Bachelor Degree Project

UNIVERSITY OF SKÖVDE

PRODUCT DEVELOPMENT OF MATERIAL SUPPLY

Implementation of Karakuri Kaizen

Bachelor degree project in Product Design Engineering
Level G2E 30 ECTS
Spring term 2019

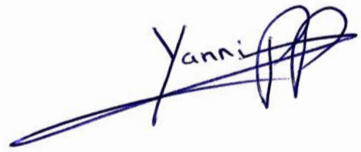
Yanni Porteiro Paraponiaris
Arturo Mateos Rodríguez

Supervisor: Nathanaël Kuipers
Examiner: Erik Brolin

Assurance of own work

This project report has on 15th May 2019 been submitted by Yanni Porteiro Paraponiaris and Arturo Mateos Rodríguez to University of Skövde as a part in obtaining credits on basic level G2E within Product Design Engineering and Mechanical Engineering.

We hereby confirm that for all the material included in this report, which is not our own, we have reported a source and that we have not – for obtaining credits – included any material that we have earlier obtained credits within our academic studies.



Yanni Porteiro Paraponiaris *Arturo Mateos rodríguez*

Acknowledgements

This thesis fulfils the dream of having the opportunity to work with one of the greatest automotive companies, something for which we have to thank Henrik, whose excellent guidance has exceeded our expectations. His spirit and dedication, beyond the role of an industrial supervisor, constituted a crucial element of this project.

Likewise, during the prototyping phase, the constant help from workshop technicians Tina and Glenn has been essential. They kindly contributed with their knowledge and tools, but also with many constructive ideas that helped us to bring the design to reality.

Special mention has to be done to assembly line workers, Viktor and Sebastian Their humble and funny way of treating us made the fieldwork much easier. Finally, our families and friends, that supported us during the intense and long development process, making us look forward and keep working to provide satisfactory results for us and Volvo GTO.

Abstract

The industry 4.0 is continuously aiming to produce faster, increasing quality, and strictly using what is necessary to achieve efficiency enhancement. Within the wide list of methods used to reach this target, robot automation is usually used, although is expensive and rigid. Alternatively, a Japanese cheap automation philosophy called "Karakuri", is being introduced by Volvo GTO to manage this goal. This thesis relies on this philosophy, which takes profit of the existing energy, like gravity, to put in motion mechanisms, in order to reduce costs and improve the production efficiency by developing a semi-automated material handling system. The design method followed, the Scrum, divides the thesis in several phases of development, presenting a fully developed solution at the end of each one and iteratively increasing the level of definition along the process, to finally provide a solution suitable to be implemented.

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1 Introduction

The focus of this document, together with its corresponding appendixes, is to thoroughly describe the development of a low-cost, semi-automatic, material supply system, based on the Japanese philosophy of *karakuri kaizen*, described in the Theory background section.

The thesis will be carried out in collaboration with Volvo Trucks (hereinafter referred to as “Volvo”, “company” or “client”), part of Volvo Group, a global manufacturer of heavy-duty trucks, buses, construction equipment and marine and industrial engines, which is based in Gothenburg, Sweden (Volvo Group, 2017). To a large extent, Volvo Trucks engines are being manufactured in Skövde for a large variety of applications. Particularly, the project will be performed within the assembly facilities, where the project group has been informed about the incoming need of streamlining the process, as the demand is continuously increasing, together with the complexity of their products.

Currently, at the area of the assembly plant that is susceptible to be studied and improved, engines are being assembled through large, straight assembly lines, which are supplied by parallel sub-flows, where the specific subassemblies are put together and transferred to the main line. This transport is done by *ad hoc* kitting carts, whose design forces material handlers to manually place them on the correct spot at a certain moment in the process. These actions represent a time waste that could be minimized through the design of any kind of automatic transport. The main purpose of the project is, therefore, to provide supply transport solutions to, at least, one of the assembly stations included in the area mentioned above. Moreover, the scope of the project includes transmitting to the stakeholders the knowledge acquired through the process. This includes material handlers, assembly operators and engineers, e.g. the entire production plant. Such knowledge is aimed to include the followed methodology and the design of the adopted solution, which would resemble the potential of the implementation of the karakuri philosophy in the plant.

Some limitations must, however, be clarified. Even though a whole redesign of the assembly station that will be studied might produce a long-term, improvement of the productivity. The time limitation that a bachelor thesis project represents will prevent the group to make major changes of the assembly process. Instead, the focus will be to develop the design of the current solution, according to the demands of the client. In the same way, a fully functional solution, ready to be usable in full production, although desired, will not be the focus of the project, which has been described above.

The following section will shed some light to the reader that is not acquainted with the karakuri philosophy, within the context of kaizen and LEAN production, and the design methodology that will hereinafter be adopted.

2 Theory background

2.1 LEAN manufacturing

From an overview, this project contributes to the implementation of the Lean philosophy. Lean production aims to reduce waste. This waste appears in many ways, time waste (in the form of waiting time and unnecessary movement or transport), overproduction, unused employee creativity, etc. By designing a machine that uses zero-external energy to transport a part that had to be manually transported by the worker before, we reduce the time wasted on this movement but also increase the time the worker may use it to do other tasks, being able to take more profit of the worker capacity without increasing the cost of human labor.

2.1.1 Stability and Standardization

To reach stability as part of the foundation of Lean Production, several other philosophies are followed. The first one is the Standardized Work, which consists of designing the tasks taking into consideration safety, easiness and effectiveness at the same time (Dennis, 2016). The second is the 5S method, composed of five steps to get well-ordered workplace and work routine. The first one is Sort, which refers to removing everything that is not strictly necessary to complete the task, in order to avoid the accumulation of objects and streamline the workflow. Secondly, Set in Order, once the workplace has only what is really needed, is time to organize it in a way that reduces time waste due to unnecessary displacement, so again the flow of work is improved. The third step is Shine, which remarks that cleaning will complete the fulfilment of an ideal workplace. The fourth step is Standardize, which consists of creating a list of standards that resume the first 3S and the task at issue. Finally, the last and fifth point of the 5S is Sustain, the task is to ensure that all the previous work remains in the mind of the worker by involving all the team members in its implementation (Dennis, 2016).

2.1.2 Jidoka

This philosophy tries to nip in the bud any kind of production problem and its source by following various steps. First, as we have standardized our work, everything that is not, will be identified easily. Once the problem has been detected, it is necessary to shut down the production to avoid the problem going further. After that, a correction of the problem is needed, followed by investigation and repair. (Dennis, 2016; Lean Manufacturing 10, 2019).

2.1.3 Just in Time

Just in Time means *'producing the right item at the right time in the right quantity. Anything else entails Muda'* (Dennis, 2016, p. 89). JIT states that no products should be manufactured until they are requested and recommends the levelling of the demand to ensure a streamlined working of the factory together with the use of Kanban cards and the maximization of workers and machinery flexibility. As it is shown in the figure above, the goal of JIT, integrated in the Volvo Production System, is focusing the product to the customer, ensuring the quality and lowering as much as possible costs and lead time (Dennis, 2016).

2.2 Kaizen

Kaizen literally means "change to improve", KAI (Change), ZEN (Improvement). It implies a change of attitude in the entire organizational structures of the company, from the management positions, until the factory workers, with the objective of achieving small but continuous improvements in all the processes that workers do. This results in a waste reduction and therefore cost reduction, increase of the quality, optimization of the company management and increase of the worker performance (Lean Manufacturing 10, 2019).

2.3 Karakuri philosophy

Karakuri is a mechanism that functions without external energy, just by storing and releasing energy such as gravitational, aided by springs, gears, or pulleys, to transform the initial input into a different kind of movement. The word 'Karakuri' originally refers to mechanical devices designed in Japan during the 18th and 19th centuries to create movement in puppets, with the main objective of teasing or tricking people, implying a component of mystery or 'magic' (Rani, et al., 2015). There are different types of karakuri dolls, some of them were used in the theatre, "*Butai Karakuri",* for leisure purposes, *"Zashiki Karakuri"*, and for religious festivities, *"Dashi Karakuri".* There are some famous puppets like the *"Zashiki Karakuri"* tea-carrying doll, shown in Figure 1, that only powered by a wound-up spring was able to move forward several steps to a certain distance only by putting a bowl of tea on the tray. Once the cup was removed to drink the tea, the empty bowl was put again in the tray, and the weight difference made the doll return to the initial position (Roser, 2017; Boyle, 2008).

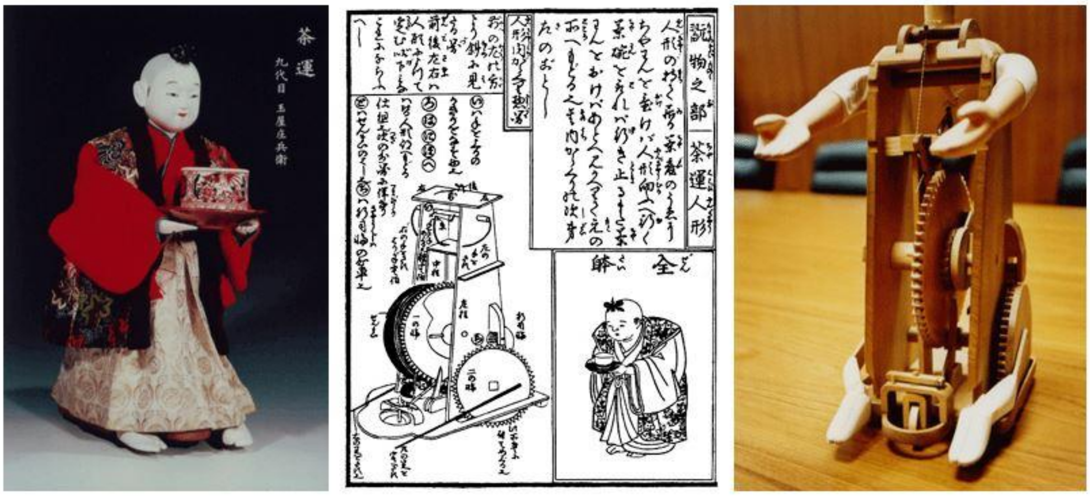

Figure 1. Chahakobi Ningyo (Tea Serving Doll) by TAMAYA Shobei IX, and plan from 'Karakuri Zuii' ('Karakuri - An Illustrated Anthology') published in 1796 (Boyle, 2008).

Other examples of famous karakuri dolls were able to dance, reload and shooting arrows and even writing, being an example of it the karakuri doll created by the Toshiba founder, capable of writing four different characters (Roser, 2017; Boyle, 2008).

Currently, the purpose of karakuri technology has turned into a way of automating objective operations, considered as a category of low-cost automation that makes objective operations easier, while increasing productivity (Murata, et al., 2013). Karakuri philosophy or 'karakuri kaizen' is being adopted in the manufacturing sector in the shape of relatively complex mechanical systems that use all sorts of energy sources but electrical, hydraulic or pneumatic. Instead, karakuri technology applies gravitational energy, human handling, magnetism or even water jets on its designs. This energy is usually transformed into the desired movements by an ensemble of existing mechanical devices, such as gears, levers, seesaws, pulleys, counterweights, dampers for energy dissipation, etc. (Roser, 2017).

Particularly, karakuri mechanical systems help reducing production times and operational costs, as well as improving material handling ergonomics and reducing operators' workload. However, probably the most distinctive feature is the reduction of electrical energy consumption in the plants, which constitutes a significant saving and a minimal environmental impact. This has recently enhanced the introduction of karakuri into the automotive industry.

