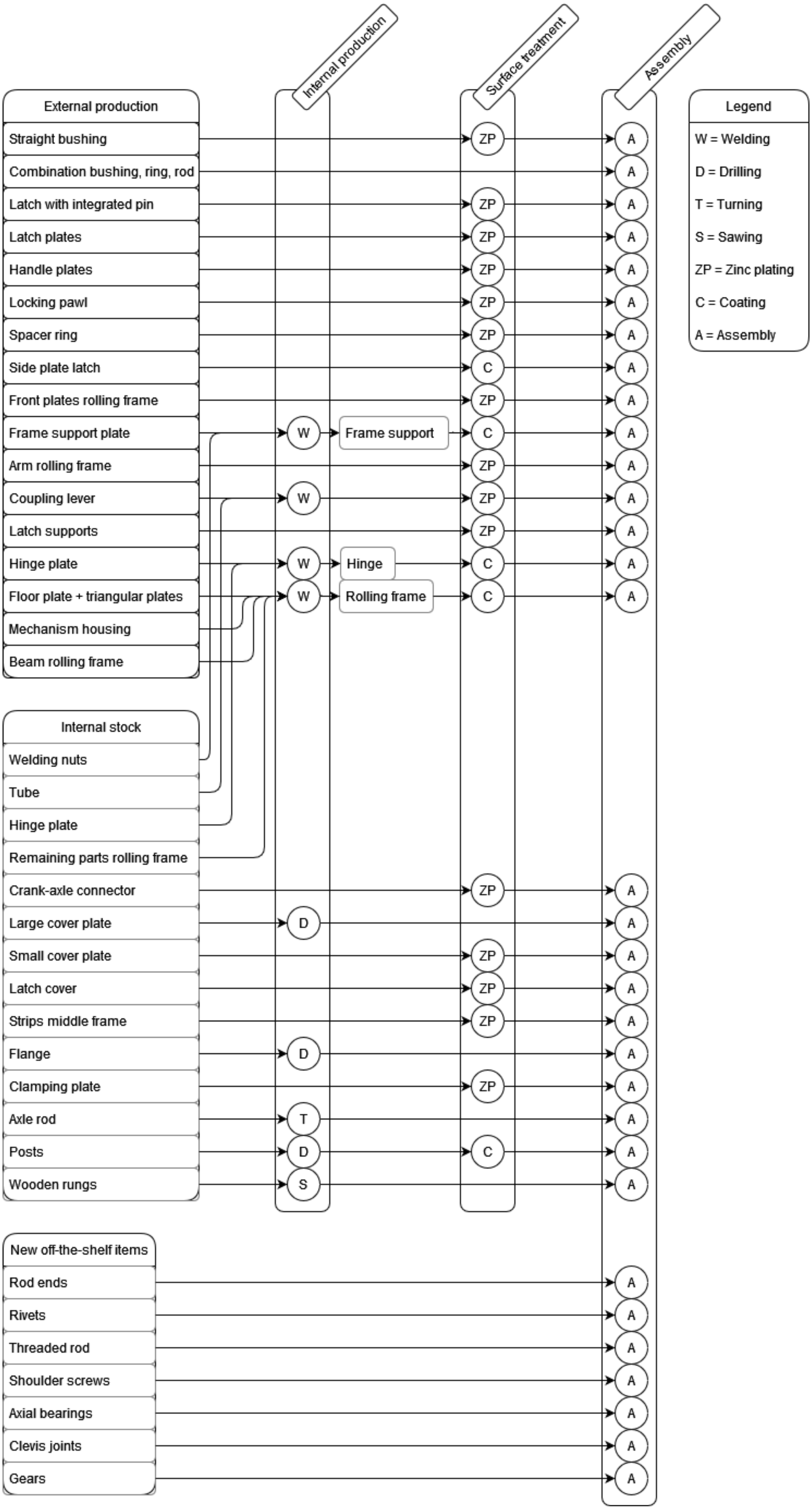


Figure 59: Prototyping processes

7.1.1 Zinc plating

As mentioned in the introduction of section 6.4, parts are zinc plated externally. To estimate the cost of zinc plating a statistical analysis is performed based on the batch sizes of the past 1.5 years found in the ERP system. The results can be found in Appendix XIV: Zinc plating statistics. The average mass of zinc plated material per batch is X kg. The cost of each batch consists of a fixed transport and handling fee of €X and a proportional fee of €X per kilogram of material. This yields the average cost per kilogram:

$$c_{kg} = \frac{X + m_b * X}{m_b} = €X/kg$$

Where c_{kg} is the cost in euros per kilogram and m_b is the mass of the batch in kilograms.

Currently, each Dorack contains 27.5kg of zinc plated material. 19.5kg of this consists of parts that are produced internally and then sent to the zinc plating partner. This means that a batch of only the parts for X Doracks would weigh X kg, and cost a total of €X, or €X/kg. If all externally produced parts would be shipped to Nijha un-plated and then sent to the plating company together with the internally produced parts this would cost €X or €X/kg.

If all proposals of this case study are followed, another X kg would be added to each Dorack, meaning an extra X kg to each batch so each batch would be X kg, costing a total of €X or €X/kg.

In short, zinc plating costs €X per kilogram on average and even if a batch would contain only parts for X Doracks, the cost would be just €X per kilogram. If all proposals of this case study are followed and all externally produced parts would be delivered un-plated, this Dorack-only cost would be reduced to €X per kilogram. In the rest of the case study, the average value of €X/kg will be used.

7.2 Prototype building

Final assembly of the prototype is the next step of the case study. Again, special attention is given to the alterations that were made. In preparation of building the prototype, several questions are formulated to aid in making the advantages and disadvantages of the prototype apparent during assembly and testing. These questions and answers can be found in Appendix XVI: Evaluation questions. During the process, these questions are answered. The questions follow this general form:

- Does part X fit correctly in part Y?
- How much time does operation X take?
- Are any differences noticeable for part X?
- Does part X have the correct dimensions?
- Can a change in strength be noticed for part X?
- Does alteration X have added benefit?

The general result is that the alterations have a positive effect. Still, some points for improvement became apparent. These are all mentioned in chapter 8.

7.3 Prototype testing

The next and major step in the verification process is testing the prototype. The prototype and its new components are tested in four categories: producibility, assemblability, functionality, and aesthetics. The main goal is to determine to which extent the alterations led to noticeable improvements and to verify that the product will still function as intended.

The producibility test is essentially the phase of producing the parts of the prototype, as described in section 7.1. The assemblability test comprised building the prototype (section 7.2). The functionality is tested for four subassemblies where the alterations may impact functionality or strength. This includes the climbing frame with wooden rungs, the climbing frame with aluminium rungs attached with screws, the rolling base, the latches, and the latch supports. These subassemblies are tested using the methods described in the following paragraphs and answer the following general questions:

- Does part X function as it should?
- Is part X strong/rigid enough?

The aesthetics tests are discussed in paragraph 7.3.4 and answer the following question:

- Is the changed aesthetic of part X worth the cost reduction?

Any points for improvement are mentioned in chapter 8.

7.3.1 Climbing frames

The question answered during the testing of the climbing frames is:

'Are the climbing frames strong and rigid enough?'

To determine the definition of 'rigid enough', the test methods specified by European standard NEN-EN 913:2018+A1:2021 (European Committee For Standardization, 2021) for testing the strength of gymnastics equipment are followed. A load of 385kg is positioned on the climbing frame in horizontal position (Figure 60). The distance between the frame and the floor is measured before, during, and after loading at eight points on the climbing frame to determine the deflection of these points. Both climbing frames show some elastic deformation but no plastic deformation. Therefore, both frames are rigid enough to withstand the forces that would be exerted on them during use.

Figure 60: Load test of climbing frame

7.3.2 Rolling base

The question answered during the testing of the rolling base is:

‘Does the rolling base assembly withstand the forces exerted on it during use and does it function as intended?’

The maximum forces the rolling base will be exposed to occur during the raising and lowering of the product. Therefore, to answer this question and test the rolling base for deformation and durability, the whole product is raised and lowered rapidly using the levers of the rolling base for a total of 100 times. After every 25 repetitions, the altered parts are inspected for deformation or any other signs of weakness. This concerns the frame, coupling levers, push-pull rod, fork joints, front plates and rivets, and rivet attachment of the wheels.

This test showed that the rolling base including all its alterations still functions as it should and can withstand the forces to which it is exposed. No deformation is visible, and all rivets are still in place. The only point of criticism are the new fork joints, as one of the clips came loose several times. A cause for this was not found.

7.3.3 Latches

The question answered during the testing of the latches is:

‘Can the latches, and the parts the latches interact with, withstand the forces exerted on them during use?’

The largest forces exerted on the latches at the bottom occur when the frame is closed from the ‘roof’ position. During normal use, the frames close slowly as a result of raising the frame using the height adjustment mechanism. In practice, it is possible to close the frames by hand from an angled position. In that scenario, larger forces are exerted and therefore this scenario is tested.

To test this for the latches at the bottom, the climbing frames are closed with force from the ‘roof position’ (Figure 61) a total of 50 times. After 25 times, the latches, latch supports, bracket and posts are inspected for deformation.

The frame with aluminium rungs showed a small deformation at the connection between the bracket and post. The frame with wooden rungs showed no deformation. The latches showed no deformation. Both latch supports, however, showed a deformation of 1mm at the top of the latch support cover.

The latches at the top are exposed to the largest forces during horizontal loading of the frame (which is tested in paragraph 7.3.1) and when the frames are forcefully closed from the ‘door’ position (Figure 62).

The strength of the latches at the top is tested by closing the climbing frames with force from the ‘door position’ (Figure 62) 50 times. After 25 times the latch, steel rod, bracket and post are inspected for deformation. No deformation was visible for the latch, bracket, pin, or post of either frame.

The latch consisting of plates is tested both at the top and bottom position and shows no deformation.

Figure 61: Latch test from 'roof' position

Figure 62: Latch test from 'door position'

7.3.4 Latch supports

The question answered during the testing of the latch supports is:

'Can the latch supports withstand the forces exerted on them during use?'

The maximum force exerted on the latch supports is one person of 74kg (as per NEN-EN 913:2018+A1:2021) standing on the latch, although this is an unintended interaction.

The loading capacity of the latch supports is tested by putting a weight of 75kg on the latches and checking for deformation. Both latch supports show permanent deformation and are therefore insufficiently strong.

7.3.5 Aesthetics

The central question when testing the aesthetics of changed parts is:

'Is the changed aesthetic of the part worth the cost reduction?'

This question is asked to a variety of employees of Nijha about the parts that are zinc plated instead of powder coated, the frame support with a hexagonal nut instead of threaded bushing and the climbing frame with wooden rungs.

The conclusion from this test is that the zinc plated parts are accepted. The frame support with hexagonal nuts received mixed reactions. Some employees found it worth the cost reduction, others were weary of the product having a 'too technical' look. This will have to be discussed further internally. The wooden rungs generally received positive reactions, saying the product looked 'fresher' and more sustainable. A negative point was that the product looks less playful and less contemporary if the red rungs are omitted.

7.4 Conclusion on prototyping

This chapter described the development of the prototype. Throughout the prototyping phase, the focus was on determining the real-life applicability and feasibility of the concepts. The prototyping phase was divided into three subphases: parts production, prototype building and prototype testing. The first two subphases focused on determining the producibility and assemblability of the prototype. These two factors both worked out well, with only a few points of attention emerging. The testing phase focused on determining whether the prototype still had the same functionality and aesthetic value as the current product. This showed that both prototypes of the climbing frame were rigid enough, the rolling base functioned as it should, the latches functioned as they should, the latch supports were not strong enough and the aesthetics were acceptable. A full overview of the evaluation of each concept will be given in the next chapter.

8 Evaluation

The building and testing of the prototype yielded a recommendation for each tested concept, which is described in section 8.1.

Section 8.2 calculates the total cost savings if all recommendations are followed. This is done in a conservative manner to calculate the minimum savings of €X and a more generous way to calculate the maximum savings of €X.

Section 8.3 states the implementation steps that followed the recommendations of the concepts as they have been determined by the stakeholders at Nijha.

8.1 Overview of concepts

Table 11 states the final recommendation for each concept. Six different categories are identified: concepts that can be proceeded without adjustments, concepts that can be proceeded with some adjustments, concepts that require further work, concepts for which internal discussion is required or trade-offs need to be made, concepts that function as a back-up choice in case other concepts turn out not to work, and finally concepts that can be discontinued with certainty. For a further substantiation of each recommendation, including certain findings of testing, see Appendix XVII: Final advice per concept.

Readers note: Appendix XI: CAD models shows an image for each concept that is not a standard part.

Table 11: Evaluation of concepts

Concept	Min. saving	Max. saving	Recommendation
Rolling base			
Purchasing rod			Proceed
Alternative sourcing of fork joints			Further work required
Combined beam with reinforcement plate			Discontinue
Altered mechanism housing			Proceed
Altered front plates			Proceed with adjustments
Combined base plate with triangular plates and strip			Further work required
Outsourcing arms			Internal discussion
Wheel attachment with rivets			Internal discussion
Symmetrical coupling lever			Proceed
Insourcing axles			Internal discussion
Middle frame			
Altered crank-shaft connector			Further work required
Zinc plating strips			Proceed
Altered flange			Proceed
Polyketone gears			Internal discussion
Legs			
Zinc plating clamping plate			Proceed
Bent clamping handle			Further work required
Clamping handle two plates			Further work required
Alternative shoulder screws			Internal discussion

Concept	Min. saving	Max. saving	Recommendation
Alternative sourcing fork joints			Further work required
Latches			
Latch housing consisting of plates			Further work required
Latch housing with integrated pin and chamfer			Back-up
Latch housing with enlarged hole			Back-up
Latch housing with spring pin			Discontinue
Zinc plating pawl			Discontinue
Moving laser joint of pawl			Proceed
Frames			
Wooden rungs			Internal discussion
Aluminium rungs and screws through all posts			Back-up
Zinc plating mounting ring			Proceed
Alternative rod ends			Proceed
Zinc plating spacer ring			Proceed
Straight bushing			Proceed
Combined rod, ring, and bushing			Back-up
Enlarged slot in leg-side post			Discontinue
Bolts			
Hinge to clamping plate			Internal discussion
Stop height adjustment			Internal discussion
Stop rolling base pedal			Internal discussion
Spindle nut to spindle guide plate			Proceed
Gear to spindle			Proceed
Gear to shaft			Proceed
Latch support to upright			Proceed
Other concepts			
Clicker on upright cover			Discontinue
Zinc plating cover plate			Further work required
Hexagonal nuts on frame support			Internal discussion
Bent latch supports			Proceed with adjustments
Zinc plating latch support cover			Proceed
Alternative thrust bearings			Further work required

8.2 Total cost savings

To calculate the total cost savings, the price difference between the old and proposed situation is calculated for each concept for which the advice is to proceed (with or without adjustments), require further work, or internal discussion. This is done in a conservative manner to calculate the minimum cost saved and in a more generous way to calculate the maximum cost saved. The minimum cost saved was €X and the maximum cost saved was €X. The difference between these has a few key contributors:

- The assumed price for zinc plating makes a difference of €X.
- The choice for latch housing makes a difference of €X.
- The assumed price for coating makes a difference of €X.
- Including the time won in assembly makes a difference of €X.
- The assumed price for the shoulder screws makes a difference of €X.
- The choice to include the fork joints makes a difference of €X.

In case the choice is made to convert to wooden rungs, an additional €X will be added to the savings.

Figure 63 and Figure 64 show the distribution of the cost savings among the various categories. It can be seen that the savings resulting from reconsidering purchasing parts have the biggest impact in both scenarios, followed by the redesign of parts. The minor changes also have a minor impact.

Figure 65 and Figure 66 show the old cost buildup (as shown in Figure 22 on page 37) and the new cost buildup. The distribution of costs among the categories has not changed a lot, Dorack-specific parts have gained a few percent, and the other categories have lost a few percent.

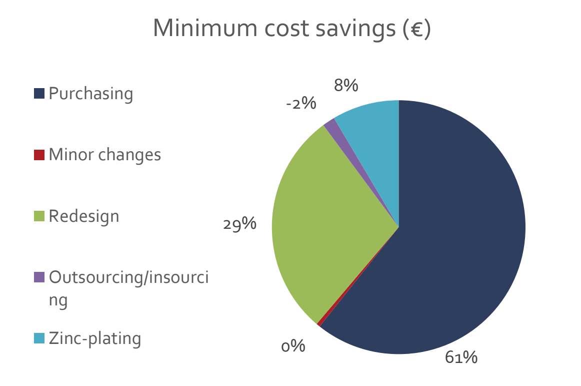


Figure 63: Minimum cost savings

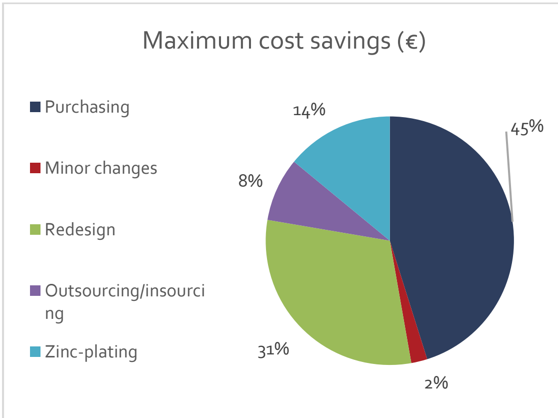


Figure 64: Maximum cost savings

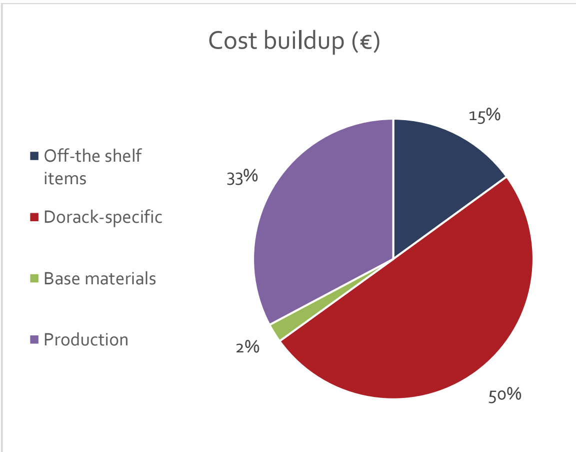


Figure 65: Old cost buildup (copy Figure 22)

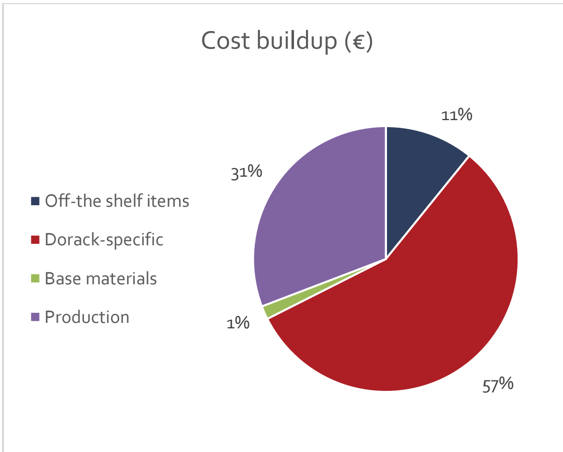


Figure 66: New cost buildup

8.3 Implementation steps

Based on the recommendations for each concept, the engineers at Nijha determined the steps towards implementation for each of the concepts. Five options were determined: concepts that can be implemented directly or have already been implemented, concepts that are realistic and will be developed further, concepts that are realistic but only under certain preconditions, concepts that require further investigation before a choice can be made, and concepts that will be discontinued. An overview can be found in Table 12.

Table 12: Implementation steps

Implement	Realistic, develop further	Realistic, but with preconditions	Further investigation	Discontinue
Altered mechanism housing (rolling base frame)	Purchasing rolling base rod	Alternative sourcing fork joints	Widened slot in leg-side post	Domed screw for attaching spindle nut to guiding plate
Altered crank-shaft connector	Altered front plates rolling base	Insourcing rolling base axles		Domed screw for attaching gear to spindle
Zinc plating middle frame strips	Combining rolling base plate with triangular plates and strip			Domed screw for attaching gear to shaft
Altered middle frame flange	Outsourcing rolling base arms			Domed screw for attaching latch support to upright
Zinc plating clamping plate	Symmetrical coupling lever			
Zinc plating mounting ring	Changing polyketone gears			
Alternative rod end	Alternative clamping handles			
Altered spacer ring	Alternative shoulder screws			
Straight climbing frame bushing	Latch consisting of plates			
Zinc plating latch support cover	Zinc plating cover plate			
Alternative thrust bearings	Bent latch supports			
	Frame support with hexagonal nut			
	Climbing frame with wooden rungs			
	Climbing frame with aluminium rungs and screws through all posts.			

9 Conclusion and discussion case study

This chapter summarizes the findings of the case study in section 9.1 and formulates the discussion in section 9.2. The discussion comprises a reflection on the limitations of the work (paragraph 9.2.1) and possible future research (paragraph 9.2.2).

9.1 Conclusion

This case study comprised a cost-reduction project for a piece of equipment used for physical education of young children. The product is one of the best-selling products that the company at hand produces in-house.

A literature study formed the theoretical basis for the project by describing methods for characterising the current state of the company and process, methods for cost reduction, methods for production process optimization, decisions for outsourcing and guidelines for DFA. The orientation phase focused on becoming familiar with the company, the product, and the process.

The combination of the findings from literature and the orientation phase formed the basis for the ideation phase. Four questions were formulated at the end of the orientation phase, and these were answered by ideas from the ideation phase. The ideas from this phase were divided into three categories: 1. Ideas to create a solid foundation of the product. 2. Major changes to the design of the product and its parts, or to the process. 3. Minor changes to the product, concerning different suppliers and different purchased parts.

The ideas that were proceeded to the conceptualization phase added up to an estimated theoretical cost saving of €X and time saving of X minutes. These ideas were converted into CAD models and sent to suppliers for quotations. Some FEAs were conducted for the parts where the change in design could lead to a change in strength. The quotations of the suppliers, including those delivering off-the-shelf parts, determined which parts would be ordered for the prototype.

The prototype consisted of a combination of externally produced parts, internally produced parts, and off-the-shelf parts. This was a first compliance test for the new parts. After some minor alterations and surface treatment (where necessary) all parts were assembled into one prototype. This prototype was tested according to questions specified in advance regarding producibility, assemblability, functionality, and aesthetics. All concepts were evaluated based on the tests and a final advice was formulated for each concept. If all concepts with the advice to proceed will indeed be proceeded, the cost savings amount to a minimum of €X (7% of the cost price) and a maximum of €X (18% of the cost price). This interval is the result of several uncertainties in the exact price of components and whether or not the idea of using wooden rungs is proceeded. This latter concept would yield a cost saving of €X.

Overall, the case study has explored a broad variety of possibilities to reduce the cost price of the product. In the scope of this thesis, the function of the case study was to establish a process that can be followed for a cost reduction project. The process followed in this case study will be used in the next segment to build the framework, combined with the findings from the literature research.

9.2 Discussion case study

Drawing from the number of proposals that will be implemented or developed further (Table 12), the case study has been useful for the company. Employees will continue working on the proposals to permanently implement them. This section will describe some of the limitations of the project, as well as opportunities for future research.

9.2.1 Limitations

Because the ERP system used by Nijha is the only source for much data in this project, it is crucial that this data is put into the system correctly. Production costs are often based on manual calculation. Because these costs are dependent on several variables, they are not constant. However, the cost listed in the ERP system is constant. This can lead to discrepancies between the cost used for calculation and the true cost of a part. This problem was also described by Probert (1997, p. 34):

> The big problem with costing systems which are already in place is usually the arbitrary allocation of overheads or other activity costs from within the organisation. If we are trying to establish our costs for a particular manufacturing process this can lead to huge variation compared with the outside world.

This especially holds true for the surface treatments of powder coating and zinc plating. These costs differ for each batch and thus the cost for an individual part is dependent on the size of the batch. This made it difficult to compare alternatives. In addition to this, the employees at Nijha were divided in their opinion on zinc plating versus powder coating. For this project, the choice was made to order all parts untreated, let them be zinc plated in one batch and divide the costs over the batch. In that way, the cost for zinc plating could be isolated, which would not be possible if the parts would be ordered including zinc plating.

Another unknown is whether the prices stated in the quotations that form the basis for a large part of the decisions made in this project are the true prices that will be charged by the suppliers. All quotations had a disclaimer that they would only be valid for several days. However, judging from the stability of the prices charged by these suppliers for other parts, this is not likely to be an issue.