Companies such as Toyota and Honda are the greatest exponent of adapting their production following karakuri principles. Nonetheless, these systems are normally designed, developed and implemented by these companies internally, which means that there is a lack of public-access information, which sometimes represents a cognitional barrier for the establishment of this technology (Mašín, 2016). This project aims, additionally, to shed some light on the matter and provide the reader with a method for the introduction of the karakuri kaizen.

2.4 Agile design. SCRUM

Under this heading the Scrum methodology will be described, as it represents the basis for the design strategy that will be applied to the project. Scrum, or agile management, is the product development strategy integrated in the SAFe model (Scaled Agile Framework) that Volvo is planning to implement in their organization in the near future, which represents a template for introducing agile principles and tools in large, Lean-focused enterprises, provided by the company Scaled Agile, Inc. (Scaled Agile, Inc., 2019).

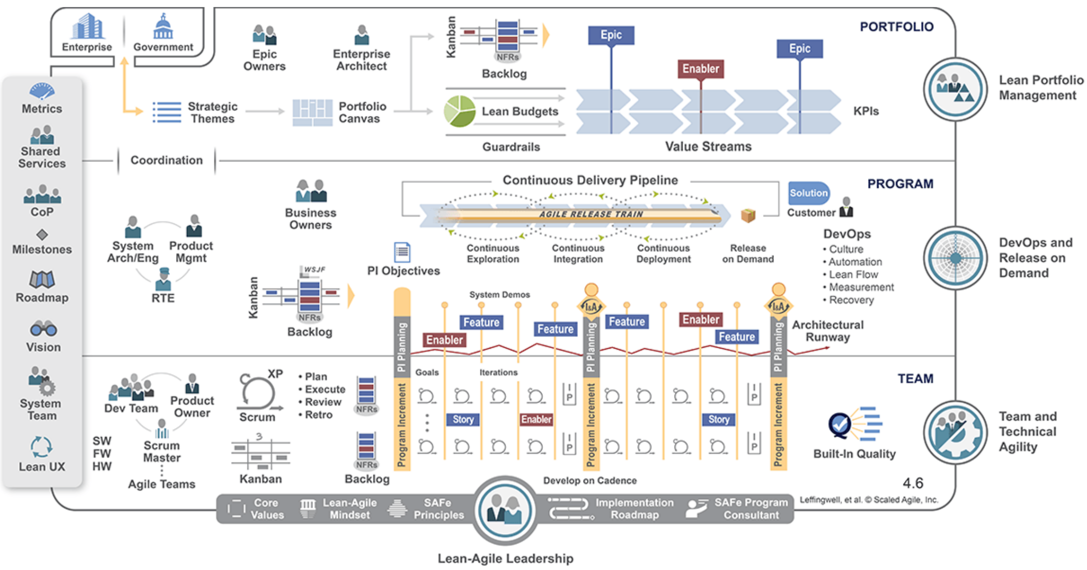

Figure 2. SAFe corporate template (Scaled Agile, Inc., 2019).

Traditionally, Scrum has been acknowledged as a development method applicable only to software projects. However, new evidence reveals that agile methods can be integrated with traditional stage-gate approaches to perform a hybrid model that can be adapted to manufactured new products. Research into recent industry experience suggests that this model has significant potential benefits for manufacturers of physical products, such as heavy industrial equipment, yielding dramatically positive results (Cooper & Sommer, 2016).

Moreover, scrum has been described as a successful way of implementing empiricism in the development of all sorts of technologically complex products through agile iteration (Scrum.org, 2019). Traditionally, product design methodologies are structured in a way that invest a considerable amount of time in pre-study and project planification. Although this can be desirable in the implementation of new products into the market, it implies a high risk of making mistakes at early stages of the development process, that could go unnoticed until it is too late to deliver a satisfactory solution. Considering the amount of time available to deliver a specific, functional, unpredictable solution for a predefined problem, an agile design strategy is needed.

According to the method, the first step is to set a large list of features, stated in descendent priority order, which the product must fulfil once the project has finished ('product backlog'). Through several design loops, hereinafter called 'sprints', these specifications are gradually accomplished, ensuring that no primary tasks are left behind if the time runs out. These 'sprints' have a durance that goes from one to four weeks and each of them embraces the whole design process, instead of simply iterating on prototyping and testing. This way, development teams are forced to iteratively deliver complete solutions. They all include the most relevant design tasks to generate a valuable increment of the product definition: Analyze (reflect on the problem, based on previous results), design (concept generation), build (prototyping, using techniques according to the current level of definition) and testing (which differs depending on the specific type of prototype). The process also involves a high effort in retrospective thinking. At the end of each sprint, a review of the achieved goals and problems found is made, together with the planification for the next sprint. This is usually carried out in the shape of a meeting with representatives of all the stakeholders, who will provide the design team with their approval and valuable feedback for the next iteration. In addition, on a daily basis, the method includes regular stand-up meetings called Daily Scrum, that must be attended, preferably always at the same time, by the whole team for inspection-and-adapt purposes. This has directly been included in the work routine of this project and sessions will be attended by the industrial supervisor and the project team (Rubin, 2013).

It is also relevant to describe the separate roles that this process establishes for the different activities, and how the group will adopt them for this specific project. According to the description that Rubin (2013) provides*,* these roles are:

- Product Owner, who represents the main responsible for the product development leadership, in charge of setting the initial list of requirements and their order of importance. It is through the appropriate communication with the other roles about the vision of the desired product that the product owner will ensure the overall success of the project. Therefore, this role must always be ready to meet the other ones if any uncertainty or problem regarding the specifications arises (Rubin, 2013).

- ScrumMaster, who will make a constant effort on illustrating the Development Team about the Scrum method itself, making sure that all the performed activities match the model standards in respect of achieving the needed goals at the correct moment of the design process. Although typically this responsibility would belong to a project manager, the ScrumMaster acts more as a coach, who does not have authority to impose design decision over the team (Rubin, 2013).

- Development Team, ideally formed by professionals belonging to all the disciplines applicable to the project. These components, instead of fragmenting the work corresponding to each one's field, should collaborate in parallel on the different steps that 'sprints' are divided in. The Development Team should be able to self-organize in order to find out the best way of achieving the goals set by the Product Owner (Rubin, 2013).

Thus, this specific project requires some adjustment of the roles described above. Analogically, except for all the stakeholders, there are three main parties: Industrial Supervisor, Academic Supervisor and Project Team. The Industrial Supervisor, who was the one that stated the problem to be solved and the main features of the desired solution, will play the role of the Product Owner. However, a considerable part of the specifications must be laid out by the Project Team, as it is a main objective of the thesis work to analyze the problem and propose a solution. The Academic Supervisor will act as the ScrumMaster, in terms of ensuring that the Project Team correctly applies relevant design methodologies, from an academic point of view, without actively interceding in the Project Team decisions. Finally, this team is formed by the two students that carry out the thesis, who match the multidisciplinarity requirement, as they respectively belong to Mechanical and Product Design Engineering and will work together in each part of the project.

2.5 Adopted design methodology.

As it has been depicted above, the implementation of the Scrum strategy would favor a correct distribution of the workload, considering the time that the team disposes of and the kind of solutions that must be delivered. Nonetheless, some aspects of more product design focused methodologies must be implemented in order to avoid adopting, by mistake, a simple 'trial-and-error' approach. These methods are:

2.5.1 Iterative Design Process Cycle (Donut model)

This method is based, as its name suggests, in an iteration process that is divided into four steps: Observation-reframing-converging-experimenting. The two first steps involve coping with the design problem, and the two last ones, in this case, would represent concept generation, prototyping and testing. This sequence seems to be appropriate, as the scope of the iteration, unlike most product development strategies, include the whole design process, instead of only a part of it, making it compatible with the Scrum approach (UNI CONCEPTS, 2018).

The main disadvantage of the Donut strategy is that the duration of the iteration is not stated. It is based on simple repetition, until a satisfactory solution is reached. This prevents from directly adopting the strategy, as there is a strict time limitation. Therefore, it has been agreed that the best way to proceed would be to implement it into the Scrum model, which better regulates the amount and duration of design loops (UNI CONCEPTS, 2018).

2.5.2 Double Diamond

Although the four-steps sequence of the Iterative Design Process Cycle method seems acceptable, it is also important to take into consideration the convergent or divergent nature of each step. For this purpose, the Double Diamond strategy, developed by the Design Council, as the advisor of the United Kingdom's government on design, provides a different, more adequate perspective than the Donut method.

Even though the sequence is not completely iterative, in the case of the Double Diamond, it consists of the same four design steps that, unlike the Donut method, are understood as divergent-convergent-divergent-convergent approach, respectively. This model is commonly accepted within the product design industry and better matches a project where several concepts or prototypes are presented to the company representatives at early stages of the process (Design Council, 2015). A scheme of these product development methodologies integrated into the Scrum model is shown in Figure 3.

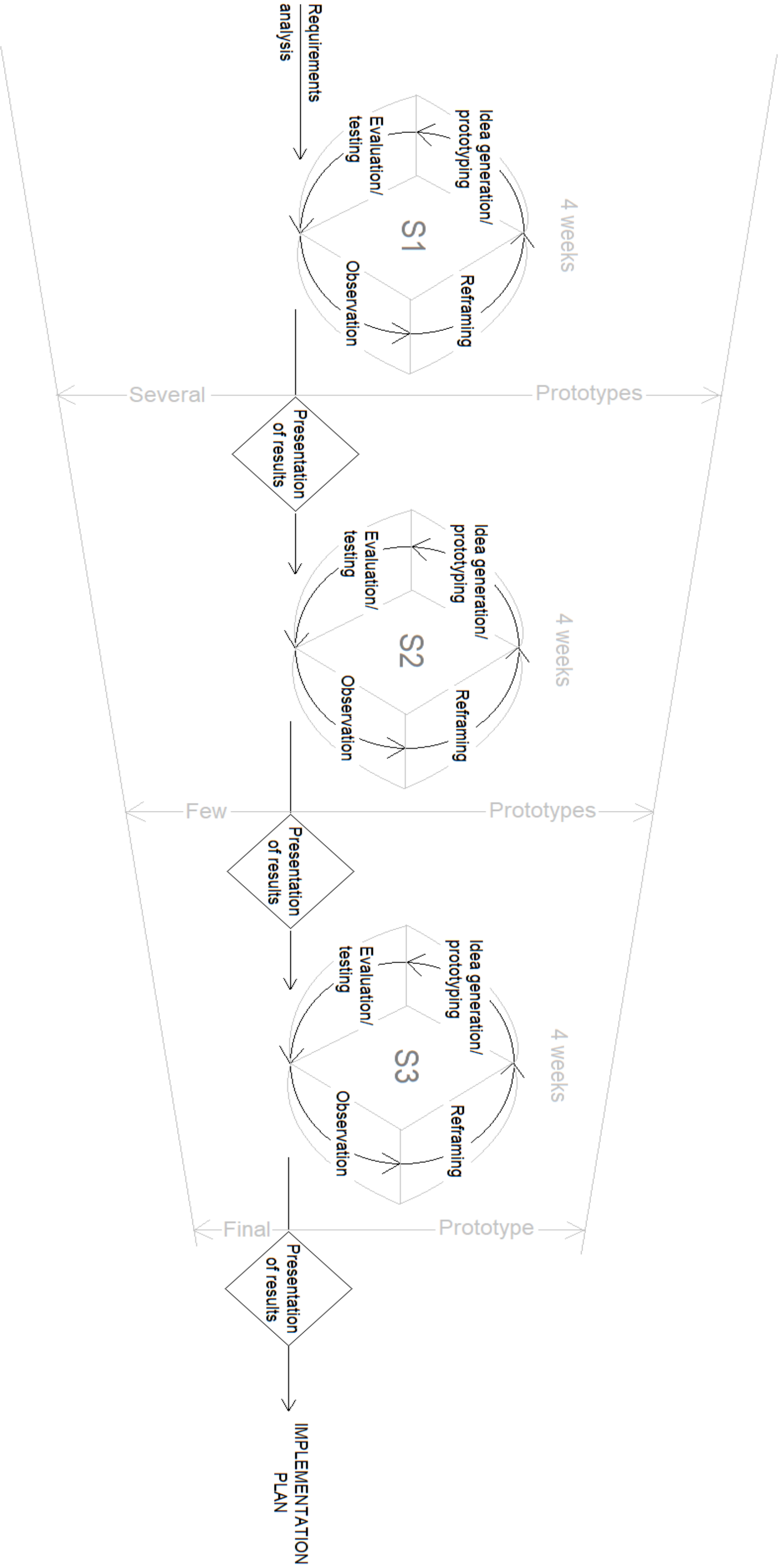

Figure 3. Implementation of product design models in the Scrum methodology.

3 Sprint 1

3.1 Preliminary study

3.1.1 Station selection

In the first instance, it was necessary to select the specific assembly station that would be considered for the introduction of the karakuri system. From the client perspective, any of the stations belonging to the first two areas of the main assembly line could be chosen for this purpose, which means that there were up to 6 different assembly stations to analyze. Two employees responsible for those areas were interviewed (assembly area team leader and WPO coach). Conclusions of the qualitative analysis, performed as a two-hour conversation, are shown below.

The criteria followed to decide the suitability of the station considers the weight of the component that will be transported, the path followed to reach the main line, depicted in Figure 4, and the positioning needs of the component transported (e.g. irregular shaped components).

Turbocharger and intake-manifold assembly station: The turbocharger and the intake-manifold are firstly assembled together along the sub-flow line in various, relatively complex operations (manifolds and turbochargers are heavy components that must be specifically positioned before joining them, using custom-designed kitting carts). After that, the subassembly is transferred to the parallel, main flow line, were it is joined to the main body of the engine in a single operation. This makes the path followed by the supplies be trapezoidal (the subassembly is transported from the sub-flow to the main one diagonally).

Conduct cover or baffle plate assembly station: In this case, some pre-assembly operation must also be done in the sub-flow line. This leads to the same problem of diagonal material transfer between lines (rectangular triangle path). Nonetheless, it should be considered that this time parts to be assembled are simpler and some redesign of the pre-assembly operation is possible, in order to make the supply transference be perpendicular to assembly lines. However, the scope of the project does not include the redesign of the plant layout or assembly operations.

Common rail, Oil pump and Oil filters and frame assembly stations: They are all being supplied by the sub-flow line placed at the left side of the main assembly line and their characteristics are very similar to the ones explained above, placed at the right side. Some of them must be pre-assembled in the supply line, which means diagonal transport again, or have to be carried in a very specific way in order to be placed correctly upon the engine block.

Oil pan assembly station: From the very beginning, this last station seemed to be the most promising in terms of its compatibility with a karakuri based, low cost automation solution. Firstly, no pre-assembly is done, except from a rubber gasket that is placed inside the oil pan. Moreover, parts are transported in pairs from the supply line to the assembly line directly, following a short, perpendicular line and, despite some material variation (metal or plastic), only one kind of component, the oil pan, is delivered.

The karakuri perspective is already slightly implemented in this station, in the shape of a big trolley build with tracks, where the oil pans are placed. Once both pans are equipped with their rubber gaskets, they are introduced into the trolley and the material handler moves the trolley forward to the assembly line, where the trolley connects with a similar, fix structure that collects both pans. Finally, as "Karakuri" philosophy tries to take profit of the existing energy, gravity becomes one of the main sources of it, and weight has much to do with the potential energy that a body has. For this reason, the stations with heavier pieces to transport are the most suitable for putting in motion the "Karakuri" mechanism that will be used. The Oil Pan was the one of the heaviest pieces, making it a good candidate.

Furthermore, many signs of improvement opportunities were observed:

- It was evident that the material handler spent a big part of the time waiting for the assembly operator to finish the task between cycles. The material handling operation was therefore considerably shorter than the assembly operation. This was confirmed by the team leaders, who stated that, according to their operation analysis (VSM), very much of the material handler activity was non-value adding.
- It was observed that, if oil pans transport was streamlined, there would be a chance of increasing the free time of the material handler, enough to assign him extra tasks during that period, which would have a positive, direct impact in the productivity.
- Current system presents a lack of ergonomics. The trolley has to be pushed forward applying a significant amount of force and manually directed following a straight line printed in the floor. Basically, its handling can become uncomfortable and risky, which was confirmed by team leaders and operators.
- The structure is getting worn and some joints and anchor points of the mechanism malfunction.
- Oil pans must be placed at a height that makes it necessary to use lifting devices, which could be avoided with a proper redesign of the trolley.

After this observation, the Oil Pan was selected as the most suitable station to focus on, as the oil pan is heavy enough to enable the mechanism operation and the path followed by it, is completely straight. It is also an easy component to put in position (as it had a plane side in which it could be easily supported) so it eases the implementation of a *karakuri* system.

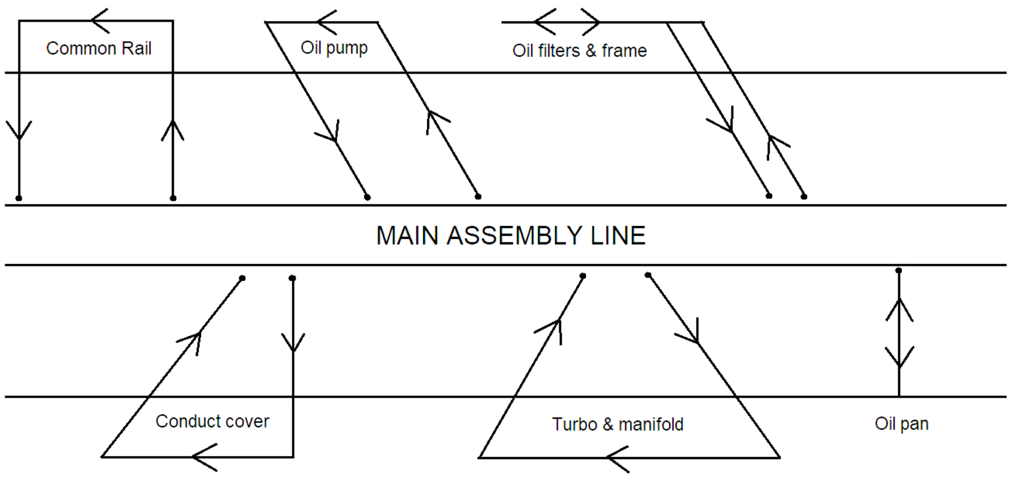

Figure 4. Scheme of the arrangement of areas 1 and 2 at the assembly line.

3.1.2 Boundary conditions

Once the station to streamline had been selected, it has been considered important to define the problem to be solved, by setting different boundary conditions. Some of them were originated from conversations with supervisors and operators and some others from simple observation of the current system. At the delivery point in the main assembly line, for example, oil pans are picked up by an automatic, pneumatic system (internally called PLC - Programmable Logic Controller- or simply “rig”), that places them on top of the engine block, positioned upside-down. This system is integrated in the fixed, ’semi-karakuri’ structure mentioned above, and has a CE mark that prevents from making any change in the design of the PLC or its structure. This means that the transport solution that might be generated must be compatible with it performing only minor design changes. In particular, this constraint results in the following requirements:

- Oil pans must be delivered at a certain height.
- Empty trays, where pans are placed over, have to be picked up, again, at a certain height and in a separate flow.
- The PLC structure includes roller conveyors to store and transport pans and trays. These conveyors present a certain slope, which, apparently, could influence the design of the transport.
- The amount of oil pans the PLC structure is able to store is limited, defining a maximum batch of two oil pans for the transport.
- The width of the transport system will not be fixed by the PLC structure, apparently, but it is desirable to be taken into consideration in terms of compatibility.

To continue, the distance of the displacement is fixed, as the delivery point is static, the space between lines must be the existing one in terms of traffic allowance and the working area of the material handler should not be reduced (Volvo Group, 2017). The weight of the oil pan, susceptible to be one of the main sources of energy, is variable. Currently, plastic and metal oil pans are assembled indistinctly at the same station, which means that the system should operate with an approximate load of 10 to 15 kg, for a batch of one, and 20 to 30 kg for a batch of two. This variation constitutes one of the main issues to be considered. Finally, in the near future, larger, aluminium oil pans from another assembly line could be included in the studied one, which means that the system should be designed to be flexible for future changes in terms of width, resistance and a maximum load of approximately 25 kg, for a batch of one.

3.2 Specifications

3.2.1 Functional analysis

First design task was to identify the needs of the customer. Based on the previous literature review, interviews to the plant employees and field observation, these main needs have been stated as functions and arranged in a function tree, shown in Figure 5. The primary function or need to be covered is the improvement of the material handling. This has to be made through the empowerment of the Lean and Kaizen Philosophies, the respect to the environment and meeting the station requirements.

Empowers Lean Philosophy: The main task of the Lean Production is to reduce waste, which in this case corresponds to time and cost wastes. Time waste appears each moment the material handler has to push the existing transport system towards the main line station. Both time and money waste can be avoided by introducing a mechanism that does not use external energy, neither an elevate budget to be developed, as would be the case of automated systems, such as the AGC vehicles used in other areas of the factory.

Empowers Kaizen and Respects the Environment: By introducing this new, faster and more efficient way of transporting parts from the supply line to the assembly line we are contributing the application of Kaizen Philosophy that aims at continuous improvement in the factory. Likewise, by implementing a zero-external-energy system, a contribution to use environmentally friendly solutions is made.

Meets the Station Requirements: The solution also has to be adapted to the station needs, this is, the ergonomics focused on the worker that will use the Karakuri system, (reducing the strenuousness, ensuring safety, providing an easy way of positioning the parts and also being easy to install) and the displacements needs of this particular station (Oil Pan), which consist on the height, distance and the path track in which the component has to be transported towards the main line.