A factor that is largely disregarded in this project are the indirect costs of handling, transportation, and overhead. The reason for disregarding is that these factors are variable and not associated with individual parts. The ERP system only tracks the absolute cost of all components and processes used in a product and does not allocate specific overhead, handling, or transportation costs to each part. To make a comparison that is as fair as possible, these factors were therefore also disregarded for the concepts of this project. The financial administration at Nijha works in such a way that all indirect costs are subtracted from the total profit of the company.

A design space was not explicitly determined, but rather phrased as a scope for the case study at the end of the orientation phase. Having a design space can help determine what can and cannot be changed about the product or process. Therefore, this is incorporated into the framework.

9.2.2 Future research

This case study mainly yielded options to reduce the absolute price of the individual components and thereby the product as a whole. Aside from reconsidering the coating or zinc plating of parts and outsourcing decisions, no other ideas were developed for changing the process. This could be the focus of a future project.

The choice between powder coating or zinc plating showed that it is difficult to compare two alternatives with a different price buildup. In this case study, zinc plating was often still cheaper if its highest price was used and compared with the lowest price for powder coating. However, if these would be closer to each other, the choice would be more difficult. Therefore, a subject for future research could be to find a way to compare such alternatives.

Segment B
Framework development

This segment describes the development of the final framework. The final framework is developed based on the process of the case study described in segment A and the literature research described in chapter 3.

10 Introduction to the framework

The framework that will be developed in this segment aims at addressing the general problem of this thesis:

> A low-volume, high-mix production company wants to increase the profit margin of one of its products by reducing the product's costs.

The accompanying research question is:

> How can companies reduce the costs of individual products and how can this process be structured?

The case study of segment A described a process for reducing the costs of one product. This yielded the following sub-question:

> How can the process followed in the case study be applied to other cost-reduction projects?

The method for addressing the problem and answering the research question is to use the process of the case study from segment A as a starting point and supplement it with additional research to form the framework.

Chapter 11 describes the process of building the framework. The takeaways from each phase of the case study are described. Chapter 12 describes the final framework, which is divided into eight phases: preparation, orientation, ideation, conceptualisation, realisation, verification, evaluation, and implementation.

The scope of the framework is to develop a framework for reducing costs of mechanical (non-electronic) products. In other words, it is a cost reduction framework.

11 Building framework

The case study has shown that a structured approach can be followed to reduce the cost price of a product by 7 to 18%. The paragraphs below will mention the takeaways from the case study for each phase of the project, and how they contribute to building the framework.

Chapter 4 showed that the orientation phase determines the focus of a cost reduction project by looking at the company, product, and process from a theoretical basis. Doing so identifies opportunities for improvement. The main contributors to a product's cost can be identified by breaking down the buildup of the costs and identifying which parts, subassemblies, or processes contribute most to the product costs. Opportunities for improvement of the process can be identified by observing the process and comparing it to an 'ideal' situation, for example by identifying various 'waste' types from Lean methodology.

The product and cost reduction target for the case study were determined before the start of the project and were therefore not part of the orientation phase. Nevertheless, because these choices are crucial for the project, a 'preparation' phase is defined for the final framework. The volume-variety chart of paragraph 4.1.1 is a useful way to illustrate the candidates for a cost-reduction project.

The scope determined in the orientation phase can be used to generate ideas in the ideation phase. The type of ideas is heavily dependent on the opportunities identified during orientation. Some main types of ideas are:

- Omitting unnecessary steps ('wastes') in the process.
- Applying the principles of DFA or DFM.
- Changing certain process steps for cheaper alternatives.
- Reconsidering make/buy decisions.
- Reconsidering material use for certain parts.
- Reconsidering suppliers for off-the-shelf items.
- Reconsidering alternative, cheaper types of off-the-shelf items.

To rank the effect of each idea, it is wise to calculate the estimated cost or time reduction that idea should create, as was done for each idea in chapter 5. All ideas can then be discussed with stakeholders to determine which should be developed further in the conceptualisation phase.

All ideas considered worthwhile for further development are worked out in the conceptualisation phase. CAD models are created, simulations are conducted, and any other steps are taken that are necessary for prototyping or testing the ideas. These are the same steps as were taken in chapter 6. In this phase, the expected cost or time reduction for each idea can become more accurate by requesting quotations, making additional internal cost calculations, or simulating the process.

To verify that the theoretical cost reductions have the desired result in reality, the concepts can be tested. In the case of altered parts this can be done by prototyping, as is described in chapter 7. The main goal of testing is to verify that the envisioned alterations have the desired positive result and no negative effect on other aspects of the product's performance like functionality, aesthetics, or safety.

Chapter 7 showed the testing phase results in three main categories of improvements: those that can be implemented immediately, those that require extra work or consideration before implementation, and those that cannot or should not be implemented.

The process followed in the case study forms the main structure of the framework. Each phase is represented. The preparation, orientation, and ideation phases are structured by a list of suggestions or questions that should motivate a user to develop several solutions. As the process continues, the framework focuses more on general actions that should be taken or goals that should be reached in each phase. The final objective, just like in the case study, is to end with a list of improvements that can be implemented. The framework is enhanced with findings from the literature research of chapter 3 of segment A that were not used in the case study but can be relevant for other applications.

12 Final framework

12.1 Aim of the framework

The framework is developed to help find opportunities for cost price reduction of individual existing mechanical products and structure the implementation of these opportunities. Some elements may be useful during earlier phases of the product development process, but this has not been investigated. The framework should not be considered a step-by-step recipe towards cost reduction, but rather a set of tools and guidelines from which users can determine which are relevant for their application. The framework is by no means exhaustive, it is likely that further research is necessary for other products or processes. The framework refers to many elaborate theories and methods that are only briefly described. To implement these theories and methods, the user of the framework should familiarize themselves with these.

The focus of the framework lies on cost reduction and has some overlap with process time reduction. For other improvements to existing products such as sustainability, accessibility, or ergonomics, other frameworks should be used.

The framework is aimed at mechanical products and does not include products with electronic components. The reason for this is that the performance of these electronic components depends on other factors than those described in this framework. Some examples of product types for which the framework should be applicable include: other gymnasium equipment, toys, bicycles, furniture, and office equipment.

12.2 Structure of the framework

The framework describes various phases of investigating the product at hand, as illustrated in Figure 67. Throughout the process, it is advisable to keep track of potential opportunities for improvement.

The framework first describes what preparation is required before starting the project, in section 12.3. The product that is the subject of the project must be chosen, a cost reduction target must be determined and linked to the potential of this process and certain prerequisites must be fulfilled.

The first phase of the cost reduction project is orientation: gathering information on various aspects of the product to identify potential opportunities for cost reduction. This phase is described in section 12.4 and ends with determining a scope for the rest of the project.

The opportunities identified in the orientation phase are answered by ideas developed in the ideation phase (section 12.5). Ideas generally fall into one of three categories: improvements to parts, to the process, or to the interdependence between the parts and process. The ideation phase ends with a (prioritised) list of ideas that should be discussed with stakeholders to determine which ideas should be concretized into concepts (section 12.6).

Conceptualisation functions as the next 'sanity check' of all ideas, which determines how realistic they are. Besides, it should indicate the improvement potential for each idea more accurately. These concepts can then be realised (section 12.7). This realisation can take various forms such as prototyping, sampling, or test runs. After this, the concepts are verified (section 12.8) to determine that the solutions actually lead to the expected improvements. After a final evaluation, certain changes can be implemented in the final product. This is described in section 12.9.

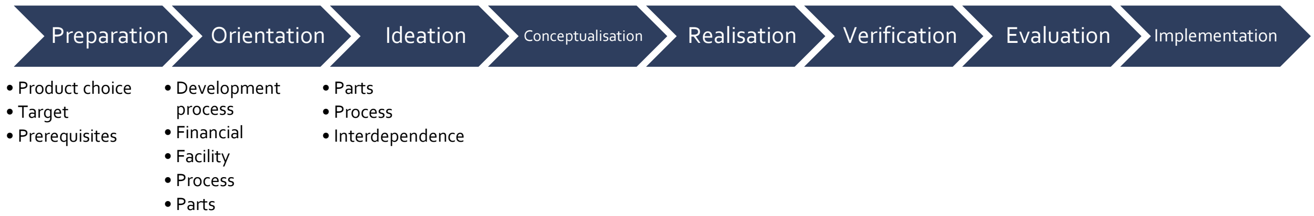


Figure 67: Framework structure

12.3 Preparation

12.3.1 Preliminary stage

Before starting a cost reduction project, two key questions must be answered:

- Which product will be the focus of the project?
- What is the cost reduction target?

One way to answer the first question is by creating a volume-variety chart (Tompkins et al., 2010, p. 49) or capacity chart. A volume-variety chart sorts all products of a company by annual sales number. Reducing the cost of the products with the largest sales numbers will have the greatest effect on the profit of the company. The capacity chart is similar to the volume-variety chart but looks at the required production capacity for each product. By multiplying the production capacity required for one product with the annual sales number of that product, its contribution to the total annual production capacity of the company can be calculated. These products that require the largest portion of the annual capacity benefit most from a cost reduction project.

The second question helps in determining the scale of the project. By setting a target for the cost reduction project, the number of ideas that should be developed and continued can be determined throughout the project. The case study of segment A showed that a cost reduction project like this can reduce a product's cost price by 7-18%. Knowing this can help determine the amount of resources that should be allocated to the project. A simple example: if the cost price of a product is €1000, this can be reduced with €70 to €180. If the company sells 10 products per month and wants to earn the investment back in two years, the total investment can be a maximum of 10*2*12*180 = €43200. The orientation phase will provide a more accurate indication of the cost reduction potential of the project.

In this framework, the target is assumed to be determined in advance.

12.3.2 Prerequisites of the framework

To maximize the effectiveness of the framework, the following prerequisites are required:

- An overview of the stakeholders. Who needs to be involved in the project, what is required from them, what information should they provide, and what decisions should they be involved in?
  - Some examples are employees from the design, production, assembly, logistics, purchasing, maintenance, sales, and management departments. These all have different perspectives on the product.
- Access to in-depth knowledge of the product across all development and lifecycle phases, and from all departments of the business.

    - This can take various forms, for example documentation of the development process, information from the ERP system and access to employees involved in the development and production process.
- A complete BOM of the product, augmented with costs, processes and other ERP data for each part.
    - This serves as the backbone of the cost reduction project. By knowing the costs and involved processes for each part the opportunities for improvement can be identified easier. In a later stage, improvements can be quantified by comparing the concept to the current data of the part.
- Access to the production process.
    - This prerequisite holds for products that are (partially) produced in-house, or where the user of the framework has influence on the production process. As the production of the product is likely to be one of the main contributors to the product's cost, having access to the process can help in identifying opportunities.
- A definition of how the improvements should be measured.
    - A starting point is to take the way the cost price is currently calculated and using the same method for the improvements. An important note here is that the current cost calculation method must be correct, or else the project may yield incorrect results. If processes are to be improved, measuring the current process times facilitates comparing envisioned changes to the current state.

12.4 Orientation

The first step of the framework is to acquire information concerning the product and process. This includes information about the development of the product (see paragraph 12.4.1) , financial information (§12.4.2), information about the production facility (§12.4.3), production process (§12.4.4), and the parts that make up the product (§12.4.5). These categories will all be discussed in the following paragraphs, where they are supported by various suggestions and questions. Where possible, users should combine the information into one file, such as an expanded BOM. This will function as the backbone of the improvement project. Studying these aspects of the product indicates areas for improvement.

12.4.1 Development process

The reason for gaining insight in the development process is to determine what aspects (design features or functionality) of the product can change and what aspects must remain as they are. This can then be used to determine a design space (Torn & Vaneker, 2021).

- What did the development process of the product look like?
    - What steps did the development process comprise?
    - What considerations and decisions were made during the development process?
    - How does the product differ from competitors?
    - Which ideas or concepts were considered but not proceeded, and why?
- What is the intended functionality of the product?
    - In case of multiple functions: does any priority exist among the functions?
- Gather as much of the design rationale as possible.
    - This can be used for future reference with proposed alternatives.

12.4.2 Financial

The financial information about the product comprises information about the sales figures and the cost price. The reason for gathering insight in the financial aspects of the product is to provide context about the costs and their buildup, which can be used at later stages in the project. This can also identify the distribution of costs among the process or parts. If either contributes significantly more to the product costs, it should receive more attention.

Sales figures

- How many units of the product are sold per year, month, week, or day? This can be useful to determine if the facility layout is suitable for the production size (§12.4.3).
- Do sales figures vary throughout the year?
  - If so, can a specific pattern be recognised?
  - And does this pattern influence the production capacity?
- What is the sales price of the product?
  - Does the sales price differ from that of competing products?
  - If the sales price is significantly lower than that of competing products, the profit margin may simply be increased by increasing the sales price.
  - If the sales price is higher, what causes this difference?

Cost price

- What is the cost price of the product?
- How is the cost price built up?
  - What does each subassembly, part, or feature cost? (Weustink et al., 2000)
  - Determine the cost of raw materials, operations, purchased parts, and other relevant cost categories per part. Figure 68 can be used for reference.
  - Calculate the aggregate cost of each of the categories mentioned above.
    - This might already indicate the largest contributors to the cost.
  - Look not only at unit costs, but multiply unit cost by the quantity of that part in the product (Meeker & McWilliams, 2003).
    - Doing so can surface hidden cost drivers. Sometimes many small parts together contribute significantly to the cost price.
  - Sort the parts by cost.
  - Divide the parts into three categories (Meeker & McWilliams, 2003):
    - A class items (10-15% of total parts count, 70% of total product cost).
    - B class items (the next 20% of the total parts count and the next 20% of the total product costs (for a total of 90%)).
    - C class items (70% of the total items, but only about 10% of the total cost.).
  - The ABC analysis creates a prioritisation of cost drivers. The largest contributors (A class) also have the most improvement potential.
  - Determine whether each of the costs is logical and reasonable. Identify the parts or processes for which this is not the case.
    - Various approaches can be taken to determine if costs are logical and reasonable:
      - Consulting (internal) experts on the parts or processes and using their intuitive reasoning or implicit knowledge.
      - Comparing the part to similar parts or parts of other suppliers.
      - Comparing the process to similar or alternative processes.

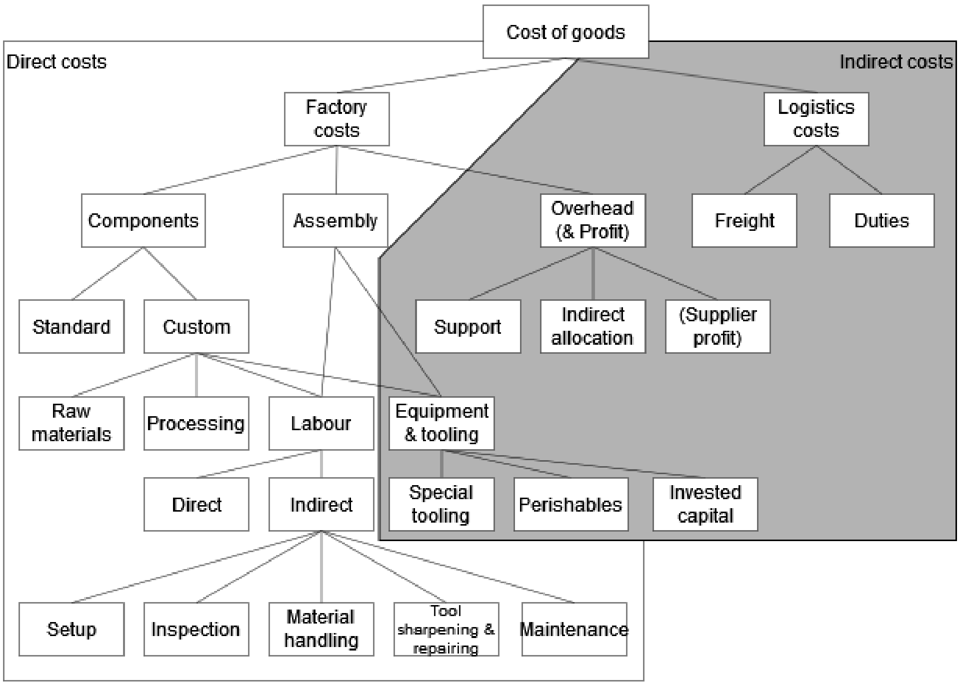


Figure 68: Elements of the cost of goods. Based on Ulrich et al. (2020, p. 267) and Bralla (1999)

12.4.3 Facility

Next, users should characterize the production facility in terms of inventory types, layout, and potential weaknesses. The reason for doing this is to identify opportunities for improvement and to determine what can and cannot be changed.

- Compare the facility to the characteristics of a well-performing production system of Koho (2010), which can be found in Appendix XVIII: Characteristics of a well-performing production system.
- Get an overview of the weak points of the facility, which can become opportunities.
  - One method is the RPA (Goodson, 2002), which comprises two tools for rating the 'Leanness' of a factory.
  - Another method is the Productivity, Manufacturing, and Training Needs Analysis (Herron & Braiden, 2006).
    - The Productivity Needs Analysis gives an overview of the current manufacturing condition of the company, identifies the key productivity measures for the plant and forms the basis for a detailed study of production efficiency.
    - The Manufacturing Needs Analysis is constructed following a plant tour and interviews or workshops with the senior management to ascertain the current level of adoption of Lean tools.
    - The Training Needs Analysis assesses the level of understanding and application of the same tools by the workforce.
- Identify the types of inventories found in the facility and determine if they have a valid reason for being there.
  - The four main types of inventory are raw materials, components (subassemblies), work-in-process (WIP, inventory waiting for processing or being processed), and finished goods (Nahmias, 1997, pp. 212-213).

- In principle, inventories should be kept to a minimum, as they are considered a type of 'waste' (Liker, 2004, p. 29; Theisens, 2016, p. 203). However, in some cases inventories can be beneficial (Nahmias, 1997, pp. 213-215):
  - If set-up costs for a process are high, it can be economical to produce more parts and create inventory.
  - If external demand varies to such an extent that production cannot respond, inventories can provide a buffer to maintain service level. Inventories can also be created in anticipation of a period of high demand.
  - If the value of an item is expected to increase, it can be economical to purchase it in a larger quantity for the lower price.
  - For certain inexpensive items it can be more economical to keep an inventory than to keep a detailed record of the item's demand.

- What is the layout of the factory? The main types are (Chryssolouris, 2006; Hayes & Wheelwright, 1979; Heragu, 1997; Nahmias, 1997; Wiendahl et al., 2015):
  - Job-shop/process layout: several general-purpose machines, grouped by capability. Parts move past the required processes. Mainly suitable for large variety, low volume (1-100) production mixes.
  - Project shop/fixed position layout: used for large or heavy products like airplanes or ships, where the product remains in one location and processes are performed on-site. Lot sizes are very small (1-10).
  - Cellular/group technology layout: processes are combined into production cells that are suited to specific families of products that share similar processes. Suitable for medium variety product mixes with a low to medium volume (50-5000).
  - Flow line/product layout: suitable for one type of product or very similar products with large volumes (500-10,000). All products follow the same line past all operations required to produce it. The order of machines is based on the process sequence.
  - Continuous system: suitable for single, continuous product types like fluids, gasses, or powders.
- Why was the factory laid out like this?
  - Speak to managers, production planners or other stakeholders involved in determining the factory layout.
  - If no clear substantiation is found for the factory layout, it may be open to being changed as part of the cost reduction project.
- Does the production mix of the company comply with its layout?
  - As described above, companies with a large variety of products and low production volumes are generally suited best to a job shop. On the other hand, companies producing single products or large volumes can profit from a flow-line layout.
- Does the layout correspond with the level of automation?
  - As processes become more complex, it becomes more expensive to automate them. The investment in automation should correspond to the production quantity of the parts produced by this automated process.
  - In general, processes dealing with low volumes and high variety (like can be found in a job shop) are more reliant on manual labour, and processes dealing with

larger volumes and lower variety (like flow lines) have more opportunities for automation (Lotter & Wiendahl, 2009).

12.4.4 Process

Next, users should map the process. By quantifying the time, money and other resources spent on each process step, cost drivers can become apparent. Knowing what drives costs can help determine what process steps to focus on. In addition to this, having clear data on the current state of the process makes it easier to compare the improvements and determine their effect. The time and effort spent on mapping the process should be balanced with the contribution of the process to the cost price. If the process does not contribute much to the cost price, it should just be described in general terms. Similarly, if certain process steps contribute significantly, they should be investigated in more detail than those contributing less.

Process mapping

- A useful method to map the process is described by Torn and Vaneker (2021):
    - Start with a walkthrough, preferably with an operation manager while the production line is in operation.
    - Thereafter, conduct a detailed observation to identify the sub-steps of each process step. Compare the observations with work instructions and document differences between these, such as rotating, touching up or reattaching parts.
    - Based on the detailed observation, each step is decomposed into three levels:
        - Functional: goal of the step.
        - Operational: starting and final condition with required action between these.
        - Kinematic level: single state change by one piece of hardware, validated by one sensor and controlled by one parameter.
- How much time does each of the operations take? Use historical data where possible, else record the time for each operation. For manual processes, a rough estimate can be made using the MOST® work measurement system of Zandin (1980).
- If certain operations contribute significantly to the production time or cost, investigate these in further detail.
- What equipment is used for the operations? Is this the best choice, or do better alternatives exist?
- Be critical to the observations of the process. 'Ask why, who, what, where, when, and how for every operation, transportation, inspection, storage, and delay so [you] can eliminate, combine, change sequence, and simplify.' (Stephens, 2019, p. 3)
- Identify the 8 types of waste distinguished by the Lean methodology (for example Theisens (2016)): over-production, waiting, transport, over-processing, inventory, movement, defects, unused expertise.
- Do internal logistics pay a significant contribution to the total cost? If so, investigate these further. What contribution is considered 'significant' is up to the discretion of the framework user.
- As part of logistics analysis, the supply of goods can be categorised further by identifying the procurement model (Wiendahl et al., 2015, p. 220). Identify which types are used and if these are suitable. The six main types are:
    - Reserve stock procurement: purchaser is responsible for planning, ordering, receipt, inspection, storage, and delivery to the place of consumption.
    - Consignment store: warehouse maintained by supplier, purchaser can withdraw goods as required. Used for high-value goods.

    - Standard part management: used for standard low-value goods. Supplier regularly fills the material buffer.
    - Contract stock: supplier maintains a warehouse close to the purchaser to allow frequent (on-call) delivery.
    - Single item procurement: supplier delivers one item at a time.
    - Synchronised production process: supplier and purchaser synchronise their manufacturing cycles.
- The interdependencies between process steps can be visualised in a precedence map (Hu et al., 2011; Tompkins et al., 2010). Which operations need to take place before certain other operations? This knowledge can be used to find opportunities for process improvement.

Strategy

- Determine whether the facility uses a push (such as MRP) or pull (such as JIT) strategy. In a push system, the production of goods is initiated by anticipation of future demand, whereas in a pull system production is initiated by current demand (Kals et al., 2019; Nahmias, 1997; Wiendahl et al., 2015).
- Many companies use a combination of push and pull strategies in the production process. This generally relates to the influence of the customer on the product, which is marked by the Customer Order Decoupling Point (CODP). Before the CODP, production is usually forecast-driven and after the CODP, production is usually demand-driven (Olhager, 2012; Theisens, 2016; Wiendahl et al., 2015). Based on the position of the CODP in the production process, the fulfilment strategy of the company can be categorised (Olhager, 2010, p. 864):
    - With an engineer-to-order (ETO) strategy, the CODP lies before the engineering phase.
    - With a make-to-order (MTO) strategy, the CODP lies between the engineering and fabrication phase.
    - With an assemble-to-order (ATO) strategy, the CODP lies between the fabrication and assembly phase.
    - With a make-to-stock (MTS) strategy, the CODP lies between the assembly and delivery phase. Products are standardised and customers have little to no influence on them.
- Determine whether the strategy is suitable for the company.
    - A push strategy works well for varying production rates, sourcing from multiple suppliers, and a larger product variety (Nahmias, 1997, pp. 372-375). Firms with many low-volume, customised products are more likely to choose an MTO approach with a push strategy (Olhager, 2010, p. 864).
    - A pull strategy works well for minimising the amount of WIP (Hopp & Spearman, 2004) and is typically used by firms producing high-volume standardized products (Olhager, 2010, p. 864) with consistent demand (Wiendahl et al., 2015, p. 222).

12.4.5 Parts

Opportunities for improvement can also be identified by taking a closer look at the parts of the product. Most of this information can usually be found in the BOM.

- What parts and subassemblies does the product comprise?
    - Which parts are standard, off-the-shelf parts?