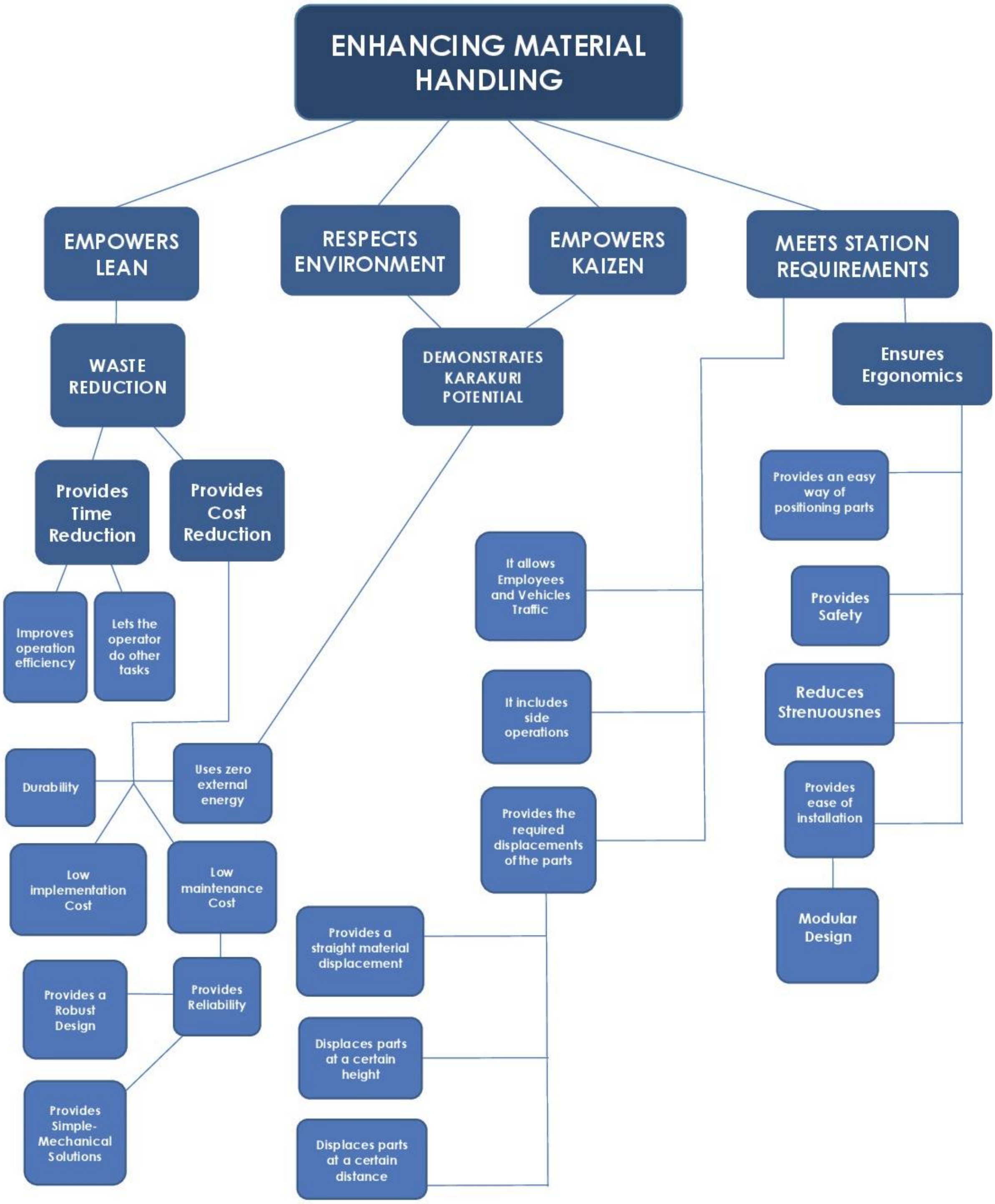

Figure 5. Functional analysis representation. Function Tree.

3.2.2 Specification benchmarking

In order to consider the existing range of karakuri systems in the market, their materials, prices and other technical data, a research on several companies that offer karakuri products has been made, as it was found necessary to have an overview of what the current market solutions are.

Regarding the materials, most of the companies manufacture their profiles in aluminium, and only a few manufacture plastic or steel profiles for the structure of the mechanism. The main feature has to be the lightness, in order to facilitate the station mobility. Also, slopes of the roller tracks, built to move the part, are normally of 3.5°. Moreover, most systems do not require an electrical external force, only using the power introduced by operators with levers. Finally, recyclability, ease to assemble, lightness and multifunctionality are the main characteristics announced in the catalogues.

Including all these characteristics in our design would position our product as a competitor for the other manufacturers. Benchmarking data has been collected from company websites shown in Table 1:

Table 1. Benchmarking references

Company	Website
Item	https://product.item24.de/en/products/product-catalogue/products/profiles-and-accessories-1001009500/
LeanProducts	http://www.leanproducts.eu/t/downloads
Flowstore	http://www.flowstore.co.uk/flowtube-tubes-joints-lean-manufacturing
Creform	http://www.creform.de/es/servicio/multimedia/catalogo-creform/

3.2.3 Target Specifications

After accomplishing the functional analysis and searching for current solutions available in the market, most of the functions from the function tree have been described as a set of concise, measurable features (metrics). This will help Identifying key, objective attributes to focus on during concept generation. However, as the future system constitutes a “technology-intensive product”, being able to specify sufficient engineering characteristics before concept generation represents a considerable challenge. Consequently, the approach will be to set, as far as possible, preliminary target specifications, which will be reviewed after generated concepts reveal the actual technology constraints that the problem represents (Ulrich, 2008).

The initial step of the followed strategy is linking previously stated functions with relevant target specifications. The result is shown in the following table, organized referring to each branch of the function tree. The generated solution should:

Table 2. Generated metrics from the corresponding requirements.

Function	Metric
Provide Time reduction	
Improve operational efficiency	• Material transport time during going movement • Material transport time during return movement • Part positioning time • Cycle time
Let the operator do other tasks	• Operator’s waiting time between cycles

Cost reduction	
Durability	• Lifespan
Use zero external energy	• Power input
Low implementation cost	• Material cost • Manufacturing labour cost • Installation labour cost
Low maintenance cost	• Preventive maintenance frequency • Corrective maintenance frequency estimation • Maintenance labour cost
Provide reliability	• Corrective maintenance frequency estimation • Number of moving parts
Provide a robust design	• Maximum load • Safety factor • Overall weight
Provide simple-mechanical solutions	• Number of components • Number of moving parts • Number of subsystems
Meet station requirements	
Allow employees and vehicles traffic	• Does the system represent a permanent obstacle? • Does the system represent a partial-time obstacle? • Is the system functioning flexible, so it does not represent an obstacle?
Include side operations	• Does the system include the delivery of screws? • Does the system assist the assembly of the rubber gasket
Provide a straight material displacement	• Angle of the track of the material displacement
Displace parts at a certain height	• Height of the oil pan at the initial placement point • Height of the oil pan at the point of delivery
Displace parts at a certain distance	• Initial-placement - delivery-point distance
Ensure ergonomics	
Provide an easy way of positioning the parts	• Height of the oil pan at the initial placement point.

	• Does the operator have to manually realign the oil pan? • Level of part-positioning assistance.
Ensure safety	• Does the system represent a potential risk that must be assessed?
Reduce strenuousness	• Level of part-positioning assistance. • Activation force • Activation force - average-theoretical muscle force ratio
Provide a modular design	• Is the system portable? • Is the system usable in other stations? • Installing time • Uninstalling time
Respect the environment	
Use zero external energy	• Power input
Respect the environment	• Percentage of recyclable materials • Maximum natural degradation time of non-recyclable materials

Once all metrics have been identified, a proper list of metrics is shown below. The table includes previous metrics divided into common fields, together with their measuring units, margin values and level of priority. A D represents a demand, e.g. a specification that all generated concepts must meet. A W means, on the other hand, that the specification is wished to be fulfilled, but not mandatory. The level of importance of these wishes decreases from W1 to W3. This classification matches the priority order that the ’product backlog’, mentioned in the theoretical background, should include.

Table 3. Table of metrics. Traditional layout.

No.	Prior.	Metric	Value	Unit
Geometry				
1	D	Angle of the track of the material displacement	90	°
2	D	Starting point - delivery point distance	3.2	m
3	D	Height of the oil pan at the point of delivery	1.3	m
4	W1	Height of the oil pan at the initial placement point	≅ 1.35	m
5	D	Total width of the system	1.16 - 1.5	m
6	W2	Roller track slope	≅ 5	%
6	W3	Number of components	<	-
7	W3	Number of moving parts	<	-

8	W3	Number of subsystems	3 - 7	-
Time				
9	D	Material handler transport time during going movement	< 4	s
10	D	Material handler transport time during return movement	< 4	s
11	W1	Part positioning time	< 5	s
12	D	Assembly time per batch	Classified	s
13	W1	Material handler work time	Classified	s
14	W1	Material handler waiting time	Classified	s
15	W3	Installing time		h
16	W3	Uninstalling time		h
Costs				
17	D	Electric power input	0	w
18	W2	Preventive maintenance frequency		times/year
19	W2	Corrective maintenance frequency estimation		times/year
20	W2	Maintenance labour cost	Classified	SEK/h
21	D	Material cost	100 000	SEK
22	W2	Manufacturing labour cost	Classified	SEK/h
23	W2	Installation labour cost	Classified	SEK/h
24	W2	Lifespan	3 - 5	years
Forces				
25	D	Maximum load	150	N/part
26	D	Safety factor	1 - 3	-
27	W2	Overall weight	< 200	N
28	W1	Activation force (If using hand lever)	< 34	N
29	W1	Activation force (If using foot pedal)	< 146	N
Materials				
30	W3	Percentage of recyclable materials	80 - 100	%
31	W3	Maximum natural degradation time of non-recyclable materials	< 400	years
Safety				

32	W1	Does the system represent a potential risk that must be assessed?	No	Yes/No
Functionalities				
33	W3	Does the system assist the assembly of the rubber gasket?	Yes	Yes/No
34	D	Does the system include the delivery of screws?	Yes	Yes/No
35	W1	Does the system represent a permanent obstacle?	No	Yes/No
36	W2	Does the system represent a partial-time obstacle?	No	Yes/No
37	W3	Is the system functioning flexible, so it does not represent an obstacle?	Yes	Yes/No
Ergonomics				
38	W2	Does the operator have to manually realign the oil pan?	No	Yes/No
39	W2	Level of part-positioning assistance	> 50	%
40	W3	Is the system portable?	Yes	Yes/No
41	W3	Is the system usable in other stations?	Yes	Yes/No

Finally, margin values have been established based on the specification benchmarking, field measurements of the assembly station and initial design demands (proposed by the company). This makes it possible to move forward to the generation of concepts.

3.3 Concept generation

In order to develop adequate solutions, as most literature of mechanical design process suggest, the material handling problem has been broken down into the main functions to be performed by the system, plotted in Figure 6:

1: Rubber gasket assembly and oil pan placement. 2: Parts storing and launching (starting point). 3: Main flow transport between assembly lines (oil pan). 4: Destination anchoring and parts release. 5: Sub-flow transport between assembly lines (oil pan screws).

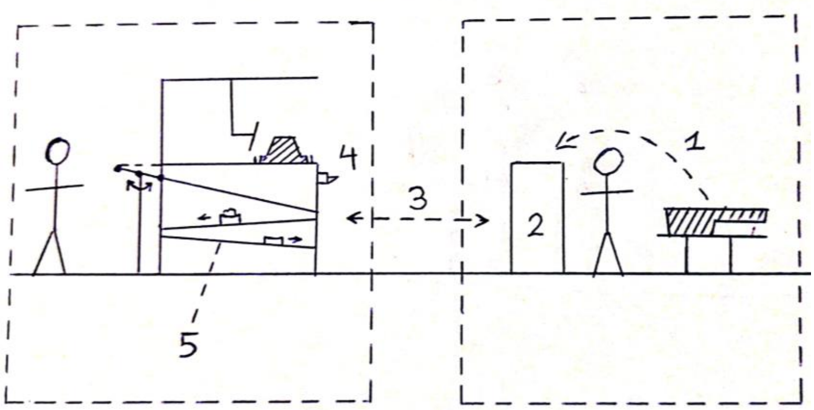

Figure 6. Division the problem into subfunctions.

Thereupon several concepts for the different sub-problems were generated through the traditional technique of brainstorming. Observation of existing solutions and nature analogies helped achieving the correct mindset to overcome the technical constraints that the current assembly layout involves. A scheme of the ideas generated is shown in Figure 7.

1. Rubber gasket assembly and oil pan placement.
   - **Maintain current system.** The rubber gasket is assembled manually while the oil pan is placed upside-down, perpendicularly to the transport posture (as shown in the figure). Once finished, the oil pan with the gasket is manually turned and placed in the transport's starting point (2).
   - **Manual placing**. In this case, the rubber gasket is assembled in the oil pan, that is directly placed in parallel to point 2. Placing the oil pan in point 2 is still manual.
   - **Automatic placing.** It replaces the manual act of placing the pan by any kind of karakuri, semi-automatic system.
   - **Eliminating the problem.** The rubber gasket is directly assembled at the starting point of the transport.

2. Parts storing and launching (starting point).
   - **Batch of one, automatic activation.** Oil pans are placed at the starting point one at a time, and directly launched to the main assembly line (the action of placing the pan directly activates the transport system).
   - **Batch of one, manual activation.** Oil pans are placed at the starting point one at a time. The transport system remains at the starting point until the operator activates it (manually or with the use of electromechanical actuators).
   - **Batch of two, automatic activation.** Oil pans are placed at the starting point two at a time, as it is the maximum that the existing assembly line can support, and directly launched to the main assembly line.
   - **Batch of two, manual activation.** Oil pans are placed at the starting point two at a time. The transport system remains at the starting point until the operator activates it.

3. Main flow transport between assembly lines (oil pan).
   - **Telescopic wheeled ramp.** The momentum of the oil pan, released from the starting point (2), is the source of energy to deploy a telescopic system with a roller track built in, which will transport the material.
   - **"Chameleon tongue".** A cantilever roller track is rolled at the starting point and deployed thanks to the momentum of the oil pan, as the component gets closer to the delivery point, the bending moment augments and the deflection of the system helps maintaining the speed of the oil pans.
   - **"Elephant trunk".** The principle is the same as the applied for the "chameleon tongue", but in this case the track is rolled at its end and the rotation direction while being deployed is the opposite.
   - **Automatic cart.** Based on a karakuri example from the Toyota Kaikan museum, in Nagoya, the idea is to use a self-propelled cart that uses the weight of the transported parts as the unique source of energy.
   - **Hanging telescopic system.** Which is a variation of the telescopic wheeled ramp. The main difference is that it hangs from fixed guides installed in the ceiling.
   - **"Bridge".** It has been thought as fixed structure that enables free traffic of walking employees and vehicles.

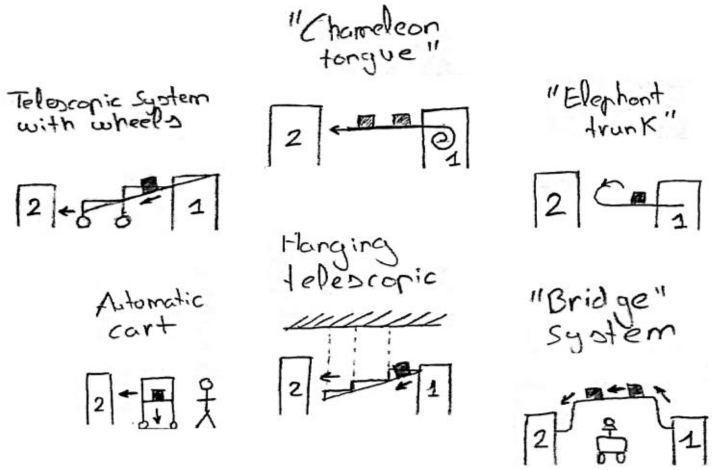

Figure 7. Scheme of the ideas generated through brainstorming for the transport function.

4. Destination anchoring and parts release.
   - **Maintain current system.** The current destination point consists on a karakuri-based structure of roller tracks with a certain slope combined with a PLC system that picks up the parts. It includes anchor points with integrated tops for preventing the parts to fall until the transport system arrives.
   - **Redesign of current system.** There is the possibility of making small modifications on the existing PLC system in order to include anchor points suitable for the selected transport solution.
   - **Eliminate anchor points.** Other option, although it might seem obvious, would be to eliminate the need of tops and anchor points, depending on the transport system functioning.

5. Sub-flow transport between assembly lines (oil pan screws).
   - **Maintain current system.** Which consist on separate, parallel roller tracks that have the same functioning of the main ones.
   - **Redesign current system.** The transport of screws could be performed together with the main flow, as there is no obvious need of doing it separately. Another option would be to place the screws in the corresponding holes of the oil pan before sending it to the main line.
   - **Separate transport.** It is also possible to disregard the transport of screws together with the oil pans and focus only on the main flow. The alternative for the transport of these components could be studied separately.

Once all functions were covered with different types of possible solutions, they were discussed with the industrial supervisor, on behalf of the stakeholders, who suggested disregarding some of the options and focusing on other ones. Following his advises concepts were developed as shown below, which revolve around the transport function (3). The now considered subfunctions 1, 2, 4 and 5 will only be examined and solved if time and resources are sufficient. However, these designs eventually include some of the other functions.

Telescopic cart:

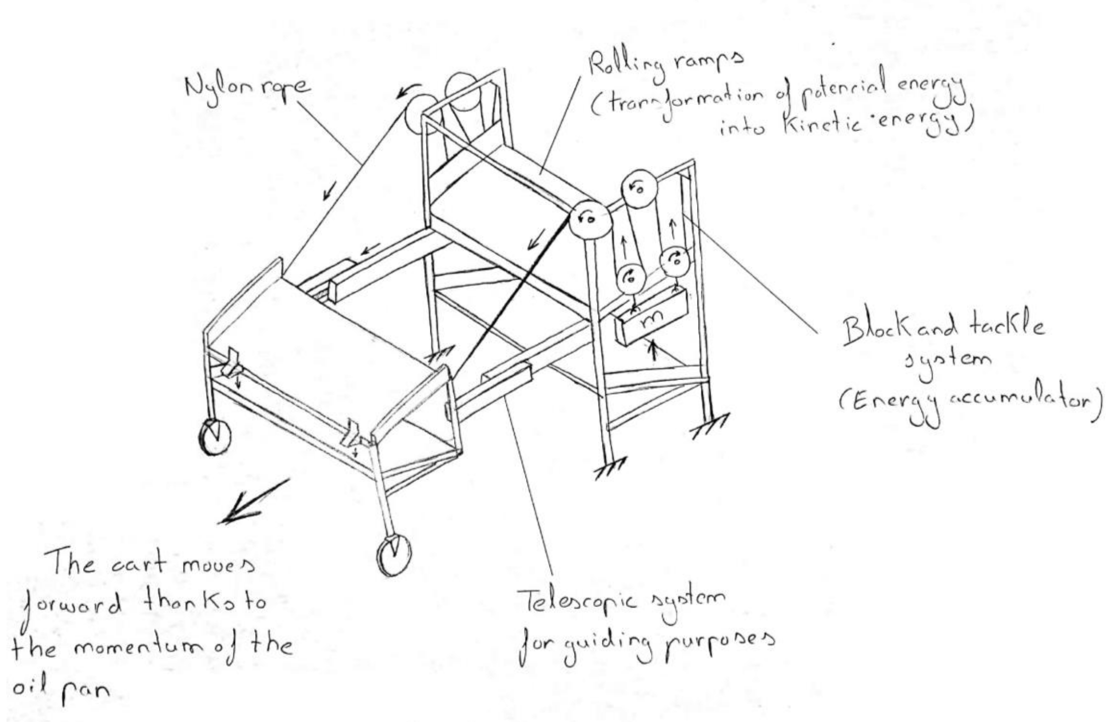

Figure 8. Sketch of the "Telescopic cart" concept.

The system described in Figure 8 is based on two separate roller ramps. The first one is fixed, and it is the spot where the operator places the oil pan on its tray. The other ramp consists of a telescopically guided wheeled cart that performs the transport and it is initially joined to the previous one. Once the oil pan is released, potential energy is transformed into kinetic and, when the parts gets to the front tops of the moving platform, the collision pushes it forward together with the oil pan. The same source of energy is used to lift a block and tackle system that accumulates the energy for the return trip. This system has been used, instead of a single pulley, to reduce the vertical displacement the counterweight should travel as the cart moves forward.

Elephant trunk:

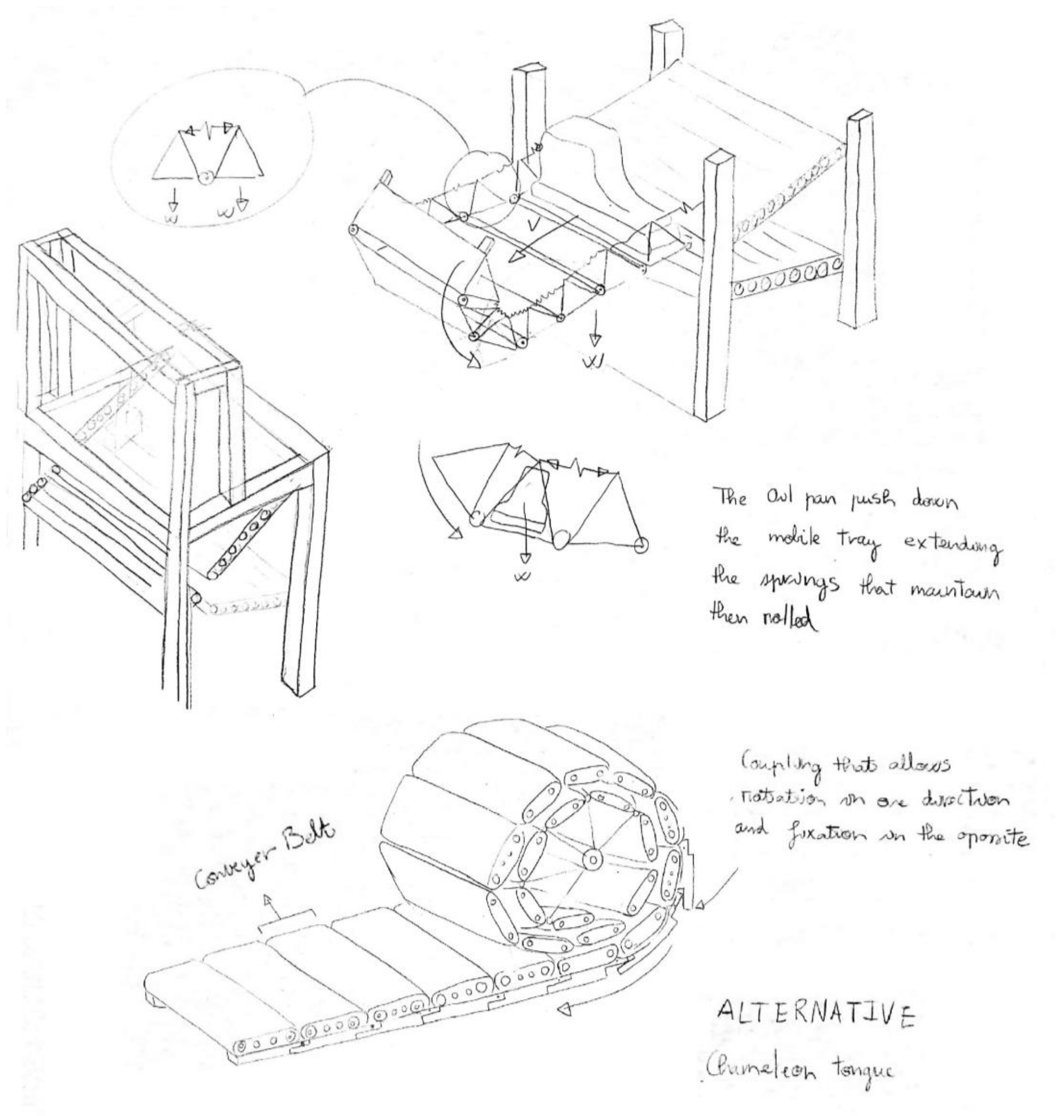

Figure 9. Sketch of the "Elephant trunk" concept.