    - Which parts are produced externally?
    - Which parts are produced internally?
    - Do product-specific parts resemble standard parts?
        - If so, could they be replaced with these standard parts?
- What does each part cost? See also paragraph 12.4.2.
- What materials are used for the produced parts?
    - Could parts be made of alternative materials?
- What tolerances are used in the specifications? Are these tolerances necessary or can they be loosened?
- If parts get surface treatment after machining to a tolerance, verify the tolerance still holds after surface treatment.

12.4.6 Conclusion on orientation

After all the categories described above have been investigated, draw conclusions based on the findings:

- What aspects of the product and process need to remain as they are and what aspects can be changed?
- What opportunities were identified from a financial perspective?
    - What parts or processes contribute most to the costs?
    - What parts have the greatest cost reduction potential?
- Does the layout of the facility provide any opportunities for improvement?
- What steps of the process can be improved?
    - Which process steps create 'waste'?
    - Does the process resemble the layout and production quantity?
- What parts of the product can be created cheaper?
    - Can parts be combined?
    - Can parts be outsourced?
    - Can parts be bought at different suppliers for a lower price?

Determine the scope for the rest of the project. Will it focus on reducing the price of parts, improving the efficiency of process steps, altering the facility layout, a combination of these, or something else? What aspects of the product (parts or processes) contribute most to the cost? Use tools like pie charts or Pareto charts to summarize and visually communicate the findings. Determine a design space (Torn & Vaneker, 2021): what aspects of the product, facility, or process can be changed and what aspects need to remain as they are? What are the current requirements of the aspects that will be changed? Make sure to adhere to these.

12.5 Ideation

The orientation phase should have brought to light several opportunities for improvement. The next step is to come up with solutions to the opportunities identified in the orientation phase. The exact solutions depend on the specific situation at hand, but the two main directions of parts and process improvements are described below. Approaches to reduce the price of parts are described in paragraph 12.5.1 and approaches to reduce the price of processes are described in paragraph 12.5.2. As the parts are the outcome of the process, the two are interdependent. A change to a part may require a change in the process and vice versa. Therefore, a third category of 'interdependence' is described in paragraph 12.5.3. Each paragraph lists a variety of actions that can be taken to reduce costs. Users of the framework should determine which are relevant to their situation. To ease choosing between ideas in a later stage, it is wise to keep track of the improvement potential of each idea. Two examples are the expected cost reduction or expected time reduction.

12.5.1 Parts

The following actions can be taken to reduce the price of parts, as suggested by Meeker and McWilliams (2004); (2003):

- Redesign (parts of) the product.
- Reduce existing component costs, either by renegotiation or sourcing through a different vendor.
- Change components for alternatives with lower costs, lower performance, lower tolerance, or lesser quality and still achieve the product requirements without sacrificing quality control. Use the design space formulated at the end of the orientation phase and adhere to the requirements of the part.
- De-featuring - offer only the features that make economic sense.

Besides these actions, reconsidering sourcing decisions can also indicate opportunities:

- Reconsider make/buy decisions.
    - One approach is that of Tompkins et al. (2010, p. 37):
        - If an item cannot be purchased, it must be made.
        - If the firm cannot make the item, it must be purchased.
        - If it is cheaper to buy the item than to produce it, it must be bought.
        - If the available capital does not allow the firm to produce an item, it must be bought.
    - Another approach is that of Berk (2010, p. 90):
        - Review the current make/buy mix.
        - Identify high cost and problem areas.
        - Identify candidates for switching.
        - Prepare a present value analysis and identify risks associated with changing.
        - Decide on making or buying.
        - Evaluate continuing the current approach during the transition.
    - A third approach is that of Probert (1997, p. 14):
        - Parts must be made if they are of strategic importance, and the firm has the capability to make it competitively or the part justifies investment in extra capacity. If parts are of no strategic importance, they must be made if the firm has capacity, and it is economic to use that capacity.
        - Parts must be bought from a strategic non-competitor supplier if they are of strategic importance, the firm does not have capability to make it and investment in extra capacity cannot be justified.
        - Parts must also be bought if they are of no strategic importance and the firm does not have capacity to produce or it is not economical to use the capacity.
- Ask suppliers for quotations of parts that are currently produced in-house and compare them to the current cost price of these parts.
- Similarly, estimate what it would cost to produce currently outsourced parts in-house.
- In making the sourcing choice, keep in mind not only costs like materials, operations, human resources, and overhead, but also risks like successful making of the part,

availability of skills and labour, delivery time and quantity, meeting of requirements, warehousing costs, and increase in price.
- Also consider additional costs like order costs, transport costs, and overhead costs for buying goods.

Some more general ways to reduce the price of parts are:

- Eliminate the use of unique parts and/or increase the use of standardized parts.
- Eliminate the use of exotic raw materials, use easily processible materials.

12.5.2 Process

If the orientation phase showed that costs occur mainly in the process, the following actions can be taken to reduce the price of the process:

Supply chain and logistics

- Simplify the supply chain, for example by reconsidering the procurement model (Wiendahl et al., 2015).
- Determine to what extent the nine laws of production logistics (Nyhuis & Wiendahl, 2007, pp. 127-135) are applied and investigate if wins can be made there:
    - The input rate and output rate of a workstation have to be balanced over the long term.
    - The throughput time and range of a workstation result from the ratio of the WIP and output rate.
    - Decreasing the utilization of a workstation allows the WIP and throughput time to be disproportionately reduced.
    - The variance and mean of the work content determine the logistic potential of the shop.
    - The size of the WIP buffer required to ensure the utilization of the workstation is mainly determined by the flexibility of the load and capacity.
    - When the orders are processed according to the FIFO principle, the inter-operation time is independent of the operations individual work content.
    - The mean throughput time can be influenced significantly by sequencing rules only in the case of a high WIP level and a broadly distributed work content.
    - The throughput time variance is determined by the applied sequencing rule, the WIP level and the distribution of the work content.
    - The logistic process reliability is determined by the mean value and distribution of the throughput time.
- Investigate to what extent the cost types of logistics can be reduced. Keep in mind that individual costs may increase in order to achieve an overall cost reduction (Rushton et al., 2021, pp. 135-140).
    - Storage and warehousing costs mainly come from the building, building services, labour, equipment, and management/supervision.
    - Inventory-holding costs mainly come from capital cost (the physical stock), service cost (stock management and insurance), and risk costs (pilferage, deterioration, damage).
    - Information system.
    - Primary transport refers to the movement of goods from their production location to an intermediate storage like a distribution centre.
    - Local delivery refers to the final stage of transportation to the point of use.

Process step improvements

- If batches are large enough (e.g. more than 10) and the products small enough (e.g. 1/8 m^3), consider using one of the assembly systems described by Wiendahl et al. (2015, pp. 151-155):
    - An assembly table consisting of two turntables can be useful for batch-wise assembly (Figure 6, page 21).
    - An assembly sledge can be useful for one-piece flow assembly (Figure 7, page 21).
    - For larger batches with fluctuating demand, a U-shaped system can work. In such a system, workers are divided into two groups assembling different products. Components are supplied to their workstations.
    - For even larger batches where manual assembly is still required, manual flow assembly systems laid out in a skeleton or lap conveyor system can be used.
- Reduce capital intensive or low-yielding process steps (Mascitelli, 2011, p. 242).
- Make use of the available facilities, redesign parts so they can be produced using these facilities (Bralla, 1999).
- Adjust the operations to the production quantity.
- Consider the numerous tools from Lean methodology (Theisens, 2016). Some examples are described below:
    - 5s is aimed at creating an organised work environment by following the five steps of sort, straighten, shine, standardise and sustain.
    - Visual management makes important information visible to everybody in the workplace. Some examples include shadow boards for tooling, floor markings, andon lights, and Kanban cards.
    - The 5 why's method aims at solving problems by asking 'why' five consecutive times. This should indicate the root cause of a problem.
    - Single-Minute Exchange of Dies (SMED) can be used to improve equipment effectiveness. This approach aims at exchanging tools in a short time by executing most of the work on the tool off the production line, so installation is the only thing that happens on the production line.
    - Poka yoke 'mistake-proofing': designing parts in such a way that they only fit together in the correct way,
- Implement (one piece) flow where possible (Theisens, 2016; Wiendahl et al., 2015). This can already be applicable for individual parts with small quantities and holds for both manufacturing and assembly.
    - With one-piece flow, a workpiece moves to the next operation after it is finished at the previous operation, without waiting for other workpieces in the batch. This reduces the total process time for the batch, as well as inventory between process steps.
- Eliminate secondary operations or aim for 'first time right'.
- Maximize the number of products in each batch, whilst avoiding excessive warehousing. This reduces set-up times and maximises utilisation of resources.
- Reconsider whether changes to the order of operations are possible. Use the precedence map from the orientation phase for this.
- Ask manufacturing personnel about their insights for improvements.

Manufacturing planning

- If opportunities lie in the planning of manufacturing, consult the work of Zijm and Regattieri (2019), which compares various approaches to manufacturing planning:

- The most basic method to calculate the optimum order or production quantity is the EOQ or EPQ formula, which yields a quantity based on demand, production rate, holding and set-up costs, and production costs per product.
    - The Silver-Meal heuristic yields the optimal number of planning periods a production run should cover based on set-up and inventory costs.
    - Materials Requirements Planning (MRP) determines the time and quantity of production of all parts of a product. It uses the BOM, Master Production Schedule (MPS), the inventory levels of materials, and the offset lead times of the materials.
    - The Manufacturing Resources Planning (MRP II) elaborates on MRP by adding the factor of capacity planning.
    - ERP systems elaborate on MRP II by adding other business functions like accounting and workforce planning.
    - Hierarchical Production Planning (HPP) does not plan individual products, but rather product *groups* and reserves capacity for these. Each product *group* is divided into several *families*, which contain individual *items.*
    - As mentioned in paragraph 12.4.4, an alternative to MRP is Just-in-Time (JIT). In this approach, production is initiated by downstream demand. Goods are only produced when they are needed, to minimise intermediate inventory.

12.5.3 Interdependence

The methods of DFM (Bralla, 1999; Ulrich et al., 2020) and DFA (Boothroyd, 1994; Boothroyd & Alting, 1992; Boothroyd et al., 2002) can be used to address issues involving both parts and processes or the interdependency between these. Appendix VII: Assembly, manufacturing, and cost-reduction guidelines lists many useful guidelines for this subject. Some key guidelines are:

- Aim for simplicity. Both in part design and process choice.
- Design for use of general tooling.
- Standardize the design of the product itself.
- Use liberal tolerances.
- Change the design of the product so cheaper operations are possible.
- Design end-to-end and rotational symmetry. If this is not possible, emphasize asymmetry.
- Arrange interchangeability of components.
- Minimise and simplify the joining methods (bolts, rivets, adhesives, mechanical fits) (Langeveld, 2009).
- Snap fits are the cheapest joining method, followed by plastic bending, riveting, and screw fastening (Boothroyd et al., 2002).
- Minimise the number of parts by using the three questions of Boothroyd and Dewhurst (1994; 1992; 2002) to identify candidates for combining (those that answer the questions with three no's).
    - Does the part move relative to all the other parts in the assembly?
    - Must the part be of a different material than the other parts?
    - Must this part be separate because otherwise other separate parts cannot be assembled?
- For candidates that still need to be separate, consider whether this choice is substantiated or can be addressed in another way. Some reasons for keeping parts separate include safety, production cost, reliability, and standardization.

- Determine the improvement potential by using the formula of Ulrich et al. (2020) (equation (3) below). If the potential is less than 10%, the current design is outstanding. A potential of 11-20% means the current design is very good, 20-40% means 'good', 40-60% is 'fair', and greater than 60% is 'poor'.

$$Potential = \frac{actual\ number\ of\ components - theoretical\ number\ of\ components}{actual\ number\ of\ components} \quad (3)$$

12.5.4 Conclusion on ideation

The ideation phase should have yielded various solutions to the opportunities identified in the orientation phase. The ideas can be categorised as either improving the parts of the product (paragraph 12.5.1), the process producing the product (paragraph 12.5.2), or the interdependence between these (paragraph 12.5.3).

In case many ideas have emerged, one way to prioritise them is by calculating the action priority number (Mascitelli, 2011, p. 244). Each idea is scored on its ease of improvement and its impact on a scale of 1 to 5. These two values are multiplied to achieve the action priority number. A higher number indicates a higher priority. Similarly, the ideas can be visualised in a Project Priority Diagram (Theisens, 2016) (Figure 69).

High impact	Quick wins	Major projects
Low impact	Not now	Don't do
	Low effort	**High effort**

Figure 69: Project Priority Diagram, adapted from Theisens (2016, p. 49)

12.6 Conceptualisation

Once a list of ideas for viable solutions is established, these can be discussed with relevant stakeholders. Which stakeholders are considered relevant varies greatly and is at the discretion of the user of the framework. The extent to which stakeholders need to be involved also depends on how radical the idea is. Changing a tolerance on one part requires fewer stakeholders than changing the layout of the factory. In general, it is wise to start with internal stakeholders throughout the value chain, because these all have different and likely conflicting insights. Some examples are employees from the design, production, assembly, logistics, purchasing, maintenance, sales, and management departments. Together with the stakeholders, determine which ideas are feasible and can proceed to the conceptualisation phase.

In the conceptualisation phase, the chosen ideas become more concrete. This phase functions as preparation for the realisation phase. Some activities of the conceptualisation phase include:

- Creating CAD models and technical drawings of new or altered parts.
- Conducting simulations of part or process functionality.
- Comparing and selecting specific suppliers and partners for off-the-shelf parts and product-specific parts.
- Planning out process changes.

The conceptualisation phase has two core functions: it serves as the next 'sanity check' of the ideas, as their feasibility becomes clearer, and it should provide a more accurate indication of the cost reduction potential of each idea. Various previously overlooked problems or opportunities are likely to emerge in this process and be included in the project.

The conceptualisation phase should end with a decision which concepts should be continued and which should be discontinued. This decision should be made in correspondence with relevant stakeholders based on each concept's improvement potential.

12.7 Realisation

Once the development of the concepts is finished, they can be realised. The realisation phase is the next step in determining the feasibility of the concepts. This realisation can take various forms, depending on what is being changed. Changes to parts can be realized using prototyping, changes in suppliers can be realised by ordering samples, and changes in the process can be realized using test runs or a zero-batch. These activities should show to what extent each concept can be implemented and what might need to change before successful implementation.

During this phase, it is important to document any differences between the envisioned improvements and how the improvements turn out eventually. This can then be used in the next phase.

12.8 Verification

The second to last step of the framework is verification. This step aims to verify whether the proposed solutions actually lead to the expected improvements or if changes are necessary. This can be done by conducting tests, asking for feedback from stakeholders, or making new calculations on the true improvements. If changes are necessary, make these changes or discontinue that idea. If not, the solution can be made permanent. Because the exact verification steps depend heavily on the specific improvements developed in the project, this section only describes the verification phase in broad terms.

The main goal of testing is determining to what extent the changes have the desired results and have not compromised other aspects of the product such as functionality, aesthetics, reliability, safety, or ease of storage. These aspects can all be determined in their own tests.

Muller (2012) distinguished between three types of tests:

- Alpha test is the formal test performed by the product creation team itself, where the specification is verified.
- Beta test is performed by the 'consuming' internal stakeholders: marketing, application, production, logistics and service. The beta test also verifies the specification, but the testers have not been involved in product creation.
- Gamma: external stakeholders, such as actual users, test the product.

Four types of tests were conducted in the case study:

- Producibility tests verified whether the envisioned changes are producible using the available production techniques.
- Assemblability tests verified whether the envisioned changes can be assembled, or if certain parts may not fit together.
- Functionality tests verified whether the altered product still functions as intended, or if the changes had negative effects on the functionality.
- Aesthetics tests verified whether the altered product has the same aesthetic value as the old product. Aesthetic choices are generally a trade-off between cost saving and aesthetics.

This phase categorises the concepts (alterations or improvements) into three categories:

- Concepts that can be implemented.
- Concepts that need some alteration before implementing.
- Concepts that need to be discontinued.

Another important part of the verification process is to discuss the outcomes of the project with stakeholders, preferably the same as throughout the other phases. By involving them, the chances of the improvements being successful in the long run are increased.

If the guidelines of this framework are followed, the project should result in a set of improvements that are measurable and ready to implement.

12.9 Evaluation and implementation

The final step of the process is to evaluate all the possible changes and decide which should be implemented. These choices should be made in accordance with the findings of the verification phase and involve the relevant stakeholders.

A final calculation can be made for the cost reduction of each concept, and these can be aggregated to determine the total cost reduction potential of the project. It is not unlikely that the exact cost reduction potential cannot be determined for all concepts. In these cases, it can be wise to determine a worst-case and best-case scenario by calculating the minimal cost reduction and maximum cost reduction per concept. These can again be aggregated to determine the total minimum and maximum cost reduction of the project.

Those concepts that are considered feasible for implementation should be implemented. The further details of the implementation process fall outside the scope of this framework.

Segment C
Thesis evaluation

This final segment comprises the overall conclusion, discussion and recommendations.

13 Overall conclusion

This thesis aimed at answering the following research question:

> 'How can companies reduce the costs of individual products and how can this process be structured?'

To answer this question, a case study was conducted and subsequently used in establishing a framework for cost-reduction projects. The case study was performed at a manufacturer of gymnastics equipment in the Netherlands and focused on one product in their portfolio. The project comprised an orientation phase, followed by ideation, conceptualization, prototyping, testing and evaluation. The project yielded potential cost savings of 7 to 18% of the cost price.

The orientation phase, described in chapter 4, aimed at establishing the current state of the company, product, and process to find opportunities for reduction of the cost price. This showed that parts contribute to 67% of the costs, and processes are responsible for the remaining 33%. The orientation phase yielded four questions to be answered during the ideation phase:

1. How can 'wasteful' operations in assembly (section 4.3) be eliminated or prevented?
2. How can powder coated parts be made cheaper, whilst not compromising functionality or aesthetics?
3. How can standard parts be purchased cheaper without compromising quality?
4. Which welded parts can be combined, to omit certain welding operations?

Chapter 5 described the ideation phase, which answered the four questions above through ideas that can be divided into three categories:

- Establishing a solid foundation of the product by improving tolerances and altering technical drawings.
- Making major changes to the parts of the product and process operations.
- Making minor changes to parts of the product and process.

All ideas generated would yield a roughly estimated cost saving of €X and a time saving of X minutes in total. These ideas were condensed into a more structured list of ideas to proceed with, in correspondence with representatives of the engineering, production, assembly, and maintenance departments. The remaining ideas theoretically added up to €X and X minutes, and were developed further in the conceptualisation phase.

Chapter 6 described the conceptualisation phase, which aimed at developing the ideas to such a level of detail that they could be sent to suppliers for quotations. Some parts were subjected to an FEA. The quotations were used to calculate the cost reductions each concept would cause. The results of this calculation were discussed with stakeholders again, to determine which concepts would be proceeded to the prototyping phase. These proceeded concepts amounted to a theoretical cost reduction of €X.

Chapter 7 described the prototyping phase, which comprised the production of parts, building of the prototype and testing of the prototype. Throughout the first two subphases, the producibility and assemblability of the new parts received special attention. The final testing phase focused on testing the functionality and aesthetics of the prototype. The aim was to determine if the envisioned alterations had no negative effect on these two factors.

Chapter 8 described the evaluation of the prototype. A recommendation was formulated for each concept. The total cost reduction was calculated in a conservative manner to determine the minimum cost reduction, and in a more generous manner to determine the maximum cost reduction. This showed that the minimum cost reduction amounts to €X (7% of the cost price) and the maximum cost reduction amounts to €X (18% of the cost price).

As the case study produced a sufficient result, the question arose how the findings of the case study could be used in the future. This yielded the following sub-question:

How can the process followed in the case study be applied to other cost-reduction projects?

The answer to this question was a framework, which was developed in segment B. The process followed in the case study formed the basis of the framework and was enhanced with additional literature research. The framework comprises eight phases: preparation, orientation, ideation, conceptualisation, realisation, verification, evaluation, and implementation.

The preparation phase aims at choosing the right product for a cost reduction project, setting a target for the cost reduction, and ensuring various prerequisites for a cost reduction project.

The orientation phase aims at determining what is known about the product at hand and establishing what can be changed, as described in paragraph 12.4.6. This includes information about the development of the product, financial information about the product, information about the production facility, information about the production process, and information about the parts of the product. Several questions guide the user of the framework in gathering the required information for each category.

The ideation phase aims at determining potential solutions for reducing the cost price of the product, based on the findings of the orientation phase. The framework divides the ideas into three categories: those concerning the product, process, or the interdependence between product and process. Various options are described for developing ideas in each of these three categories. The framework refers to findings from literature and combines this with experience from the case study.

The next step of the framework is conceptualisation, where ideas are concretised. Which ideas should be concretised can be determined by discussion with stakeholders. Some activities in the conceptualisation phase include developing CAD models, conducting simulations, and selecting suppliers. This phase functions as a 'sanity check' of the ideas, as their feasibility becomes clearer during further development. The conceptualisation phase should end with an evaluated list of concepts to proceed to the next phase. This evaluation should again involve relevant stakeholders.

In the following phase the concepts are realised into prototypes, samples, or test runs. This phase will test the concepts on their applicability in the real world. The activities in this phase should show to what extent each concept can be implemented and what might need to change before successful implementation.

The second to last phase is verification, which aims at verifying if the proposed solutions actually lead to the expected improvements or if adjustments are required. This can be done by conducting tests, asking for feedback from stakeholders, or making new calculations on the true improvements.

The last phase is evaluation. In this phase all possible changes are evaluated, and decisions are made which concepts should be implemented permanently. A final calculation can be made for each concept to determine its individual cost reduction. These values can then be aggregated to determine the total cost reduction of the project. The final implementation phase is not part of the framework but is a logical next step.

14 Overall discussion and recommendations

14.1 Discussion

The framework was developed with one specific case study in mind. The processes of creating the framework and executing the case study were performed in parallel, inevitably influencing each other.

Although the framework is aimed at application for a variety of products, it may not prove as functional when the product at hand differs from the product in this case study on too many points. For example, the framework would be less applicable to products containing electronic components as the performance of these components can vary greatly from one alternative to the other. A mechanical component made of material X with strength Y will perform the same, regardless of production process or supplier.

Some examples of product types for which the framework should be applicable include: other gymnasium equipment, toys, bicycles, furniture, and office equipment. To truly verify the applicability of the framework, it should be used in a new case study. In that way, its strengths and weaknesses will become apparent and the conclusion on its applicability can be substantiated better.

The framework itself has not been tested for intuitiveness for other users than the author of this thesis.

14.2 Recommendations

To truly verify the applicability of the framework established in this thesis, it should be used in another cost-reduction project for another product. This can be the subject of a future project. In that project, the framework should be taken as the roadmap. All steps prescribed in the framework should be followed and all points where the framework lacks something should be documented.

Another opportunity lies in expanding the framework to be applicable to other categories of products, such as those containing electronic components or products that are produced by a (largely) automated process.

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Appendices

Appendix I: Justification on use of Artificial Intelligence

General

During the preparation of this work, the author used DeepL Translator to translate words, phrases, and sentences from Dutch to English and vice versa. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

During the preparation of this work, the author used the spelling and grammar check of Microsoft Word to remove spelling and grammar mistakes, improve readability, improve formal language usage, distinguish between US and UK English, and find synonyms. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

During the preparation of this work, the author used Google Gemini, as part of Google Chrome, to distinguish between US and UK English, and answer questions regarding grammar and spelling. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

Literature research

During the preparation of this work, the author used the Copilot of Microsoft Edge to increase the number of keywords used in the search for literature. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

Appendix II: Assembly tree

Table 14 below shows the structure of the assembly of the Dorack. Parts consisting of multiple parts are indicated by the indented cells. The main part is positioned in the left-most column and subsequent sub-parts are in the columns further to the right. The production steps for each part are indicated with letters in the columns further to the right. See Table 13 for the definition of each letter. Letters in *italics* indicate external processes.