As Figure 9 suggests, this cantilever system would be made of a rolled roller track that is deployed like an elephant trunk. The source of energy would be, again, the kinetic energy and weight of the part. As the oil pan moves forward, it pushes down the different trays the trunk is divided into, extending the springs that keep together the mobile structure and accumulating the energy to roll the trunk back at its initial position, once the oil pan has been delivered. A possible alternative would be the previously mentioned “chameleon tongue”, which would use gravity as the only source of energy and therefore deployed with a certain angle, enough for the part to reach its destination. Energy accumulation would this time be made by any sort of torsion spring, roller tracks would be replaced by conveyor belts and supporting parts would be installed underneath, to prevent an excess of flexion in the undesired direction.

Self-propelled Cart:

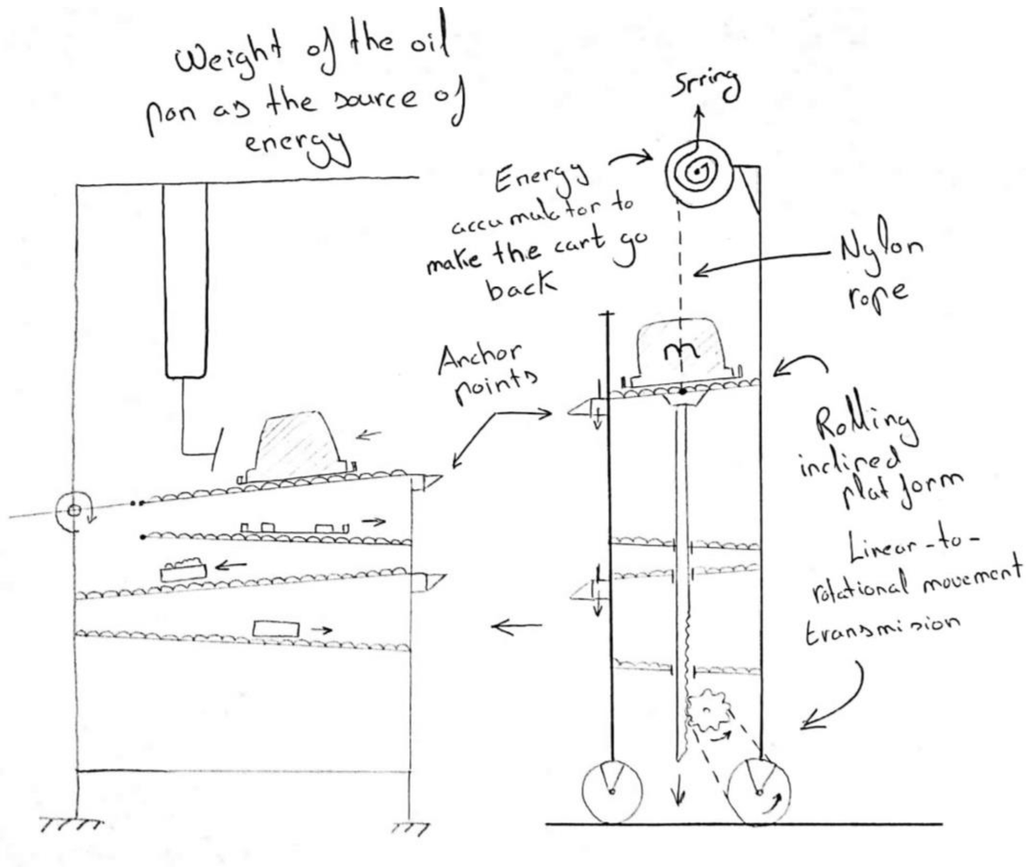

Figure 10. Sketch of the "Self-propelled cart" concept.

The operator places the oil pan on top of a sliding roller track platform, which is pushed down due to the weight of the part. Fixed to the platform there is an axis with a straight gear set, which transmits the vertical displacement to a rotatory gear, joined to a pulley that moves the rear wheels of the cart and it therefore starts moving forward. While this platform is moving down, nylon ropes tense a torsion spring that accumulates energy to repeat the process in the opposite direction and move the cart backwards once it has released the oil pan and picked up the previous empty tray.

Pendant Bridge:

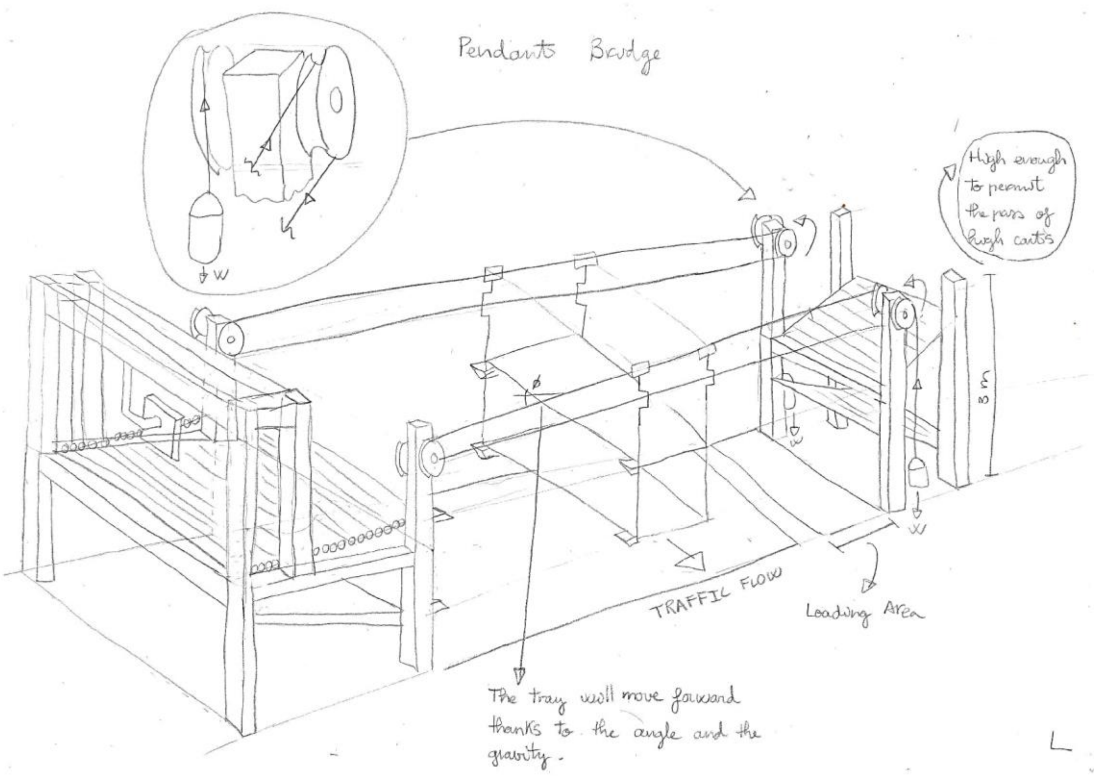

Figure 11. Sketch of the "Pendant bridge" concept.

The transport system of the image above consists of a platform that hangs from tensioning steel cables running on pulleys positioned at a certain height, so the system allows human and vehicle traffic. The platform includes two parallel rolling tracks for releasing the oil pan and picking up empty trays. It is anchored to the PLC system thanks to electromechanics actuators, which are remotely unpinned when the assembly operator finds it convenient. The movement is done, again, thanks to the gravitational energy, as steel cables are set with a certain slope that helps the platform with the oil pan move forward and accumulate energy by lifting counterweights linked to the previous mentioned pulleys. This energy will be used in pulling the platform back to the material handler workplace.

Rigid Bridge:

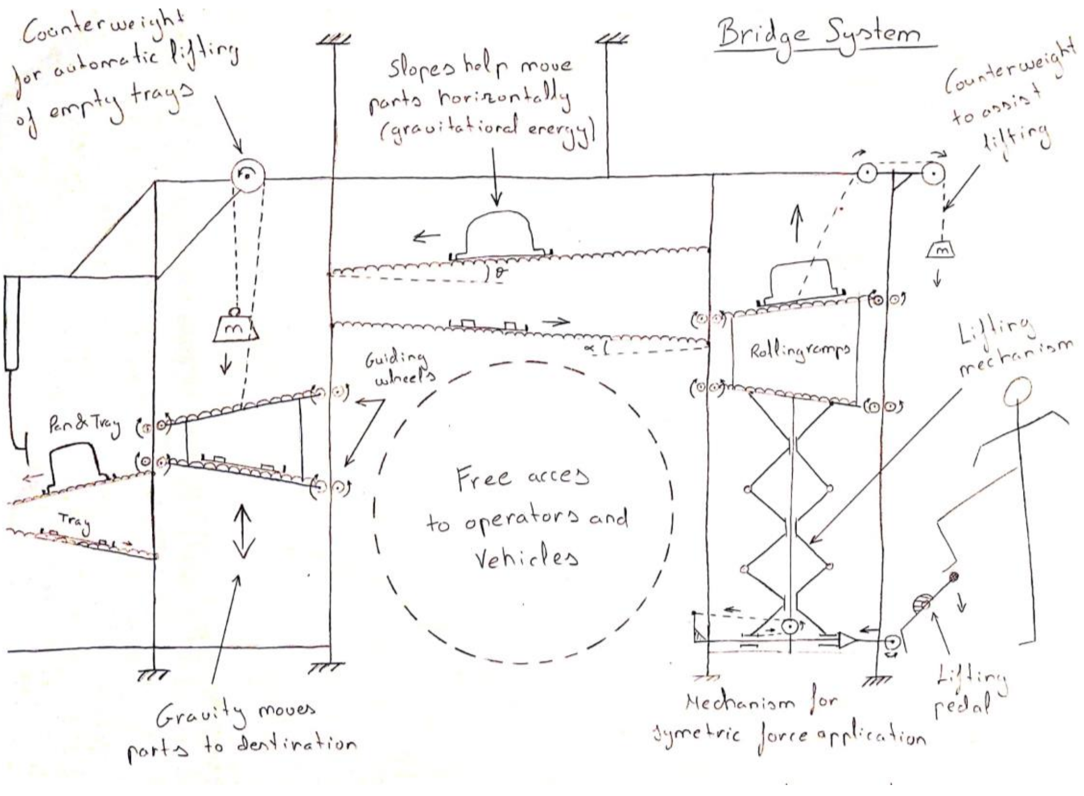

Figure 12. Sketch of the "Bridge" concept.

The oil pan on its tray is lifted by the operator through a seesaw mechanism activated by a pedal and assisted by a counterweight, as it is schematized in Figure 12. Once the platform where the oil pan is placed gets to the walkway, parts are released and travel to the other side of the bridge thanks to the slope of the roller tracks the walkway is made of. Once at the destination platform, the weight of the oil pan pushes it down and a counterweight accumulates the energy for pulling up again the platform, which once arrives releases the part and picks up the empty tray of the previous one. The empty tray repeats the process in the opposite direction until it gets the operator, who places it in the upper rolling track of the platform to put another oil pan.

3.4 Concept evaluation

3.4.1 Criteria definition

To evaluate the concepts, a particular criterion is needed. For this purpose, it has to be considered that the level of definition of the concepts does not allow a direct comparison with some of the previous metrics at this point. According to Ullman (Ullman, 1994, p. 171) *"If sufficient knowledge is not immediately available for the evaluation, then it must be developed. This is accomplished by developing models that can be easily evaluated"*. However, the level of detail of the concepts developed is such that enough information was observed for the evaluation as, usually, abstract features that concepts already present can be used instead. "Concepts are abstract, have little detail and can't be measured" (Ullman, 1994, p. 168). Therefore, the criteria used in the concept evaluation are the metrics that are at the same level of abstraction as the concepts previously described, and the inputs provided by an interview carried out with some of the factory operators. The method used to analyze all this information is the Pugh Matrix. Finally, the technology necessary to carry out the manufacturing of the system is also important to consider, "Can the technology be manufactured with known processes?" (Ullman, 1994, p. 172) as it may increase enormously the cost of building a model.

3.4.1.1 Interview with material handlers in the plant.

An interview with workers from the supply line was done in order to collect valuable feedback of the group that will potentially take profit of the result of this thesis. The eyes of the workers where mainly pointing to the "Self-propelled cart" model as it was the closest to become a reality because of the mechanical simplicity and ease to handle, from their perspective. They also took into consideration the improvement potential of the system, to fit future changes in the station (as the oil pan weight may vary in the future), and the ease of repairs in case of failure. The importance of reducing the failure risk and the maintenance cost was emphasized as well, as it is one of the aims of this thesis. Regarding the "Bridge System" model, it was noticed by the workers that the mechanical complexity and number of mobile parts could unnecessarily increase the maintenance cost and also the risk of failure. Another remarkable input was that they found it difficult for the "Telescopic cart" model to be put in motion just because of the hit of the oil pan against the telescopic tray.

As well as pointing out design inconsistencies, interviewees were opened to propose new insights and possible design changes. Some of the ideas proposed are the following: First, the excess of the cart's kinetic energy may be dissipated by dampers, leaving only the necessary to go back to the initial position. Second, part of the initial energy needed to put in motion any of the systems may be introduced by the workers using their own weight to push down a platform where they can step on. Finally, every model has some interesting features that shouldn't be disregarded, as they could be combined to yield more solutions.

3.4.2 Concept Screening. Pugh's Method

As it was stated before, the method used is the decision-matrix method or Pugh's method, shown in Table 4, as it is able to assess all the criteria in comparison with a reference concept and is a proven useful method, as stated by Ullman (Ullman, 1994, p. 175), *'The decision-matrix method, or Pugh's method, which is fairly simple, has proven very effective for comparing concepts that are not defined enough for direct comparison with the engineering requirements'.* In this case the reference will be the "Self-propelled" cart, which was the most complete concept in terms of requirements fulfillment and interviewee's approval.

Table 4. Concept screening matrix.

	Concepts				
Selection Criteria	(DATUM)	Telescopic C.	Bridge	Elephant T.	Pendant B.
Dependency of external energy	0	-1	-1	0	1
Allowance of aisle traffic	0	-1	1	-1	0
Mechanical simplicity	0	0	-1	-1	1
Robust Design	0	0	1	0	0
Low cost	0	1	-1	-1	1
Lightness	0	-1	-1	0	1
Ensures safety	0	1	0	0	0
Sensibility to load variation	0	0	1	0	0

Modularity/Portability	0	-1	-1	-1	-1
Ease of parts positioning	0	1	-1	1	1
Compatibility with the existing PLC	0	0	-1	-1	0
Mechanical Efficiency	0	-1	-1	-1	1
Maximum Load	0	0	1	-1	-1
Components Availability in the market	0	1	1	0	1
Activation Force Needed	0	0	-1	0	0
Ease of handling	0	-1	-1	-1	-1
Dirt Accumulation	0	1	0	1	1
Improvability	0	-1	-1	-1	-1
Ease of fixing	0	-1	-1	-1	-1
Accessibility in case of Malfunctioning	0	1	-1	1	0
Risk of Material Deviation	0	1	-1	-1	0
Sum of +'s	0	7	5	3	8
Sum of 0's	21	6	2	7	8
Sum of -'s	0	8	14	11	5
Net score	0	-1	-9	-8	3
Rank	2	3	5	4	1
Continue?	Yes	No	No	No	Yes

3.4.3 Concept refining

The previous matrix yielded a rank where the “Self-propelled” cart and the “Pendant Bridge” concept had the two highest scores. As the difference between them was not big enough to declare a winner, a refining of both concepts was required. For that purpose, a more detailed description, corresponding to Figure 13 and Figure 14 was done of each of them.

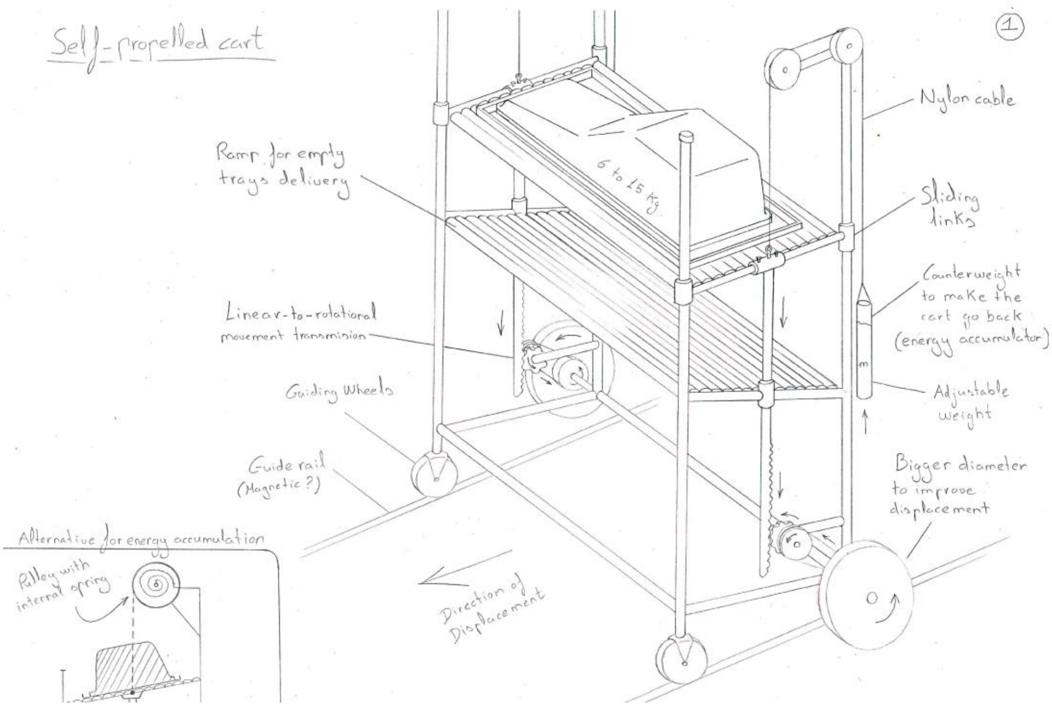

Figure 13. "Self-propelled cart". Refined concept.

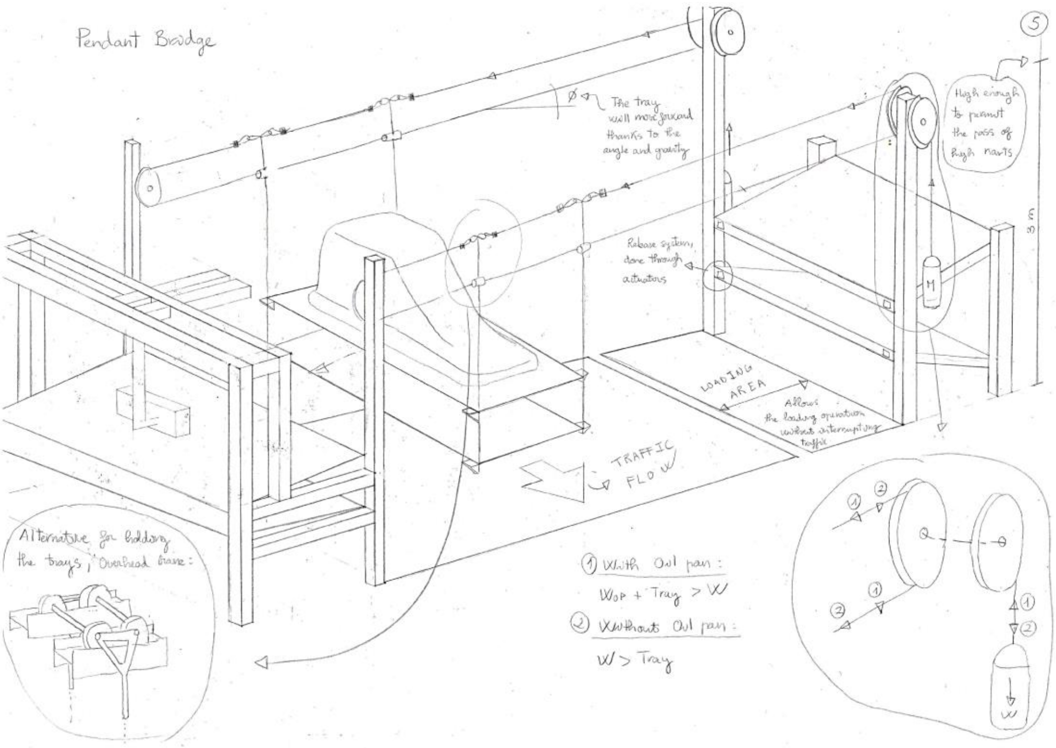

Figure 14. "Pendant bridge". Refined concept.

3.4.4 Concept Scoring

After refining the two best ranked concepts, as Table 5 resembles, a weight has been added to each criterion in order to make a final sum where a more precise evaluation is provided. This kind of scoring matrix has proven to be especially useful to better differentiate between competitive solutions (Ulrich, 2008).