Table 13: Legend for production processes

P	Purchasing
E	Extrusion
D	Drilling
B	Bending
L	Laser-cutting
W	Welding
S	Sawing
C	Coating
T	Turning
An	Anodizing
Z	Zinc plating
Dm	Drum treatment
M	Milling
A	Assembly
Pr	Pressing
R	Rolling
RM	Rotational Moulding
3D	3D printing

Table 14: Assembly tree

A Artikel					**A Omschrijving**							
741237-584086					Klimrek Dorack, verplaatsbaar							
		311407			Sluitring DIN 125 A 6,4 Zn	P						
		345103			Schroef M6x16 ISO 7380 Zn	P						
		311402			Sluitring DIN 125 A 8,4 Zn	P						
		345128			Laagbolkopschroef bzk m8x16 zn	P						
	-	568067-88			Staander tbv klimrek Dorack	*E*	*An*	D				
			568069-88		Profiel alu 1768 geanodiseerd							
	-	568068-88			Staander slingerzijde Dorack	*E*	*An*	D				
			568069-88		Profiel alu 1768 geanodiseerd							
		311435			3D-ring DIN 9021 A 8,4 Zn	P						A
		312345			Blindklinkmoer M8 0,7-3,8 Zn	P						
	-	600480-40			Handgreep Dorack RAL 3020							
		-	600480		Handgreep Dorack							
				152102	Gasb. 1" gelast	S	B	W	C			
				553072	Flensplaat handgreep Dorack	L						
		333602			T-moer M8x10 alu	P						
		345129			Laagbolkopschroef bzk m8x20 zn	P						
		544175			Koppelstuk Dorack	*T*	*Z*					

A Artikel					A Omschrijving							
		358106			Handgreep, klapbaar	P						
		311425			Sluitring DIN 125 A 10,5 Zn	P						
		345153			Schroef M10x20 ISO 7380 Zn	P						
		553183-88			Afdekkap tbv klimrek Dorack	*L*	*B*	*Z*				
		361215			Glijlager GFM-1416-08	P						
	-	553184-86			Afdekplaat tbv klimrek Dorack							
			553184		Afdekplaat tbv klimrek Dorack	*L*	Dm	C				
		342135			Schroef M10x30 DIN 912 8.8 Zn	P						
		331423			Moer M10 DIN 985 Zn	P						
	-	553181-86			Reksteun tbv klimrek Dorack							
			553181		Reksteun tbv klimrek Dorack	*L*	Dm	C				
	-	603176-86			Reksteun klimrek Dorack							
		-	603176		Reksteun klimrek Dorack							
				135202	Rond 25 h9 St37 blank	S	T	W	C			
				553182	Plaat reksteun klimrek Dorack	*L*	Dm					
	-	603149-86			Grendelsteun onder Dorack							
		-	603149		Grendelsteun onder Dorack							
				553067	Basisplaat klimrek Dorack	*L*	W	C				
				553068	Schoor klimrek Dorack	*L*						
		311601			Veerring DIN 128 A 8,1 Zn	P						
		346232			Bout tap M8x16 DIN 933 8.8 Zn	P						
	-	553077-86			Kap Dorack RAL 9006							
			553077		Kap Dorack	*L*	*B*	C				
		345121			Schroef M6x10 ISO 7380 Zn	P						
		342163			Schroef M12x35 DIN 912 8.8 Zn	P						
		775190			Nijha transfer 132x87 PMS 1807	P						
		775225			Sticker klimrek Dorack 510x73	P						
		775226			Sticker Dorack tijdens gebruik	P						
	731851				Hoogteverstelling							
		553159			Lagerblok klimrek Dorack	*M*			A			
		361212			Axiaallager 51202	P						
		361213			Kogellager 6202-2rs1	P						
		544161			Spindelas TR 20x4 RH Dorack	*T*						
		544178			Spindelas TR 20x4 LH Dorack	*T*						
		512028			Bus 20x8.3 voor klimrek dorack	*T*						
		318100			Inlegspie 5x5x16 DIN 6885 A5	P						
		553164			Kegeltandwiel Z15 M2.5 Dorack	P						
		311439			3D-ring DIN 9021 A 6,4 Zn	P						
		346231			Bout tap M6x12 DIN 933 8.8 Zn	P						
		344207			Schroef M6x25 DIN 916 Zn	P						
		553163			Glijstuk klimrek Dorack	*M*						
		553162-88			Geleidingsplaat klimrek Dorack	*L*	*B*	*Z*				
		553160			Moer TR20x4 RH klimrek Dorack	*M*						
		553161			Moer TR20x4 LH klimrek Dorack	*M*						
		331401			Zeskantmoer DIN 934 M6 Zn	P						
		311731			Afstandsbus 12x10 lengte 8	*T*						
		311425			Sluitring DIN 125 A 10,5 Zn	P						
		346228			Bout tap M10x20 DIN 933 8.8 Zn	P						
		346237			Bout tap M6x25 DIN 933 8.8 Zn	P						

A Artikel					A Omschrijving							
	783998				Tussenframe							
	-	553166-86			Flensplaat Tussenframe Dorack							
			553166		Flensplaat Tussenframe Dorack	*L*	C					
	-	553165-40			Buis 35x2 - 1687 Al 3.3206							
			553165		Buis 35x2 - 1687 Al 3.3206	*E*	*S*	C				
	-	534006-58			Middenstijl tussenframe Dorack							
			534006		Middenstijl tussenframe Dorack	*L*	C					
	-	553051-58			Moerplaat klimrek Dorack							
		-	553051		Moerplaat v klimrek Dorack			C				
				131514	Plat 20x6 St37 wg	S	D					
		544173			As 20 H9 L=1815 Dorack	*T*						
		553170			Kegeltandwiel Z30 M2.5 Dorack	P						
		355211			Inslagdop 80x30	P						
		361211			Glijlager JFM-2026-25	P						
		318111			Spie ronde einden 6x6x18	P				A		
		311604			Veerring DIN 128 A 10,2 Zn	P						
		346201			Bout tap M10x25 DIN 933 8.8 Zn	P						
		345123			Schroef M6x30 ISO 7380 Zn	P						
		344205			Stelschroef bzk M6x12,verzinkt	P						
		311435			3D-ring DIN 9021 A 8,4 Zn	P						
		346232			Bout tap M8x16 DIN 933 8.8 Zn	P						
		312306			Popnagel grotekop 5x12 Al k14	P						
	-	603173-40			Stijl Horiz lang tussenframe							
		-	603173		Stijl Horiz lang tussenframe							
				553168	Buis 35x2 - 1704 Al 3.3206	*E*	*S*	Pr	C			
				553167	Groefmoer M10 Dorack	*T*						
		343645			Schroef zebra pias 5.5x60	P						
		553169-88			Flens tbv tussenframe Dorack	*T*						
		345103			Schroef M6x16 ISO 7380 Zn	P						
	765902	Schoren										
	-	551080-58			Schoorstrip schoor Dorack							
			551080		Schoorstrip voor schoor Dorack	*L*	C					
	-	541002-40			Scharnierblok schoor Dorac							
			541002		Scharnierblok schoor Dorack	*M*	C					
	-	603140-58			Schoor voor Dorack RAL 5022							
		-	603140		Schoor voor Dorack							
				152201	Buis 21,3x2,65 St33 gelast	S						
				135109	Rond 10 St37 wg	S	B	W	Pr	C		
				551045	Bevestigingsplaat 20x24 gat 7	*L*						
				544527	Groefmoer M10 d=18.8	*T*					A	
	-	551046-58			Klemplaat klimrek Dorack							
			551046		Klemplaat	*L*	Dm	C				
		346227			Bout tap M6x20 DIN 933 8.8 Zn	P						
		311407			Sluitring DIN 125 A 6,4 Zn	P						
		548005			Arreteerblok schoor Dorack	*M*						
	-	551047-58			Afstandring Dorack							
			551047		Afstandring voor Dorack	*L*	Dm	C				
	-	603141-40			Scharnier schoren Dorack							
		-	603141		Scharnier tbv schoren Dorack				C			

A Artikel					A Omschrijving							
				551048	Scharnierplaat	*L*		W				
				551049	Schoorplaat	*L*	*B*					
		358105			Handgreep GN 917-10-17	P						
		311435			3D-ring DIN 9021 A 8,4 Zn	P						
		331420			Zelfborgendemoer DIN 985 M8 Zn	P						
		345129			Laagbolkopschroef bzk m8x20 zn	P						
		368112			Stelgaffel Din71752-M10	P						
		344214			Schroef M10x25 DIN 916 Zn	P						
		343106			Passchroef M6 8x8	P						
		333123			Moer dop M6 DIN 986 A2	P						
		311402			Sluitring DIN 125 A 8,4 Zn	P						
		311458			Pasring DIN 988 10x16x0.5 St	P						
	-	355248			Omsteekdop met schuine bodem							
			355247		Rubber voet	*T*						
		342125			Schroef M6x35 DIN 912 8.8 Zn	P						
	787329				Verrol							
	-	544432			Stang verrol klimrek Dorack							
			135209		Rond 10 h9 St37 blank	S	T					
		331404			Zeskantmoer DIN 934 M10 Zn	P						
		368112			Stelgaffel Din71752-M10	P						
		575111			Voetplaat verrol Dorack	*L*						
	-	603146-40			Verrol frame klimrek Dorack							
		-	603146		Verrol frame klimrek Dorack							
				534007	Tussenbalk verrol dorack	*L*	*B*					
				603145	Huis bedienings mechanisme	*L*	*B*					
				553052	Bodemplaat verrol dorack	*L*						
				553054	Schoorplaat verrol Dorack	*L*						
				553055	Staanderbevestiging Dorack	*L*	*D*					
				553056	Versteviginsplaat verrol Dorack	*L*		W	C			
				548010	Stijlmontageblok verrol dorack	*M*						
				553057	Strip verrol klimrek Dorack	*L*						
				331398	Moer M6 DIN 6330 1,5D	P						
				131521	Plat 30x5 St37 wg	S				A		
				131543	Plat 20x10 St37 wg	S						
				131572	Plat 30x4 St37 wg	S	R					
		312344			Blindklinkmoer M6 0.7-4.2 Zn	P						
	-	603147-88			Draagarm verrol klimrek Dorack							
		-	603147		Draagarm verrol klimrek Dorack							
				553058	Wielsteun links klimrek Dorack	*L*	*B*					
				553059	Wielsteun R klimrek Dorack	*L*	*B*					
				553060	Verstevigingsstrip verrol	*L*		W	*Z*			
				173320	U-profiel 40x100x40x3 St37 kg	S						
				131517	Plat 40x6 St37 wg	S	D					
	-	544431			As verrol klimrek Dorack							
			135508		Profielstaal C45K rond 12 h9	S						
	-	553061-58			Hefboom verrol klimrek Dorack							
			553061		Hefboom verrol klimrek Dorack	*L*	*Dm*	C				
		553062-88			Schalm verrol klimrek Dorack	*L*	*Z*					
		368707			Stelring rond 12 DIN 705A	P						

A Artikel					A Omschrijving							
		311715			Bus 25x12.6x5 PA6	P						
		544439			Scharnieras verrol Dorack	*T*						
		311402			Sluitring DIN 125 A 8,4 Zn	P						
		345128			Laagbolkopschroef bzk m8x16 zn	P						
	-	603148-88			Koppelhefboom verrol Dorack							
		-	603148		Koppelhefboom verrol Dorack							
				553063	Koppel hefboom verrol Dorack	*L*	W	*Z*				
				151119	Buis 20x3,5 St35	Z						
		544430			As 215 verrol klimrek Dorack	*S*						
	-	553064-88			Schalm lang verrol Dorack							
			553064		Schalm lang verrol Dorack	*L*	*Z*					
	-	553066-58			Ontgrendel hefboom Dorack							
			553066		Ontgrendel hefboom Dorack	*L*	*Dm*	C				
		346212			Bout tap M8x40 DIN 933 zn	P						
		331403			Zeskantmoer DIN 934 M8 Zn	P						
	-	553065-88			Voorplaat verrol							
		-	553065		Voorplaat verrol Dorack			*Z*				
				131511	Plat 30x10 St37 wg	S	D					
		345139			Schroef M6x16 flens Zn	P						
		345147			Schroef M6x10 flens Zn	P						
		346232			Bout tap M8x16 DIN 933 8.8 Zn	P						
		362102			Wiel 125x40 H=156	P						
		544428			Ontgrendelstang verrol Dorack	*T*						
		544429			Pedaalstang verrol Dorack	*T*						
		345129			Laagbolkopschroef bzk m8x20 zn	P						
		346239			Bout tap M6x30 DIN 933 8.8 Zn	P						
		331401			Zeskantmoer DIN 934 M6 Zn	P						
		341122			Schroef flens M6x25 ISO7380 zn	P						
		575110-40			Verrolkap m sleuf kleuterklim	*RM*						
		575109-40			Verrolkap z sleuf kleuterklim	*RM*						
	726123				Grendels							
		553157-88			Grendelhuis klimrek Dorack	*M*						
		553070			Houdpal klimrek Dorack (RVS)	*L*						
		312612			Parallel pen ISO 8734-6m6x10	P						
	-	544185			Blokkeerschuif grendel Dorack							
			358610		PLA filament Ø1,75, 0,75kg, zw	3D						
		368819			Drukveer D11760	P						
	-	553158-58			Zijplaat grendel Dorack							
			553158		Zijplaat grendel Dorack	*L*	Dm	C				
		544179			Pal grendel klimrek Dorack	3D			A			
		368818			Drukveer D11530	P						
		311716			Afstandsbus 5.2x10x4	P						
		345133			SchroefM5x20 ISO7380 Zn	P						
		358202			Kogelknop D20 M5 rood	P						
		345124			Schroef M8x25 ISO 7380 Zn	P						
		331420			Zelfborgendemoer DIN 985 M8 Zn	P						
		333708			Moer flens M6x15 RVS	P						
		345147			Schroef M6x10 flens Zn	P						
		345126			Schroef M4x6 ISO 7380 Zn	P						

A Artikel					A Omschrijving					
	741238				Klimrek					
	-	553171-58			Buitenstijl schoorzijde Dorack					
			553171		Buitenstijl schoorzijde Dorack	*L*	C			
	-	553176-58			Binnenstijl grendelzijd Dorack					
			553176		Binnenstijl grendelzijd Dorack	*L*	C			
	-	534004-58			Binnenstijl Dorack RAL 5022					
			534004		Binnenstijl Dorack	*L*	C			
	-	553179-58			Buitenstijl tbv Dorack					
			553179		Buitenstijl tbv Dorack	*L*	C			
	-	603175-40			Stijl Horiz kort Dorack					
		-	603175		Stijl Horiz kort Dorack					
				553180	Buis 35x2 - 526 Al 3.3206	*E*	*S*	Pr	C	
				553167	Groefmoer M10 Dorack	*T*				
	-	553185-40			Buis 35x2 - 1531 Al 3.3206					
			553185		Buis 35x2 - 1531 Al 3.3206	*E*	*S*	C		
	-	603174-40			Stijl Horiz lang Dorack					
		-	603174		Stijl Horiz lang Dorack					
				553178	Buis 35x2 - 1526 Al 3.3206	*E*	*S*	Pr	C	
				553167	Groefmoer M10 Dorack	*T*				
	-	603142			Beugel voor klimrek Dorack					
			135301		Rond 20 h9 RVS 304L	S	B	W		A
			551075		Strip RVS tbv beugel Dorack	*L*				
		362105			App.wiel diam.75x25	P				
		355211			Inslagdop 80x30	P				
		343645			Schroef zebra pias 5.5x60	P				
		544158			Wielas voor Dorack	*T*				
		345126			Schroef M4x6 ISO 7380 Zn	P				
		345158			Laagbolkopschroef M6x50 zn	P				
		345108			SchroefM10x16 ISO 7380 Zn	P				
		345104			Schroef M10x25 ISO 7380 Zn	P				
		312344			Blindklinkmoer M6 0.7-4.2 Zn	P				
		553172-88			As tbv Dorack	*T*	*Z*			
		553173			Glijlager tbv Dorack	P				
	-	551050-58			Montagering koppeling Dorack					
			551050		Montagering v koppeling Dorack	*L*	Dm	C		
		333112			Moer dop M6 DIN 986 Zn	P				
		553177-88			Sluitring 12x50x3 tbv Dorack	*L*	*Z*			
		346183			Bout M12x150 DIN 931 8.8 Zn	P				
		361416			Stangkop 648.5-12-M12-WH	P				
		553174-88			Tussenring tbv Dorack	*L*	*Z*			
		553175-88			Bus tbv Dorack	*T*	*Z*			
		237715			Cyanoacrylaatlijm CA1500V					

Appendix III: RPA

Source: Goodson (2002)

Category	Rating (1-11)
1. Customer satisfaction	6
2. Safety, environment, cleanliness, and order	8
3. Visual management system	6
4. Scheduling system	8
5. Use of space, movement of materials, product line flow	8
6. Levels of inventory and work in progress	8
7. Teamwork and motivation	7
8. Condition and maintenance of equipment and tools	6
9. Management of complexity and variability	8
10. Supply chain integration	5
11. Commitment to quality	8
Total	78

1 Are visitors welcomed and given information about plant layout, workforce, customers, and products?	No
2 Are ratings for customer satisfaction and product quality displayed?	No
3. Is the facility safe, clean, orderly, and well lit? Is the air quality good, and are noise levels low?	Yes
4 Does a visual labeling system identify and locate inventory, tools, processes, and flow?	Yes
5 Does everything have its own place, and is everything stored in its place?	Yes
6 Are up-to-date operational goals and performance measures for those goals prominently posted?	No
7 Are production materials brought to and stored at line side rather than in separate inventory storage areas?	Yes
8 Are work instructions and product quality specifications visible at all work areas?	Yes
9.Are updated charts on productivity, quality, safety, and problem solving visible for all teams?	No
10 Can the current state of the operation be viewed from a central control room, on a status board, or on a computer display?	Yes
11 Are production lines scheduled off a single pacing process, with appropriate inventory levels at each stage?	Yes
12 Is material moved only once and as short a distance as possible? Is material moved efficiently in appropriate containers?	Yes
13Is the plant laid out in continuous product line flows rather than in 'shops'?	No
14 Are work teams trained, empowered, and involved in problem solving and ongoing improvements?	No
15 Do employees appear committed to continuous improvement of tools and processes?	Yes
16 Is a timetable posted for equipment preventive maintenance and ongoing improvement of tools and processes?	Yes
17 Is there an effective project-management process, with cost and timing goals, for new product start-ups?	Yes
18 Is a supplier certification process – with measures for quality, delivery, and cost performance – displayed?	No

19 Have key product characteristics been identified, and are fail-safe methods used to forestall propagation of defects?	No
20 Would you buy the products this operation produces?	Yes
Total number of yeses	12

Appendix IV: Semi-structured interview transcripts

For the sake of the privacy of the interviewees, the interviews have been omitted in the public version. The interviewees had the following roles: co-developer of the Dorack, assembly employee, production coordinator, production planner, and operational manager/director.

Appendix V: Competitor analysis

All competitors of Nijha have one or several products that share similarities with the Dorack. The first is the 'climbing island' of Bosan, which is freestanding and movable. These two properties are the main similarities. It consists of a central frame of 220cm height, two attached frames with varying height (175 and 135cm) that can be hinged, and two mats. The attached frames each have two supporting legs. The main differences are that this product does not have the functionality of putting the frames at an angle, this product has integrated mats, the rungs are made of wood, and the frames have a varying height. The sales price of this product is €5864.69 excluding VAT.

Figure 70: 'Bosan Klimeiland Vrijstaand en Verrolbaar' Source: Bosan B.V.

A similar product by Bosan is the 'Klim-Klauterrek Junior'. This product also has three frames with varying height (220, 150 and 130cm), but is not movable and does not have integrated mats. It is mounted to a wall, where it can also be stored in collapsed form. At a sales price of €3773.72 excluding VAT it is a cheaper option compared to the climbing island.

Figure 71: Bosan 'Klim-Klauterrek Junior 3-delig' Source: Bosan B.V.

A product that is also similar to the climbing island of Bosan is the climbing island of Janssen Fritsen. This product is also movable, contains three frames (two rotatable with supporting legs), and integrated mats. The main rack is of similar height, but the smaller racks are 125cm each. This product is sold for €5870 excluding VAT.

Figure 72: Janssen-Fritsen Klimeiland, source: Janssen-Fritsen B.V.

Janssen-Fritsen also has a wall-mounted alternative, which is very similar to the movable climbing island. The frames have the same dimensions and can also be rotated almost 360 degrees. The main rack also has a hinge, so it can be stored flat against a wall. This product is sold at €3350 excluding VAT.

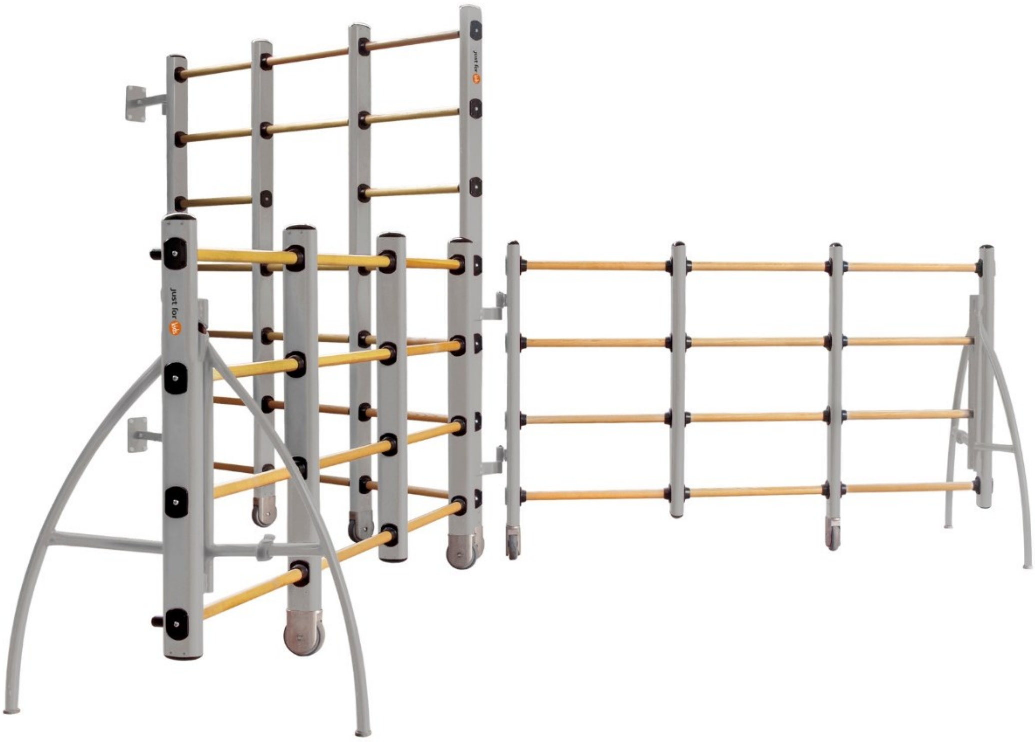


Figure 73: Janssen-Fritsen Sterraam, source: Janssen-Fritsen B.V.

A third competitor is Jeka, with their 'Klimrek Spin'. It is very similar to the previous wall-mounted climbing frames. It also has wooden rungs and two rotatable frames of 150 and 180cm.

Figure 74: JEKA Klimrek Spin, source: Jeka Service B.V.

The last competitor is the 'Sterwand' of Idema. This climbing frame is also mounted to the wall, has wooden rungs, and three frames of varying height (217, 181 and 151 cm). It is sold at €3433.98 including VAT.

Figure 75: Idema sterwand, source: idema.com

Appendix VI: Process observations

Powder coating

- Before the coating operation, all parts requiring the same colour get combined in one production order.
- These parts get picked from storage and put together on one cart.
- All parts that have already been drum treated are put in a separate container on the cart.
- Once the coating process starts, parts are sorted in two categories: 1. Steel parts and thick aluminium parts, and 2. Thin aluminium parts with drum treated parts.
- Parts of category 1 are sand blasted and subsequently sanded to remove sharp residue, parts of category 2 only get degreased.
- After sanding and degreasing, the parts are put in a cart and a wire passes through all.
- After wiring, any remaining dust is removed from the parts first by pressurized air and subsequently by a gas burner.
- This process is repeated for the other carts in the batch.
- Once a cart is full, it gets transferred to the spraying cabin, where powder is applied.
- Once the powder has been applied, the cart is rolled towards the oven, where it waits for the remaining carts of the batch.
- If all carts of a batch are ready, they are rolled into the oven and baked at 190 °C for X minutes. The maximum capacity of the oven is X carts.
- After baking, the carts are rolled out of the oven and cooled down for X to X minutes, depending on the material and thickness of the parts.

Four employees work in the coating street: One for sand blasting, one for hanging, sanding, blowing, and burning the parts, one for powdering and one for assisting and order picking.

The timed operations are put in Table 15 below.

Table 15: Timing of powder coating operations

Action	Time (per cart) mm:ss
Sand blasting	
Sanding	
Degreasing	
Degreased parts waiting to be placed on cart	
Placing parts on cart	
Wiring parts	
Blowing off dust	
Gas burner	
Rolling cart to spraying cabin and positioning	
Applying powder to one side	
Rotating cart	
Powdering other side	
Baking	
Cooling	

Four carts were taken as a sample to determine to what extent the price mentioned in the ERP system corresponded to the real situation. These can be seen in the figures below. The comparison between the ERP price and the real situation can be found in Table 16. To determine the price based on the observation, a total price of €X was distributed over the parts in each cart, proportional to their price in the ERP system. The analysis showed that for most parts the price of the observation was twice as low as that in the ERP system.

Figure 76: Powder cart sample 1

Figure 77: Powder cart sample 2

Figure 78: Powder cart sample 3

Figure 79: Powder cart sample 4

Table 16: Comparison ERP and real situation coating

Sample	Onderdeel	art.nr	Aantal op foto	Stuksprijs Isah (€)	Theoretische prijs op foto (€)	Aandeel in geheel	Prijs gebaseerd op observatie (€)	Verschilfactor
1	Schoorstrips	551080	12			0,076923		2,08
	Hefboom	553061	6			0,076923		2,08
	Ontgrendelhefboom	553066	6			0,076923		2,08
	Zijplaat grendel	553158	24			0,230769		2,08
	Klemplaat	551046	6			0,057692		2,08
	Afstandsring	551047	6			0,057692		2,08
	Moerplaat	553051	24			0,153846		2,08
	Schoor	603140	12			0,269231		2,08
	Totaal							

2	Stijlen		12			0,802817		1,42
	Stijlen tussenframe		6			0,197183		1,42
	Totaal							
3	Schoorstrips	551080	12			0,078431		2,04
	Hefboom	553061	6			0,078431		2,04
	Ontgrendelhefboom	553066	6			0,078431		2,04
	Zijplaat grendel	553158	26			0,254902		2,04
	Klemplaat	551046	6			0,058824		2,04
	Afstandsring	551047	6			0,058824		2,04
	Moerplaat	553051	24			0,156863		2,04
	Montagering	551050	24			0,235294		2,04
		totaal						
4	Bedieningsarm tbv koordklem	562028	22			0,15493		2,366667
	Moerplaat	553051	24			0,135211		2,366667
	Montagering	551050	24			0,202817		2,366667
	Zijplaat grendel	553158	24			0,202817		2,366667
	Schoorstrips	551080	12			0,067606		2,366667
	Hefboom	553061	6			0,067606		2,366667
	Ontgrendelhefboom	553066	6			0,067606		2,366667
	Afstandsring	551047	6			0,050704		2,366667
	Klemplaat	551046	6			0,050704		2,366667
	Totaal							

Assembly

Information about the assembly process is considered confidential. Therefore, this table has been removed from the public version. The observations identified 'overprocessing' 13 times, 'transport' 3 times, and 'movement' 2 times.

Appendix VII: Assembly, manufacturing, and cost-reduction guidelines

	(Boothroyd et al., 2002)	(Andreasen et al., 1983)	Lucas (Miles, 1989)	(Barnes et al., 1997)	(Corbett, 1991)	(Syan & Swift, 1994)	(Edwards, 2002)	(Ulrich et al., 2020)	(Ullman, 1997)	(Bralla, 1999)	(Meeker & McWilliams, 2003)	(Berk, 2010)	(Mascitelli, 2011)
Part count													
Minimize parts and fixings			X			X	X	X	X	X	X		X
Minimize design variants			X			X							
Processes													
Reduce assembly steps requiring a high skill level													X
Reduce capital intensive process steps													X
Resolve low-yielding process steps							X						X
Minimize production steps							X						
Avoid secondary operations										X			
Manual processes													
Manual processes should be reduced to a minimum.						X	X						
Design end-to-end and rotational symmetry	X	X	X		X	X	X	X	X	X			X
If symmetry is not possible, emphasize asymmetry	X	X	X		X	X	X	X	X				
Prevent jamming & tangling	X	X				X	X			X			
Avoid sticking together, slippery, delicate, flexible, very small or large, hazardous parts.	X					X			X	X			
Avoid adjustments	X					X			X	X			
Avoid visual obstructions						X							
Avoid orientation								X					
Minimize the need for tools								X					
Simplify handling of components							X						
Compatibility													
Interchange ability of components should be arranged.						X	X						
Standardize by using common parts	X				X	X	X			X			X
Avoid incompatibility with existing flow lines or work cells							X						X
Design components to serve more than one function							X						
Features													
Examine what features and options are valued											X		
Materials													
Do not use exotic materials							X			X		X	X
Use the most processible materials										X			
Tolerances													

	(Boothroyd et al., 2002)	(Andreasen et al., 1983)	Lucas (Miles, 1989)	(Barnes et al., 1997)	(Corbett, 1991)	(Syan & Swift, 1994)	(Edwards, 2002)	(Ulrich et al., 2020)	(Ullman, 1997)	(Bralla, 1999)	(Meeker & McWilliams, 2003)	(Berk, 2010)	(Mascitelli, 2011)
Minimize tolerance and surface finish demands on components so that production costs are reduced							X	X		X			
Do not specify tolerances tighter than essential for correct functioning							X	X		X		X	X
Eliminate high precision fits whenever possible.							X						
Use the widest possible tolerances and finishes on components.							X	X					
Insertion & fastening													
Sharp corners must be removed from components so that they are guided into their correct position during assembly.	X				X	X	X	X	X	X			
Apart from product simplification, great improvements can often be made by the introduction of guides and tapers which directly facilitate assembly.	X	X			X		X		X	X			
Use pyramid assembly, assemble from above, linear	X	X	X	X		X	X	X	X	X			
Avoid holding parts down	X									X			
Design so a part is located before it is released, natural alignment	X					X				X			
Avoid repositioning an assembly	X												
Avoid connections/fasteners	X				X	X			X	X			X
Design so that access for assembly operations is not restricted.	X					X							
Make merging unambiguous		X								X			
Use slots or oversized holes for aligned holes										X			
Sub-assemblies													
Orientation of a sub-assembly must remain known and constant throughout the assembly sequence			X										
When a sub-assembly is being moved, it should be structurally sound.			X										
Do not commit a sub-assembly to a particular product until as far up the assembly chain as possible.			X							X			
Ensure that the items and sub-assemblies can be handled and processed without marring			X										
Assembly system													
Few, short stops or disturbances		X											
high degree of exploitation		X											
Short assembly time: Few or no assemblies, simple, quick assembly, simultaneous assembly, combined operations		X											

	(Boothroyd et al., 2002)	(Andreasen et al., 1983)	Lucas (Miles, 1989)	(Barnes et al., 1997)	(Corbett, 1991)	(Syan & Swift, 1994)	(Edwards, 2002)	(Ulrich et al., 2020)	(Ullman, 1997)	(Bralla, 1999)	(Meeker & McWilliams, 2003)	(Berk, 2010)	(Mascitelli, 2011)
Large capacity		X											
Reliable manning: Few operators, small operator effort, motivating jobs.		X											
Use magazines		X							X	X			
Use components in 'bandform'		X							X	X			
Maintenance													
Keep internal mechanisms accessible										X			
Cost													
Use lower-cost parts											X		
Decrease how much you are paying for parts											X	X	
Substitute parts for similar parts with lower cost											X		
Substitute parts with lower, but sufficient performance											X		
Sourcing													
Re-source or outsource to a lower cost producer											X	X	

Appendix VIII: DFA criteria

Boothroyd et al. (2002) described three criteria for separating parts. If none of these criteria are fulfilled, the part could theoretically be combined with another. If the part should still be separated, there should be a justification for it. Table 17 shows these criteria for all parts in the Dorack

Table 17: DFA criteria

Part number	Description	Purchased subassembly?	Separate fastener?	Movement relative to other parts?	Different material?	Separate because of assembly of other parts	Justification
311407	Sluitring DIN 125 A 6,4 Zn		Yes				
345103	Schroef M6x16 ISO 7380 Zn		Yes				
311402	Sluitring DIN 125 A 8,4 Zn		Yes				
345128	Laagbolkopschroef bzk m8x16 zn		Yes				
568067-88	Staander tbv klimrek Dorack			No	No	No	Production cost
568069-88	Profiel alu 1768 geanodiseerd						
568068-88	Staander slingerzijde Dorack			No	No	No	Production cost
568069-88	Profiel alu 1768 geanodiseerd			No	No	No	Production cost
311435	3D-ring DIN 9021 A 8,4 Zn		Yes				
312345	Blindklinkmoer M8 0,7-3,8 Zn		Yes				
600480-40	Handgreep Dorack RAL 3020			No	No	No	Production cost
152102	Gasb. 1" gelast			No	No	No	Production cost
553072	Flensplaat handgreep Dorack			No	No	No	Production cost
333602	T-moer M8x10 alu		Yes				
345129	Laagbolkopschroef bzk m8x20 zn		Yes				
544175	Koppelstuk Dorack			No	No	No	Production cost
358106	Handgreep, klapbaar	Yes					
311425	Sluitring DIN 125 A 10,5 Zn		Yes				
345153	Schroef M10x20 ISO 7380 Zn		Yes				
553183-88	Afdekkap tbv klimrek Dorack					Yes	
361215	Glijlager GFM-1416-08			Yes			
553184-86	Afdekplaat tbv klimrek Dorack			No	No	Yes	
342135	Schroef M10x30 DIN 912 8.8 Zn		Yes				
331423	Moer M10 DIN 985 Zn		Yes				
553181-86	Reksteun tbv klimrek Dorack			Yes			
603176-86	Reksteun klimrek Dorack			Yes			
135202	Rond 25 h9 St37 blank			No	No	No	Production cost
553182	Plaat reksteun klimrek Dorack			No	No	No	Production cost
603149-86	Grendelsteun onder Dorack			No	No	No	Production cost
553067	Basisplaat klimrek Dorack			No	No	No	

Part number	Description	Purchased subassembly?	Separate fastener?	Movement relative to other parts?	Different material?	Separate because of assembly of other parts	Justification
553068	Schoor klimrek Dorack			No	No	No	
311601	Veerring DIN 128 A 8,1 Zn		Yes				
346232	Bout tap M8x16 DIN 933 8.8 Zn		Yes				
553077-86	Kap Dorack RAL 9006			No	No	No	Safety
345121	Schroef M6x10 ISO 7380 Zn		Yes				
342163	Schroef M12x35 DIN 912 8.8 Zn		Yes				
775190	Nijha transfer 132x87 PMS 1807				Yes		
775225	Sticker klimrek Dorack 510x73				Yes		
775226	Sticker Dorack tijdens gebruik				Yes		
553159	Lagerblok klimrek Dorack			Yes			
361212	Axiaallager 51202			Yes			
361213	Kogellager 6202-2rs1			Yes			
544161	Spindelas TR 20x4 RH Dorack			Yes			
544178	Spindelas TR 20x4 LH Dorack			Yes			
512028	Bus 20x8.3 voor klimrek dorack			No	No	No	
318100	Inlegspie 5x5x16 DIN 6885 A5			No	No	No	Reliability
553164	Kegeltandwiel Z15 M2.5 Dorack			Yes	No	No	
311439	3D-ring DIN 9021 A 6,4 Zn		Yes				
346231	Bout tap M6x12 DIN 933 8.8 Zn		Yes				
344207	Schroef M6x25 DIN 916 Zn		Yes				
553163	Glijstuk klimrek Dorack			Yes			
553162-88	Geleidingsplaat klimrek Dorack			No	No	No	Production cost
553160	Moer TR20x4 RH klimrek Dorack			Yes			
553161	Moer TR20x4 LH klimrek Dorack			Yes			
331401	Zeskantmoer DIN 934 M6 Zn		Yes				
311731	Afstandsbus 12x10 lengte 8			No	No	No	
311425	Sluitring DIN 125 A 10,5 Zn		Yes				
346228	Bout tap M10x20 DIN 933 8.8 Zn		Yes				
346237	Bout tap M6x25 DIN 933 8.8 Zn		Yes				
553166-86	Flensplaat Tussenframe Dorack			No	No	Yes	
553165-40	Buis 35x2 - 1687 Al 3.3206			No	No	No	Production cost
534006-58	Middenstijl tussenframe Dorack			No	No	No	Production cost
553051-58	Moerplaat klimrek Dorack			No	No	Yes	
544173	As 20 H9 L=1815 Dorack			Yes			
553170	Kegeltandwiel Z30 M2.5 Dorack			Yes			
355211	Inslagdop 80x30			No	No	No	Safety

Part number	Description	Purchased subassembly?	Separate fastener?	Movement relative to other parts?	Different material?	Separate because of assembly of other parts	Justification
361211	Glijlager JFM-2026-25				Yes		
318111	Spie ronde einden 6x6x18			No	No	No	Reliability
311604	Veerring DIN 128 A 10,2 Zn		Yes				
346201	Bout tap M10x25 DIN 933 8.8 Zn		Yes				
345123	Schroef M6x30 ISO 7380 Zn		Yes				
344205	Stelschroef bzk M6x12,verzinkt		Yes				
311435	3D-ring DIN 9021 A 8,4 Zn		Yes				
346232	Bout tap M8x16 DIN 933 8.8 Zn		Yes				
312306	Popnagel grotekop 5x12 Al k14		Yes				
603173-40	Stijl Horiz lang tussenframe			No	No	No	Production cost
553168	Buis 35x2 - 1704 Al 3.3206			No	No	Yes	
553167	Groefmoer M10 Dorack			No	No	No	
343645	Schroef zebra pias 5.5x60		Yes				
553169-88	Flens tbv tussenframe Dorack			No	No	No	Production cost
345103	Schroef M6x16 ISO 7380 Zn		Yes				
551080-58	Schoorstrip schoor Dorack			Yes			
541002-40	Scharnierblok schoor Dorack			Yes			
603140-58	Schoor voor Dorack RAL 5022			Yes			
152201	Buis 21,3x2,65 St33 gelast			No	No	No	Production cost
135109	Rond 10 St37 wg			No	No	No	Production cost
551045	Bevestigingsplaat 20x24 gat 7			No	No	No	Production cost
544527	Groefmoer M10 d=18.8			No	No	No	Production cost
551046-58	Klemplaat klimrek Dorack			Yes			
346227	Bout tap M6x20 DIN 933 8.8 Zn		Yes				
311407	Sluitring DIN 125 A 6,4 Zn		Yes				
548005	Arreteerblok schoor Dorack			Yes			
551047-58	Afstandring Dorack			No	No	Yes	
603141-40	Scharnier schoren Dorack			Yes			
551048	Scharnierplaat			No	No	No	Production cost, strength
551049	Schoorplaat			No	No	No	Production cost, strength
358105	Handgreep GN 917-10-17	Yes					
311435	3D-ring DIN 9021 A 8,4 Zn		Yes				
331420	Zelfborgendemoer DIN 985 M8 Zn		Yes				
345129	Laagbolkopschroef bzk m8x20 zn		Yes				
368112	Stelgaffel Din71752-M10	Yes					

Part number	Description	Purchased subassembly?	Separate fastener?	Movement relative to other parts?	Different material?	Separate because of assembly of other parts	Justification
344214	Schroef M10x25 DIN 916 Zn		Yes				
343106	Passchroef M6 8x8		Yes				
333123	Moer dop M6 DIN 986 A2		Yes				
311402	Sluitring DIN 125 A 8,4 Zn		Yes				
311458	Pasring DIN 988 10x16x0.5 St		Yes				
355248	Omsteekdop met schuine bodem				Yes		
342125	Schroef M6x35 DIN 912 8.8 Zn		Yes				
544432	Stang verrol klimrek Dorack			No	No	No	Production costs
331404	Zeskantmoer DIN 934 M10 Zn		Yes				
368112	Stelgaffel Din71752-M10	Yes					
575111	Voetplaat verrol Dorack				Yes		
603146-40	Verrol frame klimrek Dorack			No	No	No	Production costs
534007	Tussenbalk verrol dorack			No	No	No	Production costs
603145	Huis bedienings mechanisme			No	No	No	Production costs
553052	Bodemplaat verrol dorack			No	No	No	Production costs
553054	Schoorplaat verrol Dorack			No	No	No	
553055	Staanderbevestiging Dorack			No	Yes		Reliability
553056	Versteviginsplaat verrol Dorack			No	No	No	
548010	Stijlmontageblok verrol dorack			No	No	No	Production costs
553057	Strip verrol klimrek Dorack			No	No	No	
331398	Moer M6 DIN 6330 1,5D		Yes				
131521	Plat 30x5 St37 wg			No	No	No	
131543	Plat 20x10 St37 wg			No	No	No	
131572	Plat 30x4 St37 wg			No	No	No	Production costs
312344	Blindklinkmoer M6 0.7-4.2 Zn		Yes				
603147-88	Draagarm verrol klimrek Dorack			Yes			
553058	Wielsteun links klimrek Dorack			No	No	No	Production costs
553059	Wielsteun R klimrek Dorack			No	No	No	Production costs
553060	Verstevigingsstrip verrol			No	No	No	Production costs
173320	U-profiel 40x100x40x3 St37 kg			No	No	No	Production costs
131517	Plat 40x6 St37 wg			No	No	No	Production costs
544431	As verrol klimrek Dorack					Yes	
135508	Profielstaal C45K rond 12 h9			Yes			
553061-58	Hefboom verrol klimrek Dorack			Yes			
553062-88	Schalm verrol klimrek Dorack			Yes			
368707	Stelring rond 12 DIN 705A		Yes				
311715	Bus 25x12.6x5 PA6				Yes		

Part number	Description	Purchased subassembly?	Separate fastener?	Movement relative to other parts?	Different material?	Separate because of assembly of other parts	Justification
544439	Scharnieras verrol Dorack			Yes			
311402	Sluitring DIN 125 A 8,4 Zn		Yes				
345128	Laagbolkopschroef bzk m8x16 zn		Yes				
603148-88	Koppelhefboom verrol Dorack			Yes			
553063	Koppel hefboom verrol Dorack			No	No	No	Production costs
151119	Buis 20x3,5 St35			No	No	No	Production costs
544430	As 215 verrol klimrek Dorack			Yes			
553064-88	Schalm lang verrol Dorack			Yes			
553066-58	Ontgrendel hefboom Dorack			Yes			
346212	Bout tap M8x40 DIN 933 zn		Yes				
331403	Zeskantmoer DIN 934 M8 Zn		Yes				
553065-88	Voorplaat verrol					Yes	
345139	Schroef M6x16 flens Zn		Yes				
345147	Schroef M6x10 flens Zn		Yes				
346232	Bout tap M8x16 DIN 933 8.8 Zn		Yes				
362102	Wiel 125x40 H=156	Yes					
544428	Ontgrendelstang verrol Dorack					Yes	
544429	Pedaalstang verrol Dorack					Yes	
345129	Laagbolkopschroef bzk m8x20 zn		Yes				
346239	Bout tap M6x30 DIN 933 8.8 Zn		Yes				
331401	Zeskantmoer DIN 934 M6 Zn		Yes				
341122	Schroef flens M6x25 ISO7380 zn		Yes				
575110-40	Verrolkap m sleuf kleuterklim				Yes		
575109-40	Verrolkap z sleuf kleuterklim				Yes		
553157-88	Grendelhuis klimrek Dorack			No	No	No	Standardization
553070	Houdpal klimrek Dorack (RVS)			Yes			
312612	Parallel pen ISO 8734-6m6x10			No	No	No	
544185	Blokkeerschuif grendel Dorack			Yes			
368819	Drukveer D11760			Yes			
553158-58	Zijplaat grendel Dorack					Yes	
544179	Pal grendel klimrek Dorack			Yes			
368818	Drukveer D11530			Yes			
311716	Afstandsbus 5.2x10x4			No	No	No	
345133	SchroefM5x20 ISO7380 Zn		Yes				
358202	Kogelknop D20 M5 rood			No	No	No	
345124	Schroef M8x25 ISO 7380 Zn		Yes				

Part number	Description	Purchased subassembly?	Separate fastener?	Movement relative to other parts?	Different material?	Separate because of assembly of other parts	Justification
331420	Zelfborgendemoer DIN 985 M8 Zn		Yes				
333708	Moer flens M6x15 RVS		Yes				
345147	Schroef M6x10 flens Zn		Yes				
345126	Schroef M4x6 ISO 7380 Zn		Yes				
553171-58	Buitenstijl schoorzijde Dorack			No	No	No	Production cost
553176-58	Binnenstijl grendelzijd Dorack			No	No	No	Production cost
534004-58	Binnenstijl Dorack RAL 5022			No	No	No	Production cost
553179-58	Buitenstijl tbv Dorack			No	No	No	Production cost
603175-40	Stijl Horiz kort Dorack			No	No	No	Production cost
553180	Buis 35x2 - 526 Al 3.3206			No	No	No	Production cost
553167	Groefmoer M10 Dorack			No	No	No	Production cost
553185-40	Buis 35x2 - 1531 Al 3.3206			No	No	No	Production cost
603174-40	Stijl Horiz lang Dorack			No	No	No	Production cost
553178	Buis 35x2 - 1526 Al 3.3206			No	No	No	Production cost
553167	Groefmoer M10 Dorack			No	No	No	Production cost
603142	Beugel voor klimrek Dorack			No	No	No	Production cost
135301	Rond 20 h9 RVS 304L			No	No	No	Production cost
551075	Strip RVS tbv beugel Dorack			No	No	No	Production cost
362105	App.wiel diam.75x25			Yes			
355211	Inslagdop 80x30			No	No	No	Safety
343645	Schroef zebra pias 5.5x60		Yes				
544158	Wielas voor Dorack			No	No	Yes	
345126	Schroef M4x6 ISO 7380 Zn		Yes				
345158	Laagbolkopschroef M6x50 zn		Yes				
345108	SchroefM10x16 ISO 7380 Zn		Yes				
345104	Schroef M10x25 ISO 7380 Zn		Yes				
312344	Blindklinkmoer M6 0.7-4.2 Zn		Yes				
553172-88	As tbv Dorack			Yes			
553173	Glijlager tbv Dorack			Yes			
551050-58	Montagering koppeling Dorack					Yes	
333112	Moer dop M6 DIN 986 Zn		Yes				
553177-88	Sluitring 12x50x3 tbv Dorack			No	No	No	
346183	Bout M12x150 DIN 931 8.8 Zn		Yes				
361416	Stangkop 648.5-12-M12-WH	Yes					
553174-88	Tussenring tbv Dorack			Yes			
553175-88	Bus tbv Dorack			Yes			
237715	Cyanoacrylaatlijm CA1500V					Yes	

This ultimately leads to the following 122 parts that need to remain separate:

- 2x frame (posts+rungs) + 'arreteerblok' + bracket
- 8x small wheels
- 8x axles for small wheels
- 4x large wheels
- 4x leg + clevis
- 4x rubber foot for leg
- 4x strips for legs
- 2x hinge + clamping plate
- 2x clamping handle
- 2x bushing + ring + rod + rod end
- 2x bushing + ring + rod + other rod
- 4x spacer ring + mounting ring
- 1x uprights + rolling base frame + handgrip + latch supports
- 2x wheel covers
- 2x rolling base arm
- 2x axle rolling base arm
- 4x adjustment ring + nylon ring
- 5x long axle
- 4x short axle
- 4x long links + nylon rings + adjustment rings
- 2x short links + nylon rings + adjustment rings
- 1x lever + rod
- 1x lever
- 1x decoupling lever + rod
- 1x decoupling lever
- 1x push/pull rod + clevis
- 2x coupling lever
- 2x front plate
- 4x rubber plates rolling base
- 2x cover plate
- 2x frame support + guide plate + spindle nut
- 4x sliding blocks
- 2x spindle + small gear
- 1x large gear + shaft
- 1x large gear
- 1x middle frame + strips
- 4x sliding bearings
- 2x thrust bearings
- 2x ball bearings
- 4x knob + spacer + locking pawl + spring
- 4x holding pawl
- 4x side plate latch
- 4x blocking pawl + spring

Appendix IX: Time standards

The time standards below are based on the work of Zandin (1980). One time measurement unit (TMU) is equal to 0.036 seconds.

Screwing fastener by handtool

Getting fastener	Placing fastener	Using tool (9 turns)	Return to starting position	Total
$A_1B_0G_1$	$A_1B_0P_3$	F_{16}	A_1B_0	220 TMU = 8s

A screw with 9 turns is assumed, grabbing and laying aside the tool is disregarded.

Screwing fastener using power tool

Getting fastener	Placing fastener	Using tool	Return to starting position	Total
$A_1B_0G_1$	$A_1B_0P_3$	F_3	A_1B_0	100 TMU = 3.6s

This goes for standard fasteners of up to m6, for larger fasteners, the F subscript should be 6.

Screwing fastener by hand, followed by a power tool

Getting fastener	Placing fastener	Using hand (3 turns)	Grabbing and placing tool	Using tool	Return to starting position	Total
$A_1B_0G_1$	$A_1B_0P_3$	F_6	$A_1B_0G_1P_3$	F_3	A_1B_0	210 TMU = 7.6s

Riveting

Getting rivet	Placing rivet	Using tool	Return to starting position	Total
$A_1B_0G_1$	$A_1B_0P_1$	F_1	A_1B_0	60 TMU = 2.2s

A placement index of 1 is used, as rivets generally fit loosely into their hole. A fastening index of 1 is used because riveting is quicker than screwing, and both are using a power tool.

Small part handling

Getting part	Placing part	Return to starting position	Total
$A_1B_0G_1$	$A_1B_0P_3$	A_1B_0	70TMU = 2.5s

Sliding rod comparison

Current	**Indices**	**TMU's**
Grabbing bolt	$A_1B_0G_1$	20
Grabbing rod	$A_1B_0G_1$	20
Placing bolt through rod	$A_1B_0P_1$	20
Grabbing ring	$A_1B_0G_1$	20
Placing ring on bolt	$A_1B_0P_1$	20
Grabbing bushing	$A_1B_0G_1$	20
Placing bushing on rod	$A_1B_0P_1$	20

Grabbing rod end	$A_1B_0G_1$	20
Placing and screwing rod end	$A_1B_0P_3F_{10}$	140
Total		300
Proposed		
Grabbing bolt	$A_1B_0G_1$	20
Grabbing rod-ring-bushing combination	$A_1B_0G_1$	20
Placing rod-ring-bushing combination on bolt	$A_1B_0P_1$	20
Grabbing rod end	$A_1B_0G_1$	20
Placing and screwing rod end	$A_1B_0P_3F_{10}$	140
Total		220

Set screw in groove nut legs

	Indices	**TMU's**
Grabbing set screw	$A_1B_0G_1$	20
Grabbing loctite	$A_1B_0G_1$	20
Applying Loctite	$M_1X_3I_1$	50
Putting away loctite	A_1B_0	10
Placing and screwing set screw	$A_1B_0P_3F_{10}$	140
Total		240

Appendix X: Discontinued ideas

This appendix lists all ideas that were developed but discontinued in some phase of the project.

Solid foundation

Holes for rungs

The holes in the posts for the rungs are often a fraction too narrow, mainly for the posts in the centre, through which the rungs need to pass a long section. This means that during assembly, they need to be enlarged again using a drill. This can be avoided by making the holes bigger on the technical drawings. An alternative is to make the rungs a smaller diameter. This idea was not presented as it would be more complex than enlarging the holes. It has been measured that these holes can be enlarged to 35.8mm. Enlarging these holes a little bit more likely will not lead to many problems because all rungs are also fixated with a long screw. The rungs themselves are designed at 35.6mm.

Estimated win per Dorack: 60*Xs = X min. Decision: discontinue, because the problem is not as prevalent as thought.

Consequence if implemented: changes need to be communicated to supplier.

Hole in wheel covers

The wheel covers have one hole that is not pre-drilled and has to be drilled during assembly. Letting this hole be drilled during production saves time in assembly. In an earlier revision, this step was taken out because the supplier was not always able to drill the hole in the correct position.

Estimated win per Dorack: X min. Decision: discontinue, as the problem is caused by the production process of the supplier which cannot be changed.

Consequence if implemented: changes need to be communicated to supplier.

Slot in sliding block

The slot in the sliding block is a little bit too wide. The plate it mounts to is 6mm thick, the slot is 6.5mm +- 0.3. This leads to some play in the system. However, this play is necessary for the tolerance on the bending of the plate.

Consequence if implemented: changes need to be communicated to supplier.

Axle hole mechanism housing

The housing for the mechanism has two holes for the axles. One always must be reamed. This is also the one without a dimension and tolerance on the drawing. Including this tolerance on the drawing might resolve the issue. It is reamed to make sure the axle fits exactly. So therefore, it is not really considered a problem.

Assembly drawing

The assembly employees have made a few notes on the physical drawings that have not all been converted to the digital drawings. Adding these changes to the drawings would make the assembly less prone to error.

Decision: discontinue, as the problem lies deeper in the ERP system. Solving this falls outside the scope of this project.

- Bolt 345124 (used in latch support) is not indicated on the main assembly drawing.
- Set screw 344207 is not indicated on the main assembly drawing.
- The correct placement of the RH and LH spindle is not clearly indicated.

- The extra drawing of the rolling frame misses an annotation that 10 and 8 adjustment rings respectively are used.

Major changes

Redesigns of parts

Rolling base

The rolling base accounts for 20% of the costs of the Dorack. It contains 171 unique parts and takes around X minutes to assemble. For a part that has the only function of rising, lowering, and rolling the product it takes up quite a large section of the costs. Therefore, the idea arose to reconsider its design.

One option is to take inspiration from the jumping boxes or movable frames for the Dorack that Nijha also produces, and which perform a similar function but in a simpler way. A second option is to use a 'pumping' mechanism to incrementally increase the height of the frame, like can be found in a car jack. A third option is to use a spindle-operated jack system. These last two options can either be implemented at both sides of the frame or in the centre. A last option is to create a different push-pull mechanism than the one currently used.

Estimated win per Dorack: maximum saving of €X + X min assembly.

Decision: discontinue for now because the other ideas have more priority and are easier to implement. Creating a new design for the rolling base that fulfils all the requirements, mainly in terms of operability and safety would be too complex for this project.

Base plate rolling base frame

A notch can be made in the base plate of the rolling base frame, so the wheel covers can be mounted using a rivet instead of a bolt. An alternative is to make the ring (131572) on the frame a little bit larger so the rivet can go through that. Estimated win: quicker assembly (8*Xs=Xs). Mounting the wheel covers with rivets is not practical from a maintenance perspective. Therefore, this idea should be discontinued.

Pawl 544179

For ease of assembling the springs, pawl 544179 can be designed with an extra pin, just like pawl 544185.

Estimated win per Dorack: easier assembly, higher reliability. Decision: not necessary, discontinue.

Combining parts

Set screw and groove nut in legs

The supporting legs each contain a set screw that connects the clevis to a specially manufactured grooved nut in the leg. The set screw could become part of the nut.

Estimated win per Dorack: €X & Xs assembly time. Decision: this will become too expensive and will save too little. So, discontinue.

Latch knob and spacer

The knob to control the latches is currently assembled with a spacer, removing this spacer would eliminate one step in the assembly process.

Estimated win per Dorack: 4*Xs = Xs. Decision: discontinue, not worth it.

Side notch and mechanism housing

The notch on the side of the mechanism housing might be integrated with the mechanism housing.

Estimated win per Dorack: two fewer welding operations. Decision: will not be strong enough so discontinue.

Changes to (order of) process operations

Not coating certain parts

Frame supports 553181-86 and 603176-86 are coated. Likely because 603176-86 is partially produced in-house. Outsourcing this would also mean it can be zinc plated externally, which would make the parts cheaper. For the sake of aesthetics, both parts need to have the same surface treatment.

Estimated win per Dorack: €X. Decision: discontinue because of aesthetics and potential sharp edges.

Tapping and reaming

Doing all tapping and reaming operations at once instead of multiple times throughout the assembly process might save some minutes in changing tools.

Estimated win per Dorack: X minutes. Decision: would be too complex, so discontinue.

Sorting rungs in one order

Currently, the rungs are not sorted together in one set. Instead, they are all separate orders. Putting them in one order would save some money.

Decision: this is a good idea, but maybe not for this project.

Blowing away drilling chips

The chips that are created during drilling are blown away regularly. This takes up quite a bit of time (about 10-15%).

Estimated win per Dorack: €X

Consequence if implemented: drilling employees need to change way of working.

Tapping after coating

During the assembly phase, it occurs often that parts are tapped again. As these parts are also tapped before coating, this means that the same operation is done twice. Tapping these parts only after coating would decrease the processing time.

Decision: would become too complex so discontinue.

Anodizing rungs

The rungs are currently anodized at the supplier, and then coated again at Nijha. One of these is unnecessary. Either the rungs can be shipped to Nijha untreated or they can be anodized in the right colour immediately.

Expected win per Dorack: €X. Decision: rungs are not anodized at the supplier, by coating them they get the right amount of grip. Besides, anodizing means the rungs are more sensitive to scratches. Therefore discontinue.

Assembly table

The latches are relatively complex subassemblies, consisting of 16 individual parts and costing approximately X minutes in assembly time. Because a series of X Doracks requires X latches, they are assembled somewhat repetitively. By using an assembly table like the one described by Lotter and Wiendahl (2009) for this the process can be made quicker.

Decision: the production quantities are too small to implement something like this. So, discontinue.

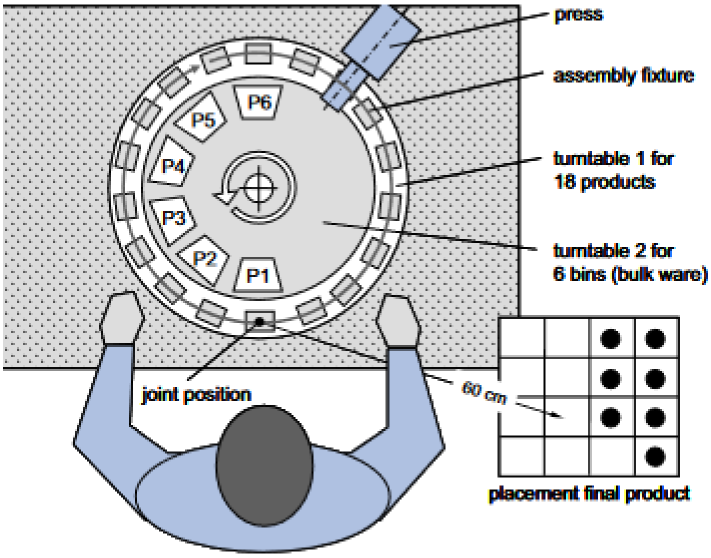


Figure 80: Assembly table (Lotter & Wiendahl, 2009)

Outsourcing

Leg hinge 603141 consists of two laser-cut and bent parts that are welded in-house. Letting the supplier weld these parts might save some money. If the supplier can also coat the part, that would save operations at Nijha.

Estimated win per Dorack: €X. Decision: discontinue, an alternative is to increase the batch size of the part.

Purchasing laser-cutter

Approximately 70 parts of the Dorack are laser-cut by external suppliers. Doing this in-house might save some money, although it would require a large investment. Also, the laser-cut parts would still need to be zinc plated at an external company.

Decision: this idea needs more investigation before a choice can be made. It falls outside the scope of this project.

Minor changes

Different suppliers

The gears and spindles are currently custom-made, which makes them expensive. Replacing them by standardized parts or asking a different supplier for a quotation may open up an opportunity for cost saving. Besides this, the gears may be made of polyketone instead of POM with a metal ring.

Estimated win per Dorack: max. €X. Decision: the spindles are already produced at a company that can make them for a low price and other suppliers are not available. Therefore discontinue. A different material for the gears can be researched.

Different (varieties of) parts

Rivets instead of bolts

Flange plate: currently, the flange plate (553166) attaches to the rolling base frame using two bolts, which screw into riveting nuts. If regular rivets are used for this, assembly will be quicker and riveting nuts are not required in this location.

Estimated win per Dorack: no nut riveting (Xs) and bolt screwing (4*X=Xs), only regular rivets 4 times. 4*(X) =€X. Decision: riveting would make these difficult to disassemble for maintenance, therefore discontinue.

Latch support cover: the cover for the latch support (553077) is currently screwed in place. This can be a rivet.

Estimated win per Dorack: quicker assembly (4*X=Xs). 4*X=€X. Decision: same as above, discontinue.

Wheel covers: the wheel covers are now attached using bolts. Using rivets here would be quicker.

Estimated win per Dorack: quicker assembly (10*X=Xs). 2*(X+X) +8*X-10*X=€X. Decision: same as above, discontinue.

Alternative materials for parts

Stainless to zinc plated steel

Bracket 603142 is now made of stainless steel. If this could be made from zinc plated steel, it will likely be cheaper. This needs to be researched. A disadvantage of zinc plating is that it is more prone to scratching. In case it is zinc plated, it will likely be cheaper to also let the part be produced at the same company as the zinc plating company.

Estimated win per Dorack: €X. Decision: zinc plated steel is more prone to damage and because this part is subjected to a lot of movement, the idea should be discontinued.

Locking pawl

The locking pawls are currently 3D printed from PLA filament. Previously, they were casted, but the supplier was not able to supply anymore. As 3D printed PLA does not look professional and this part is used a lot, a need to create a more permanent solution arises. These pawls sometimes also malfunction.

Machining these parts has been considered already but was deemed too expensive. The new idea is to investigate if the parts can be 3D printed from metal. Powder metallurgy is another option.

Estimated win: more professional and durable. Decision: would be interesting but is not urgent.

Links 553062, 553064

The links are currently made of zinc plated steel and combined with plastic washers for smooth rotation. If the parts can be made from nylon with equal strength, the washers are no longer required.

Estimated win per Dorack: quicker assembly (25s), cheaper material. Decision: assembly would be easier, ask for quotation. However, this idea is not feasible because it would not fit on the side of the pedals. Making it fit would require altering the coupling lever and adding extra washers.

Wishes

Sustainability

Recycled plastic

The wheel covers can be made from recycled plastic.

The rungs might also be made from recycled plastic, in which case they can be made from extruded plastic. This removes the need for the grooved nuts but will likely add a need for screw thread inserts.

Stability of racks

Legs

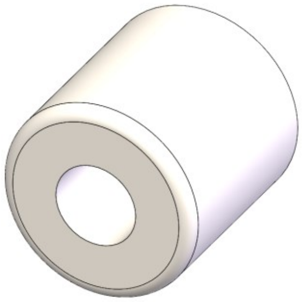
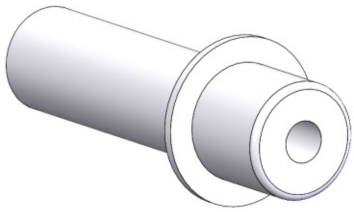
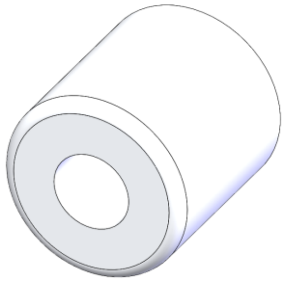
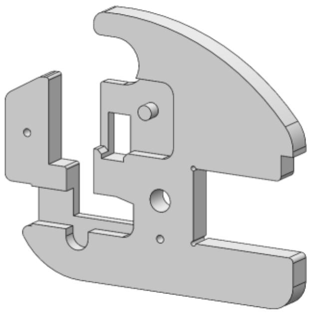
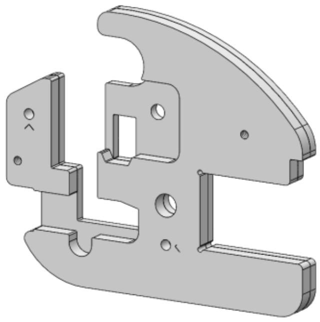
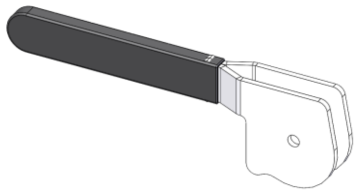
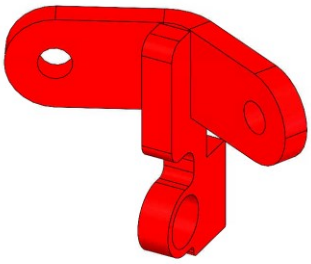
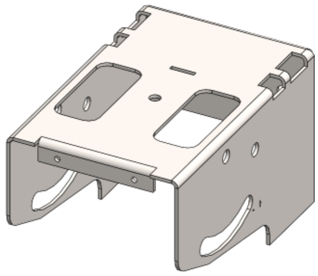
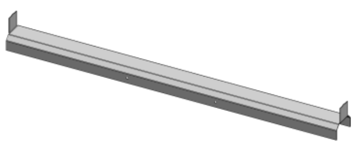
The climbing racks are stabilized by two legs each. The mechanism with which these are fixated is quite expensive and not very stable. A wish is to improve this stability arises.

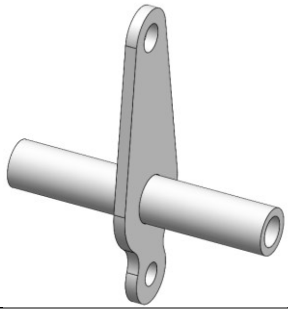
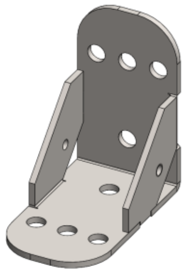
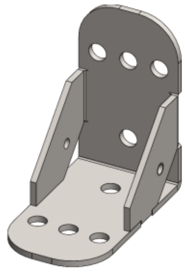
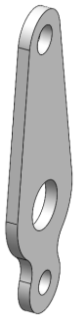
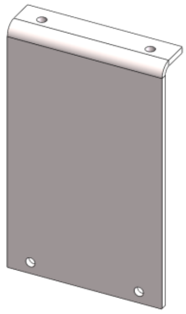
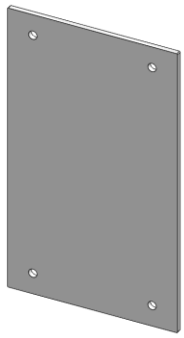
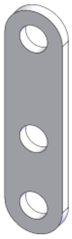
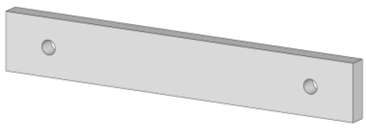
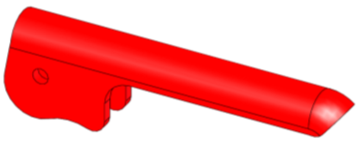
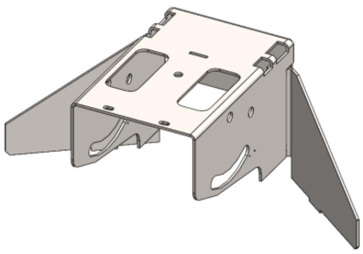
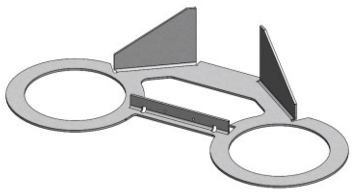
One solution could be to adjust the height of the legs using a small crank, which can be detachable and stored near the large crank.

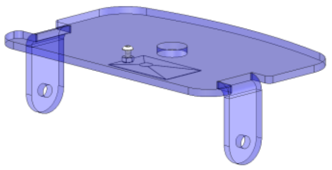
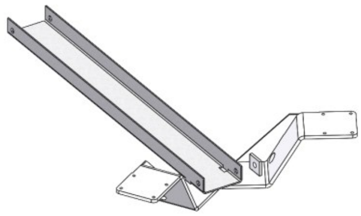
Another idea is to make the legs come out of the side of the posts.

Appendix XI: CAD models

Table 18: CAD models of prototypes

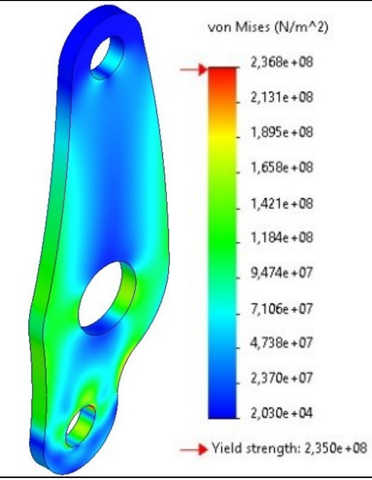
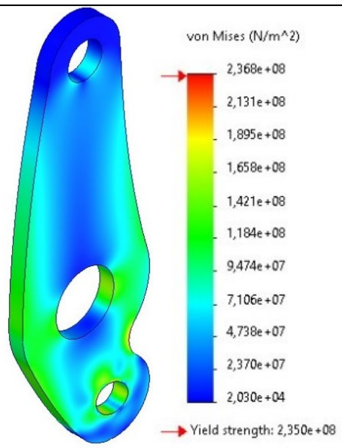
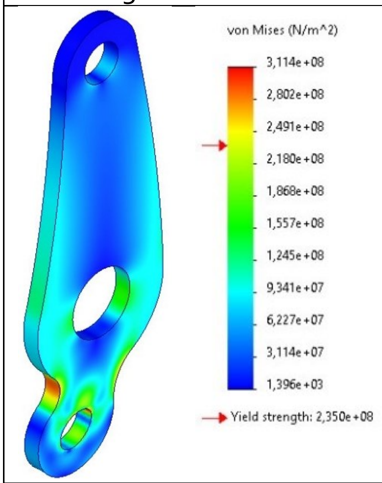
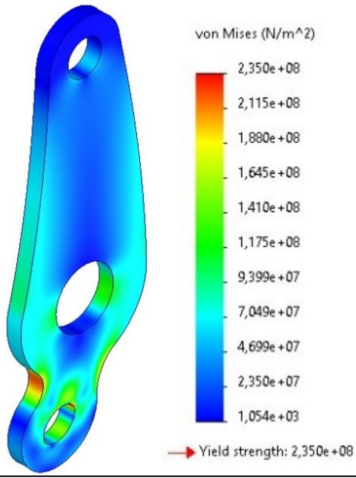
		
Straight bushing nylon	Combination bushing, ring, rod	Straight bushing metal
Rechte bus nylon	Combinatie bus, ring, staf	Rechte bus metaal
		
Latch housing with integrated pin and chamfer	Latch housing plates	Clamping handle two plates
Grendelhuis met geïntegreerde pin en afschuining	Grendelhuis platen	Handvat twee platen
		
Leg hinge	Mechanism housing with strip front plate	Rolling base frame beam and reinforcement plate
Scharnier schoren	Bedieningshuis met strip voorplaat	Balk verrol met verstevigingsplaat

		
Symmetrical plate lever	Latch support trans symmetry	Latch support cis symmetry
Koppelhefboom symmetrisch	Grendelsteun trans symmetrisch	Grendelsteun cis symmetrisch
		
Coupling lever symmetrical plate	Front plate bent	Front plate straight
Koppelhefboom plaat symmetrisch	Voorplaat gezet	Voorplaat breed
		
Universal link	Middle frame strips	Short axle
Universele schalm	Strips tussenframe	Korte as
		
Clamping handle bent	Mechanism housing with triangular plates	Base plate with strip + triangular plates
Handvat gebogen	Bedieningshuis met schoorplaten	Bodemplaat met strip + schoorplaten

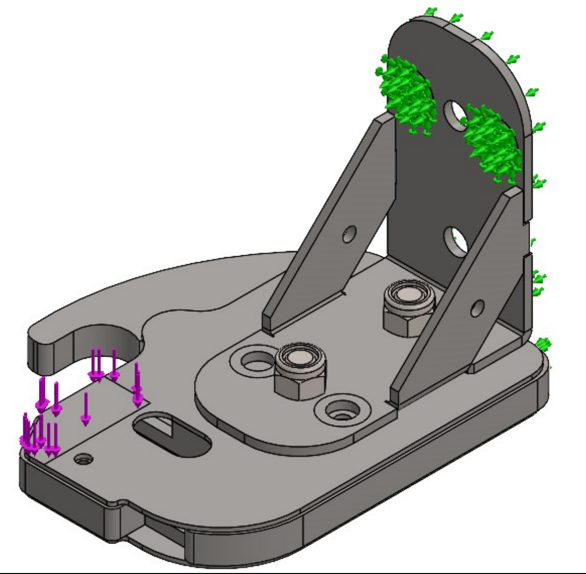
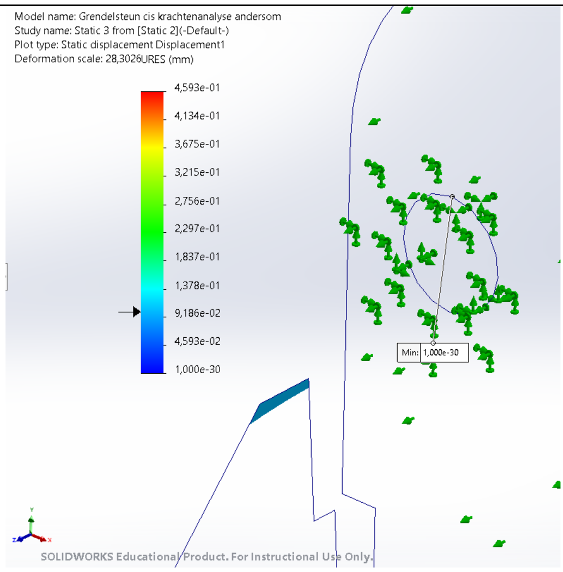
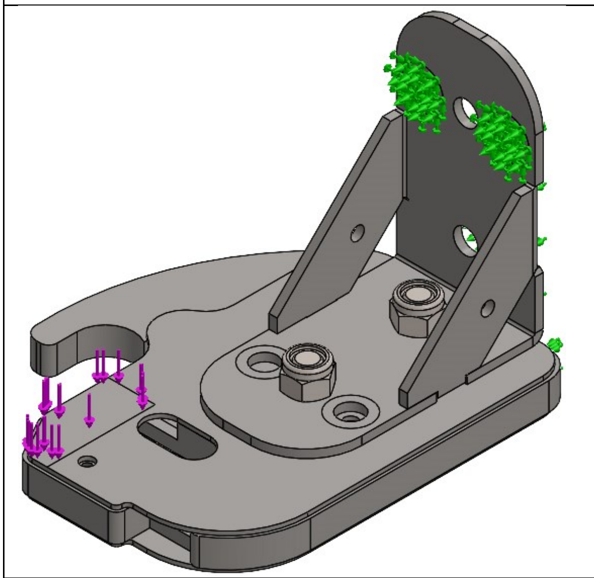
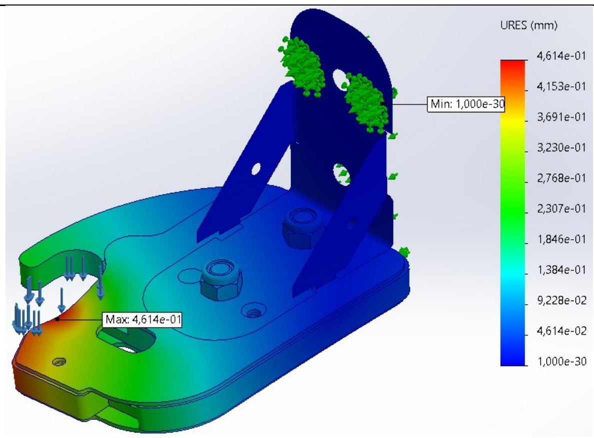
		
Upright cover with clicker	Frame support hex nuts	Rolling base arm
Afdekplaat met klikker	Reksteun zeskantsmoeren	Verrol arm

Appendix XII: Simulation results

Coupling lever

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Current design</td><td>Current design</td></tr>
<tr><td>Material: S235JR, F=5.4kN (to the left). Holes as fixed hinges.</td><td>Material: S235JR, F=5.4kN (to the right). Holes as fixed hinges.</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Symmetric design</td><td>Symmetric design</td></tr>
<tr><td>Material: S235JR, F=5.4kN. Holes as fixed hinges.</td><td>Material: S235JR, F=4.075 kN. Holes as fixed hinges.</td></tr>
</table>

Latch supports

<table>
<tr><td></td><td>
</td></tr>
<tr><td>Cis, openings towards vertical plate</td><td></td></tr>
<tr><td>1.0037 (S235JR)
F = 1332N
All interactions ‘bonded’
Max. displacement at connection 0.10mm
All stresses below yield strength.
Some stress singularities in bottom of the latch</td><td></td></tr>
<tr><td></td><td>
</td></tr>
<tr><td>Cis, openings towards hotizontal plate</td><td></td></tr>
<tr><td>1.0037 (S235JR)
F = 1332N
All interactions ‘bonded’
Max. displacement at connection 0.46mm
All stresses below yield strength.
Some stress singularities in bottom of the latch</td><td></td></tr>
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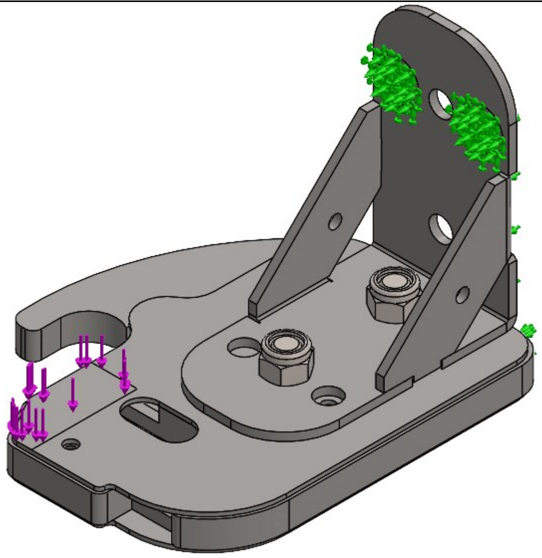
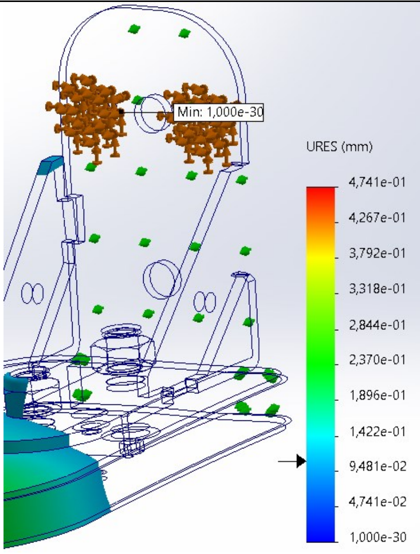
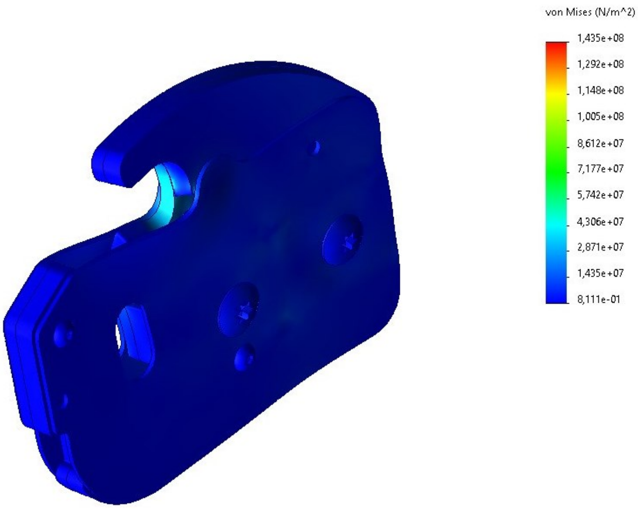
	
1.0037 (S235JR) F = 1332N All interactions 'bonded' Max. displacement at connection 0.11mm All stresses below yield strength. Some stress singularities in bottom of the latch	

Latch consisting of plates

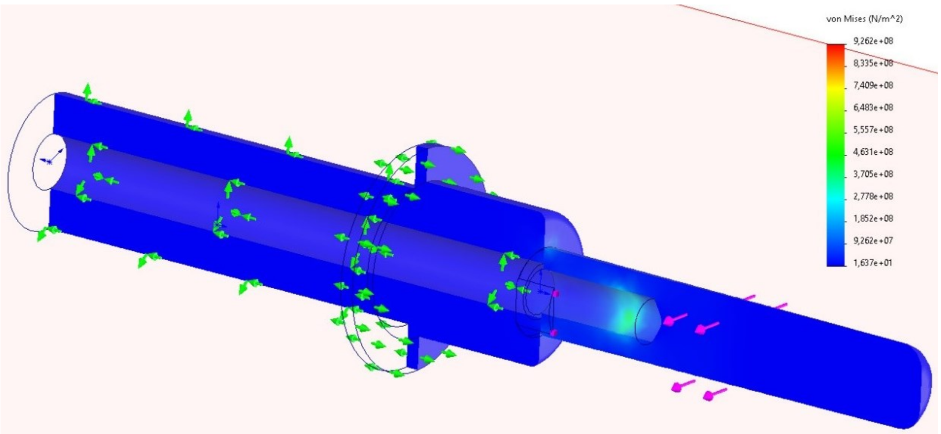
An assembly of the latch consisting of plates with the screws that hold it together was analysed. In the 'roof' position, the climbing frames have a load bearing capacity of 388kg distributed over the frame. Adding the mass of 39.8 kg of the frame itself and including the dynamic and safety factors used in EN:1236 yields the frame should be capable of withstanding forces of: (388+39.8)*10*1.5*1.2=7704N. This is then assumed to be distributed evenly over the supports at the top and the wheels at the bottom. The load at the top is then again distributed evenly over the left and right support. This means each support should withstand 7704/4=1926N

The stresses remained far below the yield stress of the material. The displacements were in micrometers, so the design is sufficiently strong.



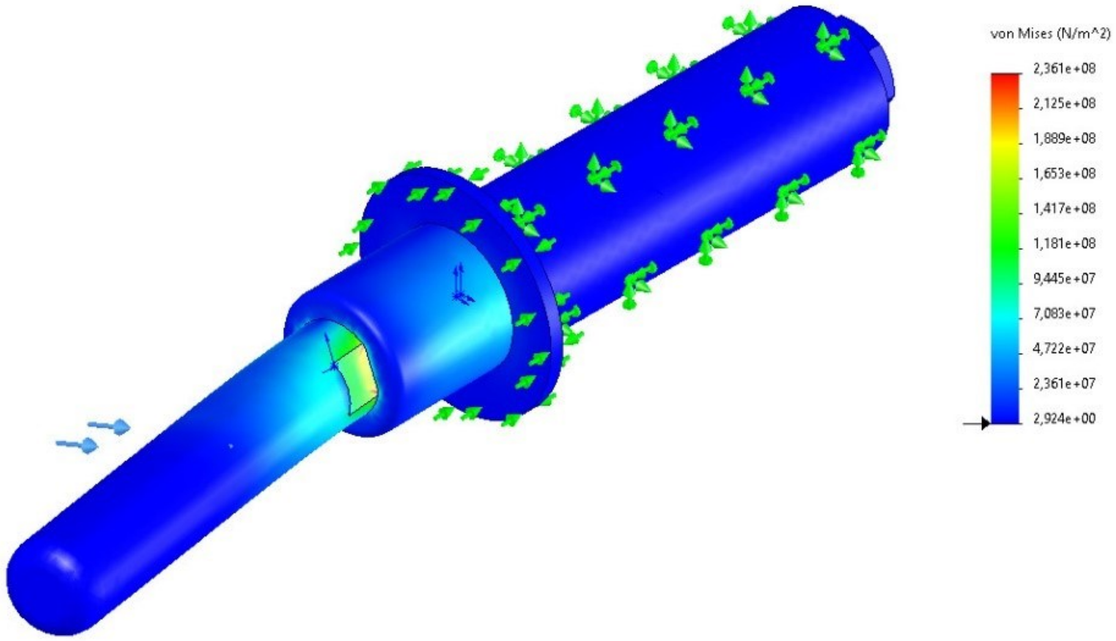
Combined bushing, ring, rod

The material for the new part was taken as PA type 6 and the other parts kept their allocated materials. The same force as for the latch was exerted only on the part that comes in contact with the latch. The stresses in the PA6 part do not exceed its yield strength. The stresses in the steel part do exceed its yield strength and are not stress singularities. The displacement is 2.0mm which is somewhat large.



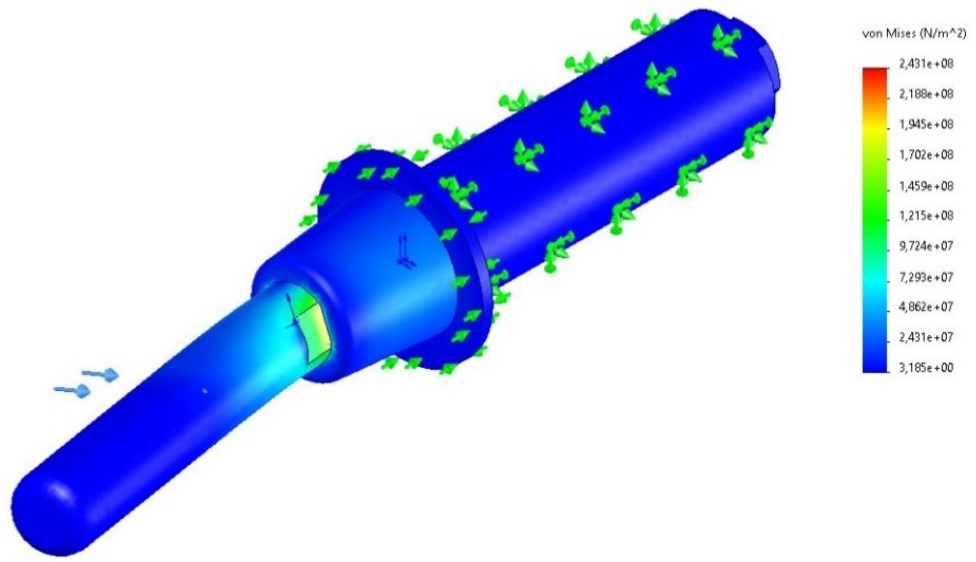
Straight bushing, ring, and rod

The idea of the straight bushing was simulated under the same load case as the combined bushing, ring, and rod. The maximum stress was 236.1 MPa, which is slightly above the yield stress of S235. However, this stress occurred only in a very small part of the model that was barely visible. It was no hot spot. The deformation was 0.22mm.



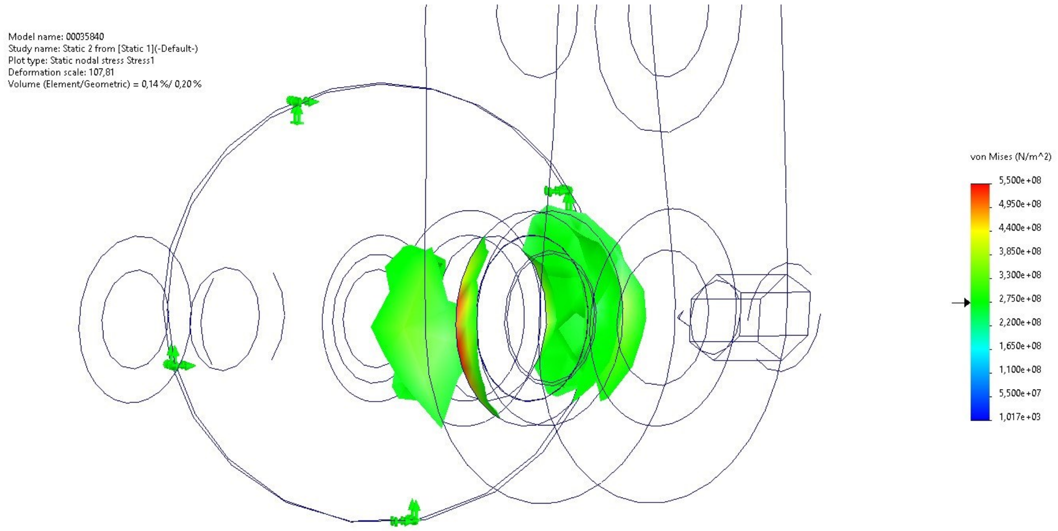
Current bushing, ring, and rod

Because the stress values for both new designs exceeded the yield stress of S235, a simulation of the current design was performed to verify if it would be strong enough. This analysis showed that also the current design exceeds the yield stress at one point, but only slightly and practically invisible.



Bracket

For the idea where the bracket is attached to the post using riveting nuts, a simulation was performed to find the force at which the first part would reach its yield strength. After an iterative process, the post was found to be the first to reach its yield stress, at a force of 700N. To verify how this relates to the current design, another simulation was performed where the same force was exerted on the current design. This showed that no part reached its yield stress. To find the first point of failure, an iterative process was again followed to find the force at which the first part would reach its yield strength. This turned out to be the bracket, which reached this point at a force of 1230N. The conclusion that can be drawn from this is that the new design is 43% weaker than the current design. The practical tests will have to show whether this is true.



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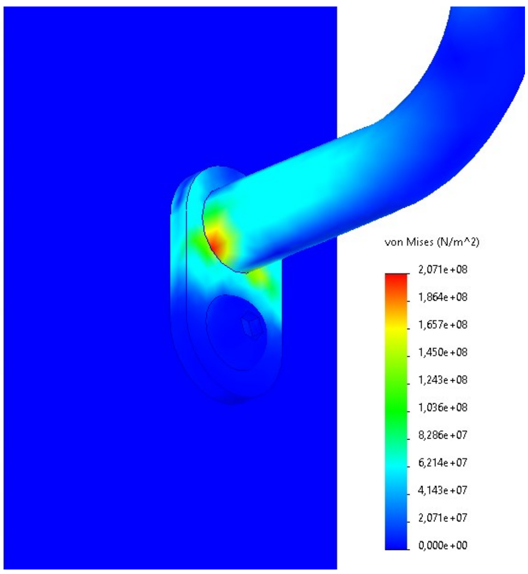
Study name: Static 2 from [Static 1](-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 107,81
Volume (Element/Geometric) = 0,14 %/ 0,20 %
von Mises (N/m^2)
5,500e+08
4,950e+08
4,400e+08
3,850e+08
3,300e+08
2,750e+08
2,200e+08
1,650e+08
1,100e+08
5,500e+07
1,017e+03

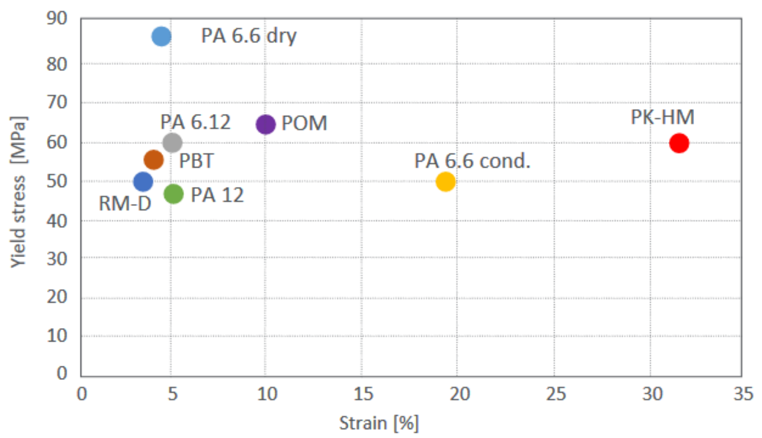


von Mises (N/m^2)
2,071e+08
1,864e+08
1,657e+08
1,450e+08
1,243e+08
1,036e+08
8,286e+07
6,214e+07
4,143e+07
2,071e+07
0,000e+00

Appendix XIII: Datasheets

Polyketone PK-HM GF 30

Typical values for natural color material at 23° C	Test specification	Test method	PK-HM GF 30 (4709)	
Mechanical properties			d.a.m.	cond.
Tensile modulus	1 mm/min	ISO 527-1/2	7,500	7,100
Yield stress[1]/Tensile stress at break	5 mm/min	ISO 527-1/2	/130	/120
Elongation at break	5 mm/min	ISO 527-1/2	3	3
Flexural modulus	2 mm/min	ISO 178	8,300	
Flexural stress	2 mm/min	ISO 178	180	
Charpy impact strength	23 °C	ISO 179-1/1eU	60	50
Charpy impact strength	-30 °C	ISO 179-1/1eU	60	
Charpy notched impact strength	23 °C	ISO 179-1/1eA	15	15
Charpy-notched impact strength	-30 °C	ISO 179-1/1eA	10	
Elektrical properties				
Spec. volume resistance		IEC 60093	10^{13}	10^{10}
Spec. surface resistance		IEC 60093	10^{12}	10^{10}
Thermical properties			d.a.m.	
Melting point	DSC, 10 K/min	ISO 11357-1/3	220	
Heat distortion temperature, HDT/A	1.8 MPa	ISO 75-2	215	
Heat distortion temperature, HDT/B	0.45 MPa	ISO 75-2	220	
Flammability				
Flammability acc.UL 94	1.6 mm	UL 94	HB	
Rate acc. FMVSS 302 (<100 mm/min)	> 1 mm thickness	FMVSS 302	+	
GWFI	2 mm	IEC 60695-12		
General Properties				
Density	23 °C	ISO 1183	1.48	
Content reinforcement		ISO 1172	30	
Moisture absorption	70 °C/62 % r.h.	ISO 1110	0.6 – 0.7	
Processing				
Flowability	Flow spiral[2]	AKRO	350	
Processing shrinkage, flow		ISO 294-4	0.7	
Processing shrinkage, transverse		ISO 294-4	1.3	



source: AKRO-PLASTIC GmbH (2014)

HOSTAFORM® C 9021 (Polyacetal, POM)

Tensile modulus	2850	MPa
Tensile stress at yield, 50mm/min	64	MPa
Tensile strain at yield, 50mm/min	9	%
Nominal strain at break	30	%
Flexural modulus	2700	MPa
Flexural strength	89	MPa
Flexural stress at 3.5%	72	MPa
Compressive stress at 1% strain	24	MPa
Tensile creep modulus, 1h	2500	MPa
Tensile creep modulus, 1000h	1300	MPa
Charpy impact strength, 73°F	220[P]	kJ/m^2
Charpy impact strength, -22°F	220	kJ/m^2
Charpy notched impact strength, 73°F	6.5	kJ/m^2
Charpy notched impact strength, -22°F	6	kJ/m^2
Ball indentation hardness, H 358/30	144	MPa
Melting temperature, 18°F/min	166	°C
Temperature of deflection under load, 260 psi	104	°C
Temperature of deflection under load, 65 psi	160	°C
Coefficient of linear thermal expansion (CLTE), parallel	110	E-6/K
Coefficient of linear thermal expansion (CLTE), normal	110	E-6/K
Thermal conductivity of melt	0.155	W/(m K)
Effective thermal diffusivity, flow	4.85E-8	m^2/s
Specific heat capacity of melt	2210	J/(kg K)
Humidity absorption, 80mil	0.2	%
Water absorption, 80mil	0.65	%
Density	1410	kg/m^3

Source: Celanese (2024)

Mädler gears

Product No. Polyacetal	Product No. Polyketone	Module	Number of teeth	d_a mm	d mm	ND mm	NL mm	L_1 mm	L mm	S mm	b mm	B mm	E mm	Torque* [Ncm] Polyacetal	Torque* [Ncm] Polycetone	Weight [g] Polyacetal	Weight [g] Polycetone
356 156 00	356 156 01	2,5	15	42	37,5	26,5	13	29,6	31,2	16,4	17,3	12	53,3	209	220	23,6	21,2
356 157 00	356 157 01	2,5	30	77,3	75	36,1	15	27,5	29,5	22,8	17,3	16	40,5	418	439	77,0	69,1

Source: Mädler GmbH (2024, p. 317)

Appendix XIV: Zinc plating statistics

This information is considered confidential and is therefore omitted from the public version of this thesis.

Appendix XV: Zinc plated parts

Art.nr.	Description	Mass per piece (kg)	Quantity plated for prototype	Price zinc plating only (€)	Price zinc plating + transportation and handling (€)
553184	Cover plate				
603149	Latch support				
553077	Latch support cover				
553051	Strips middle frame				
551046	Clamping plate				
	Clamping handle plates				
603147	Arm rolling base				
603148	Coupling lever				
	Front plate rolling base				
	Latch housing 6mm part 1				
	Latch housing 6mm part 2				
	Latch housing 4mm				
553070	Latch pawl				
551050	Mounting ring				
553174	Spacer ring				
	Frame bushing				

Appendix XVI: Evaluation questions

Productie

Art.nr.	Omschrijving	Vraag	Antwoord
00035649	Scharnierplaat aangepast_2	Is de plaat even makkelijk aan het scharnier te lassen als de bestaande?	Ja levert geen problemen op
	Bodemplaat met strip en schoorplaat	Past het geheel goed in de rest van het frame?	Ja geen problemen, vinden het een mooie verbetering
00035658	Tussenbalk verrol met verstevigingsplaa t	Past de verstevigingsplaat goed in de uitsparing in het bedieningshuis?	Ja, de vraag is alleen hoe hard hij nodig is.
	Frame verrol	Leiden de aanpassingen tot een verkorting van de lastijd?	In totaal Xu mee bezig geweest. Xu lassen, X min handling.
	Frame verrol	Hoe lang duurt het lassen van het frame nu? Ook de overige handelingen hierbij meegenomen.	Xu
	Frame verrol	Is het frame nog voldoende sterk met de aanpassingen?	Ja, geen merkbare veranderingen
	Houten sporten voor rek	Hoe lang duurt het om de sporten te produceren?	X min zagen, X voorboren middenframe, X voorboren kopse kanten klimrek. X voorboren en schroeven dwarsverbinding.
	Koppelstuk	Wat is de diameter van de staaf voor verzinken? Wat is de diameter van de staaf na verzinken/voor assemblage?	15,07 tot 15,05 voor 14,99 tot 14,96 na
00035805	Reksteun met gelaste moer	Is de moer goed aan de reksteun te lassen?	Ja, geen merkbare verandering.

Assemblage

Art.nr.	Omschrijving	Vraag	Antwoord
00035653	Bedieningshuis met grotere gaten en stripje voorplaat	Wat is de diameter van de gaten na coaten? Passen de klinkmoeren nu beter in de behuizing?	10,0 Ja
00035775	Popnagels wielen	Levert het popnagelen een merkbare verbetering	Tappen is niet meer nodig, maar nu wel ombouwen popnageltang. Als er een speciale voor zou komen is dat probleem opgelost. Want andere popnagels zijn wel 5mm.

Art.nr.	Omschrijving	Vraag	Antwoord
		op in de assemblagetijd? Hoe lang duurt het popnagelen?	X minuten in proto.
	Verrol arm	Zijn er merkbare verschillen met de intern geproduceerde verrol arm?	Tolerantie op de breedte van het u profiel.
	Draadstang verrol	Heeft de stang de juiste lengte of moet hij worden ingekort?	Draadstang moet 1cm in gaffel doorsteken om te passen. Verrol komt niet over zijn dode punt heen en valt dus naar beneden bij lichte trilling. Oplossingen: Draadstang korter, positie assen veranderen, positie nok verrol arm veranderen, positie draaipunt assen veranderen. In proto nu 2cm van stang afgezaagd.
00035653	Bedieningshuis met grotere gaten en stripje voorplaat	Levert het popnagelen een merkbare verbetering op in de assemblagetijd? Hoe lang duurt het popnagelen van de voorplaat?	X minuten, maar moeilijk te zeggen hoe snel het in de praktijk van serieproductie zal gaan.
312306	Popnagels voorplaat verrol	Zijn deze popnagels sterk genoeg?	Sterkte moeilijk te zeggen maar lijkt wel zo Sleufgaten bovenin voorplaat maken
312306	Popnagels voorplaat verrol	Passen de popnagels goed?	Een gat moest iets uitgeboord, in vervolg wellicht sleufgat of grotere diameter bovenaan.
553051	Moerplaten	Moeten de moerplaten nog worden nagetapt, of is de draad goed?	Draad is goed van 1 kant, dus functioneel. Van andere kant nog een braam
00035680	Grendelhuis geïntegreerde pin	Past de grendelpal goed over de pin?	Ja, het gat in de pal moet nog iets afgevijld maar dat hou je toch volgens Gerard.
00035680	Grendelhuis geïntegreerde pin	Werkt de afschuining goed voor de veren? En is het van toegevoegde waarde?	Weinig van te merken.
	Grendelhuis met spanbus	Past de spanbus goed in het gat?	Nee, uiteindelijk normale pin gebruikt.
00035685	Grendelhuis platen	Is het assembleren van de platen goed te doen? Hebben de graveringen toegevoegde waarde?	Boutjes 4x12 hadden een flens. Oplossingen: Boutje zonder flens bestellen of gat in grendelsteun vergroten. Lijkt iets stroever te lopen. Gravering is niet te zien. Beter om op tekening aan te geven dat men moet kijken naar de draad.
	Grendelhuis ruimere passing	Past de pin beter in het grendelhuis?	Pin past beter. Valt er wel uit maar is niet erg want wordt toch opgesloten.

Art.nr.	Omschrijving	Vraag	Antwoord
		Valt de pin niet uit het grendelhuis?	
	Koppelstuk	Past het koppelstuk nu beter in de as?	Nee nog steeds niet.
00035706	Flens	Is de popnagel nu makkelijker te plaatsen?	Ja en past ook mooi in de groef van de sport. Daarnaast is de popnagel niet scherp dus levert dit geen probleem op.
	Klikker	Levert het assembleren van de klikker problemen op?	Ja, aanslag zat onder de beugel waardoor beugel eerst klikker raakte en verboog. Als aanslag er boven blijft betekent dat dat de rekken lager eindigen en eventueel over de vloer slepen. Daarnaast is klikker heel kwetsbaar. Een keer te hard doordraaien en hij is gebogen. Uiteindelijk ook niet meer werkend gekregen.
00035726	Handvat platen	Hoe lang duurt het om het handvat te assembleren?	Assemblagetijd was X, maar is niet heel representatief.
	Pasbouten	Is het sleufgat in de kop een obstakel?	Ja, tevens is de draad te kort waardoor de bout net niet in de borging van de dopmoer komt. Minkop is wel echt een nadeel. Dus eventueel alternatieve bouten van Bossard proberen.
	Rek alu sporten + schroeven	Is de uitlijning van de stijlen nog even gemakkelijk?	Nee, veel moeilijker Bijkomend nadeel is dat van de buitenste stijlen nu ook een links en rechts gemaakt moet worden. Schroeven van schoorzijde zitten aan de onderkant. Ondanks scheve stijlen kan combi bus ring staf nog wel vrij draaien. Scheve stijlen evt op te lossen met herontwerpen tafelmal. Met juiste uitstekende lengte van de sporten aangegeven.
	Rek alu sporten + schroeven	Hoeveel tijd kost het om alle schroeven in het rek te draaien?	X
	Rek houten sporten	Hoeveel tijd kost het om alle schroeven in het rek te draaien?	X
	Rek houten sporten	Is de uitlijning van de stijlen nog even gemakkelijk?	Sporten lijken 1mm te kort.
			Ook uitkijken met vieze handen op hout.
			Schroeven met kruiskop het liefste niet, zebra schroeven geprobeerd. Zorgen wel voor meer frictie, begon zelfs te roken. Dus echte houtschroeven zijn beter. Uiteindelijk 345167 gebruikt. Idealiter torx bolkop voor zowel kopse kant als dwarsverbinding.

Art.nr.	Omschrijving	Vraag	Antwoord
			In klimrek houtdraadbout 8x40, opgeboord met 6mm op kopse kant gebruikt. En ringetje ertussen. Richting tov nerf maakt niet uit. Splijt niet.
			Voor dwarse eerst 5x50 (345167) gebruikt, maar barstten toch zonder voorboren. Daarom uiteindelijk toch eerder bedachte 6x65 gebruikt en voorgeboord met 5,5. Kortom, voor productieserie moet gekeken worden naar meest geschikte schroeven voor dwars en kopse kant.
	Combi bus ring staf		Metalen ring functioneerde oorspronkelijk als drukverdeler op plastic. Anders zet het plastic uit wanneer je het te hard klemt Hard klemmen is eigenlijk niet meer nodig want wordt nu met loctite bevestigd.

Functionaliteit

Art.nr.	Omschrijving	Vraag	Antwoord
	Gebogen handvat met nieuw scharnier	Werkt het handvat naar behoren?	Kan iets wiebelen wanneer vastgeklemd. Mag iets meer speling in het glijden krijgen. Tijdens testen bleek dat klemkracht niet genoeg is en het geheel kan schuiven nadat het is vastgeklemd. Eventueel zou met wat aanpassingen getest kunnen worden of het dan beter werkt.
00035726	Handvat 2 platen	Is het handvat rigide genoeg of wiebelt hij? Werkt het handvat naar behoren?	Handvat is zelf nog ietwat flexibel in niet-samengeperste deel (zie video 27-8 14:23). Wiebelt nog wel aan het scharnier. Scharnier zelf wiebelt ook. Na klemmen wel rigide. Kan niet helemaal gesloten worden (zie foto)
00035680	Grendelhuis geïntegreerde pin	Kan de grendelpal nog soepel scharnieren?	Ja
	Grendelhuis spanbus	Kan de grendelpal nog soepel scharnieren?	Nee
553184	Afdekplaatje verzinkt	Is het plaatje bot (niet scherp) genoeg?	Ja, hoewel dit misschien komt doordat het plaatje al getrommeld was.
	Klikker	Is de klik goed hoorbaar/voelbaar?	Heeft niet gewerkt
	Axiaallager	Werkt de lager naar behoren?	Ja, los van het feit dat er eentje de verkeerde diameter had in de afmontage.
	Tandwielen	Zijn de tandwielen sterk genoeg?	Geen problemen gemerkt, maar ook niet heel goed kunnen testen. Eventueel zouden de tandwielen nog apart in een testopstelling kunnen worden getest op hun belastbaarheid.
	Draadstang verrol	Werkt de bediening van de verrol nog zoals bedoeld?	Draadstang lijkt flexibeler dan bestaande.
	Verrol arm	Is de arm zoals die moet zijn?	Geen problemen gemerkt

Art.nr.	Omschrijving	Vraag	Antwoord
	Koppelhefboom	Is de hefboom sterk genoeg?	Geen problemen gemerkt
	Voorplaat verrol	Is de voorplaat sterk/stijf genoeg?	Geen problemen gemerkt
	Tussenring met grotere binnendia	Lopen de ringen nu niet meer vast op elkaar?	Lopen nu goed
	Klinkmoeren RVS beugel	Hoe ver staat de beugel van de stijl af? En is dit een probleem?	0,9mm. Lijkt een probleem te zijn bij krachtig sluiten van de beugel in de grendel. Tevens zou in theorie het boutje eerder los kunnen raken. Ook zou er een veter tussen kunnen blijven haken, maar dit is geen officiële reden voor afkeuren.

Esthetisch

Art.nr.	Omschrijving	Vraag	Antwoord
553184	Afdekplaatje verzinkt	Is het verzinkte plaatje esthetisch acceptabel?	Ja, geen negatieve reacties op gehad.
551050	Montagering verzinkt	Zijn de verzinkte ringen esthetisch acceptabel?	Ja, geen negatieve reacties op gehad.
553175	Rechte bus	Is de rechte bus esthetisch acceptabel?	Ja, geen negatieve reacties op gehad. Wordt mooier bevonden dan de kunststof gecombineerde bus, ring en staf.
	Gecombineerde bus, ring en staf	Is de combinatie esthetisch acceptabel?	Wordt minder mooi bevonden dan de verzinkte bus.
00035805	Reksteun met gelaste moer	Is de gelaste moer esthetisch acceptabel? Besparing per Dorack is €X of 1/14e van de oorspronkelijke prijs.	Enkele punten over of het niet te technisch eruit gaat zien. Sommige mensen vinden het minder mooi, anderen vinden het de besparing wel waard.
53077	Afdekkap grendelsteunen verzinkt	Is de kap esthetisch goed genoeg?	Ja, geen negatieve reacties op gehad.
	Houten sporten	Wat is de reactie op de houten sporten? Totale besparing is €X per Dorack	De meeste reacties zijn positief. Een enkeling is van mening dat het een minder eigentijdse uitstraling heeft.

Praktische tests

Art.nr.	Omschrijving	Vraag	Antwoord
00035649	Scharnierplaat aangepast_2	Is de plaat sterk genoeg voor de krachten die er tijdens bedienen op komen?	Lijkt geen problemen te vertonen.
	Verrol	Is de verrol nog stijf genoeg, na de	Geen problemen gemerkt

		aanpassingen aan het frame?	
312306	Popnagels voorplaat verrol	Zijn deze popnagels sterk genoeg?	Geen problemen gemerkt
00035775	Popnagels wielen	Zijn de popnagels sterk genoeg voor de wielen?	Geen problemen gemerkt
		Blijven de popnagels goed zitten?	Geen problemen gemerkt
00035685	Grendelhuis platen	Is het grendelhuis sterk genoeg?	Geen problemen gemerkt
	Rek alu sporten + schroeven	Is de stijfheid van het rek nog voldoende?	Ja, uit de belastbaarheidstest is gebleken dat het rek geen permanente vervorming vertoont.
	Rek houten sporten	Is de stijfheid van het rek nog voldoende?	Ja, uit de belastbaarheidstest is gebleken dat het rek geen permanente vervorming vertoont. Dit rek is stijver dan dat van de aluminium sporten.
	Grendelsteunen	Zijn de grendelsteunen stijf genoeg? Ook wanneer er kracht op komt? Is er een voorkeur merkbaar voor een van de twee?	Nee, bij belasting vervormen de steunen permanent. Er is verder geen voorkeur te merken voor een van beide.
	Pasbouten	Zijn de pasbouten sterk genoeg?	Lijkt wel zo, alleen komt de schroefdraad niet tot in de borging van de dopmoer.
	Rechte bus	Is de bus en het geheel waar de bus in zit sterk genoeg voor de krachten die erop komen?	Geen problemen gemerkt
	Combi bus, ring,staf	Is het geheel sterk genoeg voor de krachten die erop komen? Kunnen de rekken nog voldoende scharnieren?	Geen problemen gemerkt Scharnieren gaat ook nog soepel.
	RVS beugel met klinkmoeren bevestigd	Is de bevestiging nog stevig genoeg?	Buigt wel door nadat er kracht op is gezet.
	Stangkop	Is de stangkop sterk genoeg?	Geen problemen gemerkt
	Symmetrische koppelhefboom	Is de hefboom sterk genoeg?	Geen problemen gemerkt
	Voorplaat	Is de voorplaat sterk/stijf genoeg?	Geen problemen gemerkt

Appendix XVII: Final advice per concept

Rolling base

- Purchasing rod: To function correctly, the rod should be 1.98m. It was sawed to length for the prototype but an advice to consider the options was given for the future. Besides, the rod was more flexible than the original, which might have been a cause of the fork joint coming loose.
- Alternative sourcing of fork joints: During testing the fork joint came loose, which can be caused either by an inferior quality of the clip, the more flexible rod or another unknown cause. An advice was given to conduct some more tests with the new joints to determine their quality and make a choice based on that.
- Combined beam with reinforcement plate: The beams were more difficult to stack on a pallet. Besides, the reinforcement plate was sensitive to bending during transportation or storage. Because the price difference was only €X and the welding time was not reduced the advice was given not to proceed with this concept.
- Altered mechanism housing: The riveting nuts fit into their holes without requiring reaming. The amount of time and money saved was minimal but because the concept had no drawbacks the advice was to proceed with the concept.
- Altered front plates: The holes of the front plates need to align with those of the mechanism housing and bottom plate in order to fit the rivets. Slotted or enlarged holes can be used to make this alignment more error-proof. The advice was to implement this change and proceed with the concept.
- Combined base plate with triangular plates and strip: The new part was cheaper than the sum of the individual parts it would replace. It was easy to stack, which made it easy to store. The welding time was not reduced noticeably. The advice was to order a first batch to verify the price, tolerances, storage, and welding time.
- Outsourcing arms: The supplier made some alterations to make welding easier, which should also lead to a reduction in welding time if the part were made internally. The u-profile was 2mm too wide. The advice was to include a tolerance on the width of the u-profile and decide on outsourcing the production of the part or implement the changed design and continue welding internally.
- Wheel attachment with rivets: No significant time difference was measured during prototyping. An extra riveting gun will have to be purchased if the concept is proceeded to accommodate for the thicker rivet mandrel. The advice was to consider the pro's and cons of this concept and make a choice based on this.
- Symmetrical coupling lever: The quotation for the part was half the original price, without a significant change in design. The advice was to proceed with this concept.
- Insourcing axles: The axles functioned as required and therefore the advice was to decide on producing all axles either internally or externally, where internal production gets preference for the sake of reliability and cost.

Middle frame

- Altered crank-shaft connector: The connector still did not fit into the shaft. Therefore the advice was to take another look at the fit of the connector and shaft and consider a regular tolerance instead of a specific fit.
- Zinc plating strips: The strips functioned properly and therefore the advice was to proceed with the concept.

- Altered flange: The alteration worked and had no drawbacks. Therefore the advice was to proceed with the concept.
- Polyketone gears: The advice was to consider whether stronger gears are beneficial and test whether the larger gear would still require a metal ring, as well as ask the supplier for a quotation on larger batches of these gears.

Legs

- Zinc plating clamping plate: No drawbacks were found so the advice was to proceed.
- Bent handle: The handle did not clamp strong enough. Therefore the advice was to take another look at the combination of the hinge, spacer ring and handle.
- Handle two plates: This design clamped stronger than the other option. Two drawbacks were it consisted of more parts and it was not parallel to the post. The advice was to make some more prototypes with small changes to the design and choose the best option.
- Alternative shoulder screws: The screws functioned and fit with the aesthetic of the product. However, they were less convenient in assembly due to their slotted head. A more important drawback was that the screw thread did not reach into the locking ring of the nut on the other side. Several alternatives were provided and the advice was given to choose one of these.
- Alternative sourcing fork joints: The fork joints were not tested for the legs, but a quality difference was noticeable in the rolling base. The advice was to let the choice depend on the rolling base.

Latches

- Latch housing consisting of plates: The latch withstood the load test. The engravings were of no added benefit and one of the holes was in an awkward position. It became clear that the tolerance of the positioning of the plates was crucial for the functioning of the locking pawls. It also became clear that the envisioned screws were not available, but only screws with a flange, which meant the latch could not be screwed flush against the latch support. The advice was to order a first batch with said alterations and verify the tolerances, as well as to decide on using different screws or altering the latch support.
- Latch housing with integrated pin and chamfer: The latch functioned but the added benefit was minimal. It is therefore a suitable alternative in case the latch consisting of plates is not proceeded.
- Latch housing with enlarged hole: The latch functioned, with the pin being loose in the housing. Here again, the added benefit was minimal. Therefore this concept too is an alternative in case the latch consisting of plates is not proceeded.
- Latch housing with spring pin: This concept did not work and therefore the advice was not to proceed.
- Zinc plating pawl: The zinc plated pawl still had to be filed and some wear was already visible after testing. Because the cost saving was minimal, the advice was not to proceed with the concept of zinc plating the part. The advice was also to move the laser joint on the technical drawing of the part because that did function well.

Frames

- Wooden rungs: The time taken for sawing and drilling the rungs was recorded but will likely be shorter when the parts are made in larger series. The screws used for the prototype were not ideal regarding assemblability and aesthetics. Another realisation was that the number of aluminium rungs required would be greatly reduced as they would only be needed for the top rungs. All in all several pieces of advice were given. The first was to decide whether it might be worthwhile to order the wooden rungs in the correct length or saw them internally, leading to more waste. The second piece of advice was to decide on which screws to use, based on a list of options provided. The third piece of advice was to decide on what to do with the top rungs.

- Aluminium rungs: It was much more difficult to keep the posts straight when assembling the frames. During testing it became clear that the attachment point of the bracket to the post with riveting nuts bended slightly. This option was less rigid than the option with wooden rungs. Another realisation was that a left and right version would be required for the outer posts as they are not symmetrical and the screws need to be on the inside of the frame. An alternative is to make one frame with screws on the inside and one with screws on the outside for each Dorack.
- Zinc plating mounting ring: No drawbacks were found, therefore the advice was to proceed with this concept.
- Alternative rod ends: The rod ends have withstood the load test and no drawbacks were found. Therefore, the advice was to proceed.
- Zinc plating spacer ring: No drawbacks were found, therefore the advice was to proceed.
- Straight bushing: No drawbacks were found, therefore the advice was to proceed.
- Combined rod, ring, and bushing: The part withstood the load test, but resistance to wear was difficult to determine. This option was considered less aesthetically attractive. The number of time saved was minimal. A benefit is that fewer parts need to be stored. The advice was to decide whether a reduction in parts would compensate for reduced aesthetics and potentially reduced wear resistance.
- Leg-side post: The slotted hole was enlarged from 10.5 to 11.0mm. This led to the hinge fitting much looser in the slot, contributing to the instability of the legs. Besides, the bottom slot would not have needed to become wider. The advice was to either proceed with only 0.1mm increased width or not proceed at all.

Bolts

In general, the domed-head bolts were considered less convenient in assembly than hexagonal bolts.

- Hinge to clamping plate: The hexagonal bolt is also used for the stop of the height adjustment where a flanged bolt cannot be used. The advice was to choose between two options: 1. Use a regular domed bolt (instead of domed with a flange) for the stops of the height adjustment and rolling base pedal, as well as connecting the clamping plate to the hinge. 2. Keep using the hexagonal bolt.
- Stop height adjustment: As mentioned above, the flanged bolt was unpractical because the wrench to tighten the nut of the stop could not reach over the flange. The same advice as above was given.
- Stop rolling base pedal: The envisioned bolt had a flange that did not fit past the strip of the bottom plate. Therefore it was not tested in the prototype. The advice was the same as the two above.
- Spindle nut to guide plate: Changing from a hexagonal to a domed bolt functioned well, therefore the advice was to proceed.
- Gear to spindle: Changing from a hexagonal to a domed bolt functioned well, therefore the advice was to proceed.
- Gear to shaft: Changing from a hexagonal to a domed bolt functioned well, therefore the advice was to proceed.

- Latch support to upright: Changing from a hexagonal to a domed bolt functioned well, therefore the advice was to proceed.

Other concepts

- Clicker on upright cover: This concept did not work out, therefore the advice was to either not proceed with this concept or develop an alternative solution.
- Zinc plating cover plate: In the prototype, the plates were not sharp. It cannot be said for sure if the plates were drum treated before zinc plating. Therefore, the advice was to zinc plate a small batch of plates that were not drum-treated and test them for sharpness. After that, the concept can be proceeded either with or without drum treatment.
- Hexagonal nuts on frame support: The hexagonal nuts were easier to weld than the cylindrical bushings. A small hole at the bottom of the nut remained which may be welded shut to prevent finger entrapment. According to some, the hexagonal nuts change the appearance of the frame. The advice was to decide whether the money saved is worth the changed appearance.
- Bent latch supports: Because both latch supports showed permanent deformation under load, the advice was to weld the parts at the connection point. The advice was to proceed with the concept and decide whether the extra welding operation should be done at the supplier or internally, keeping in mind the subsequent zinc plating operation.
- Zinc plating latch support cover: No drawbacks were found, therefore the advice was to proceed.
- Alternative thrust bearings: The bearings functioned properly, but one was delivered with the wrong washer. The advice was to order a first batch and check if the bearings have the right combination of washers. If not, they can be paired or the individual components can be stored separately.

Appendix XVIII: Characteristics of a well-performing production system

Decision area	Key characteristics	Production objectives					
		Q	T	R	VF	PF	C
Product architecture	Product architecture is modular	X	X			X	X
	Product platforms are used		X			X	X
	Product structure consists of predefined parts and subassemblies		X	X		X	X
	Levels in product structure simplify the structure of the production system and support production control		X	X			
Production system structure	Production system consists of production units that are responsible for certain parts of a product	X	X	X		X	X
	Production system structure corresponds to the structure and production process of products	X	X	X			X
	Distances between production units and distances between production equipment are short	X	X	X			X
	Production system structure makes it possible to observe the state of and the prerequisites for production	X		X			
	Layout and organisation of workplaces eliminate non-value-adding work and support value-adding work		X				X
Production processes and management	Dissimilar main processes of production are identified and separated from each other		X	X			X
	Processes of production units are defined	X	X	X			X
	Processes and procedures between production units are defined			X			X
	Plans and procedures for responding to production disruptions, problems and delays are in place	X		X			
	Cost-efficient and flexible processes are combined by late-point differentiation and appropriate positioning of order penetration point					X	X
	Responsibility for production control is allocated to production units			X	X	X	
	Close cooperation between production units is supported and enabled	X	X	X			X
Production equipment	Production equipment fits the requirements of the products and processes and the objectives of production	X	X		X	X	X
	Changeover and set-up times of equipment are short		X			X	
	Production equipment enables integration and reduction of production phases	X	X	X			
	Production equipment is reliable and available for use	X	X	X			
	Production equipment is easy to use		X		X	X	X
	Production equipment supports occupational safety and ability to work		X	X			X
	Value-adding work, transportation and handling are supported and simplified by appropriate tools and auxiliary devices		X				X
Information and communication	Information and communication support and enable decision-making	X		X			
	Information transfer and communication follow systematic and predefined principles and procedures		X	X			
	Information and communication systems used in the production system are compatible and integrated	X	X	X			X
	Information and communication systems are reliable and available for use	X	X	X			
	Visual information and control systems are used in the production system	X	X	X			
Human resources	Teamwork and team organisation are used in production	X		X	X	X	
	Employees are cross-trained and skills of employees meet the requirements of work tasks and processes	X		X	X	X	
	Personnel policy and arrangement of working time support operational flexibility and reliable deliveries			X	X		
	Commitment to work and involvement in improving production system and production processes are promoted	X	X	X			X
	Occupational safety and ability to work are emphasised and ensured			X			X

The production objective Q refers to quality, T to time, R to reliability or lead or delivery time, VF to volume flexibility, PF to product flexibility and C to cost.