Table 5. Scoring matrix

		Self-propelled cart		Pendant Bridge	
Selection Criteria	Weight	Rating	Score	Rating	Score
Dependency of external energy	7	2	0,14	3	0,21
Allowance of operators and vehicles traffic	4	3	0,12	3	0,12
Mechanical simplicity	5	3	0,15	3	0,15
Robust Design	5	2	0,1	2	0,1
Low cost	5	2	0,1	3	0,15
Lightness	3	1	0,03	2	0,06
Ensures safety	6	1	0,06	1	0,06
Sensibility to load variation	7	2	0,14	2	0,14
Modularity/Portability	3	3	0,09	1	0,03
Ease of parts positioning	4	2	0,08	3	0,12
Compatibility with the existing PLC system	5	3	0,15	3	0,15
Mechanical Efficiency	6	3	0,18	3	0,18
Maximum Load	5	2	0,1	1	0,05
Components Availability in the market	3	2	0,06	3	0,09

Activation Force Needed	4	3	0,12	3	0,12
Ease of handling	7	3	0,21	1	0,07
Dirt Accumulation	2	2	0,04	3	0,06
Improvability	6	3	0,18	2	0,12
Ease of fixing	7	3	0,21	1	0,07
Accessibility in case of Malfunctioning	3	2	0,06	2	0,06
Risk of Material Deviation	3	3	0,09	3	0,09
	Total Score	2,41		2,2	
	Continue?	Yes		No	

The matrix yielded a result where the "Self-propelled" cart obtained the highest score, demonstrating to be the best candidate in which the group will focus in Sprint 2.

3.5 Prototyping. 3D Mock-up

According to the time plan and the Scrum model, it was appointed to deliver a result of the adopted solution (self-propelled cart), concluding with Sprint 1, in the shape of a 3D mock-up. Although the model is not functional and it is not stable enough for simulations so far, its level of definition provided the project group with satisfactory insights of possible arrangements of standardized components. The confirmation of the feasibility of these constructive solutions was crucial to be able to order specific components from external suppliers, whose delivery times could compromise the manufacturing of a definitive prototype further in Sprint 3. An overview of the result is shown in Figure 15:

Figure 15. 3D mock-up overview

During the benchmarking phase the observation was made that most karakuri solutions by manufacturers use specific tubular aluminium profiles. This observation motivated the use of this kind of profiles, designed to be compatible with a specific, adjustable gripping system and all sorts of karakuri-focused components.

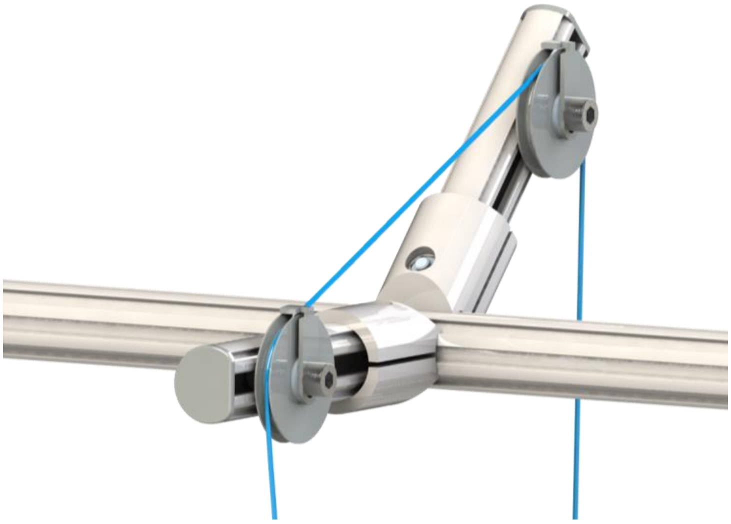

Figure 16. Detail 1. Constructive solution for adjustable counterweight pulleys.

The image above shows a possible lightweight arrangement with a placement adjustability of three degrees of freedom. Likewise, pulleys are equipped with metal plates that prevent the belt from leaping out of the rail.

Figure 17. Detail 2. Constructive solution for adjustable counterweight.

The counterweight itself (Figure 17) consists of a simple container that is fillable with any kind of material that would add the needed weight to the system, e.g., sand, plumbs or water. It is fixed to a vertical guiding system, which prevents the counterweight from swinging when the cart breaks and accelerates. It also allows adjusting the horizontal position of the weight, to be able to modify the center of gravity of the cart, seeking for stability.

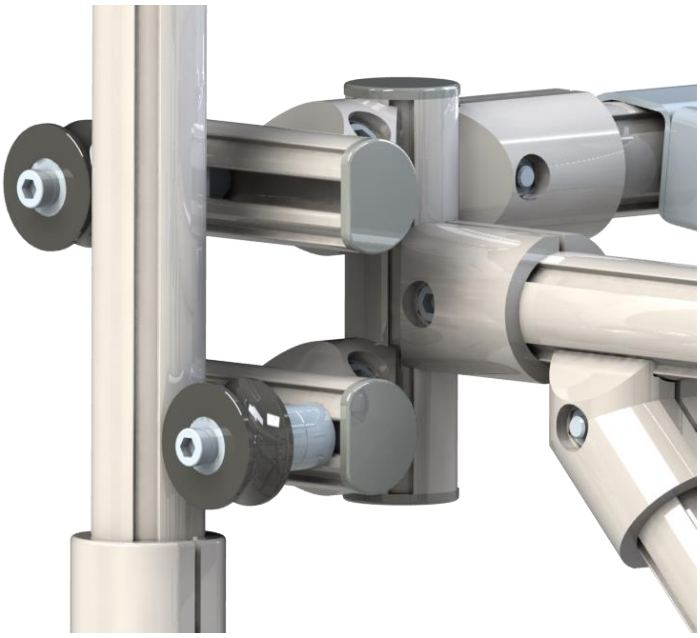

Figure 18. Detail 3. Constructive solution for the guiding system of the lifting platform.

The guiding system (Figure 18) is equipped with roller sets that reduce the friction, decreasing energy losses that can be destined to the transport function. They are installed in grooved profiles that permit their horizontal displacement, easing installation.

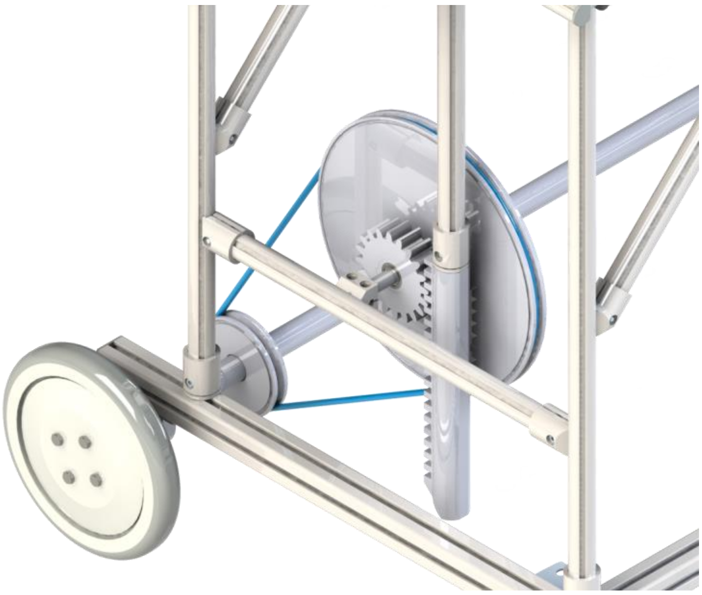

Figure 19. Detail 4. Constructive solution for the transmission system.

The transmission functioning principle (Figure 19) has been described during the concept generation phase. Furthermore, the rotatory gear is mounted on a sleeve with internal bearings that is solidary with a pulley, which transmits the movement to another one, placed in the rear axis, through a rubber belt. This axis is shared with the rear wheel, so they will spin together. The diameter of the pulleys will be designed to enhance the horizontal displacement of the cart with a minimum height variation of the lifting platform, where the oil pan is placed.

Once the group has verified that the different components could be placed in a manner that, from an overview, would satisfy the primary functional requirements, it is possible to move forward to the next sprint and make the corresponding analysis and calculations: Estimate the overall weight of the structure, ensure the resistance of joints and profiles, dimensioning the diameters of pulleys and gears, assessing the dynamic behaviour of the system, etc. After setting the specific parameters that had been proven to work through this analysis and future prototyping, the group plans to iteratively “go back” to the 3D model to make the required changes. The goal is to achieve a stable, virtual prototype at the end of the process that could serve as a medium of transmission of the adopted solution towards the group of stakeholders.

4 Sprint 2

4.1 Mechanical analysis

4.1.1 Introduction

In order to describe the internal working of the cart, a mechanical analysis will be developed, which will be constituted of a kinetic and dynamic analysis, for both backward and forward motion. The aim of the dynamic analysis is to find the minimum counterweight that is able to move the cart backwards and check afterwards if the forward motion is possible, this is, the lifting platform is able to lift the counterweight, making sure at the same time (through a kinetic analysis) that the speed and time values are suitable as working conditions. Once the counterweight value has been found, the translational speeds and therefore the transporting time values of the cart computed are, as it is stated in *Theory of Ground Vehicles* (Wong, 2001), *"*coupled to the rotational motion of the components connected with the wheels*"*. This means that the final vehicle acceleration has to be calculated drawing from the rotational ones of the internal components. All these calculations will be arranged in order to create a sort of simulator, which will be used to adjust different parameters of the cart, as the dimensions of the transmission components (pulleys, gears and wheels), which will determine the relation of the horizontal displacement versus the vertical displacement of the lifting platform, and will also allow to compute the kinetic behavior of the cart with several counterweight values at the same time.

4.1.2 Assumptions

In order to find an expression that resumes the behavior of the cart, the essential equation of motion of ground vehicles has been applied to this case. As this equation considers four resistance forces (rolling, gravitational, aerodynamic and drawbar load) acting in the opposite direction than the cart, some assumptions have been made:

- The cart structure is made of slender bars and the low values of speed reached will make the aerodynamic resistance forces negligible.
- The gravitational resistance force is also negligible, as the cart is moving along a horizontal surface.
- There is no drawbar attached to the cart.

As a conclusion, the only resistance force acting in the cart is the rolling resistance between the plastic wheels and the concrete floor. This assumption allows considering that the cart moves under constant acceleration, as the forces applied throughout the entire transmission system are generated due to the gravity acting on the lifting platform and resistance forces that might vary with the cart speed can be disregarded.

4.1.3 Essential Equation of Motion of the Self-propelled Cart

In order to find a unique expression of the cart behavior that includes all the forces, losses and inertias of the mechanical system, an essential equation of motion has been developed. The basic principle from which the equation of motion will be developed is the first Newton's Law:

$$\Sigma F = m \cdot a$$

According to the *Theory of Ground Vehicles* (Wong, 2001), the sum of forces of the system is constituted by:

$$\Sigma F = m \cdot a = F_f + F_r - R_a - R_{rf} - R_{rr} - R_d - R_g$$

Where:
$R_a = Aerodyanmic\ Resistance\ Force$
$R_{rf}, R_{rr} = Rolling\ Resistance\ of\ the\ front\ and\ rear\ tyres$
$R_d = Drawbar\ Load$
$R_g = Grade\ or\ gravitational\ Resistance$
$F_f, F_r = Traction\ Force\ from\ the\ front\ and\ rear\ tyres$

The two rolling resistance forces may be united and written as a unique force. Likewise, both traction forces can be identified as a total one. Adding the inertias from the entire cart, the previous expression may be written as:

$$F_t - R_a - R_r - R_d - R_g = m \cdot a + \frac{I_{wr} \cdot \alpha_r}{r_{cr}} + \frac{I_{wf} \cdot \alpha_f}{r_{cf}}$$

Figure 20 represents the typical diagram of vehicle acting forces transmitted to momentum values in the wheel:

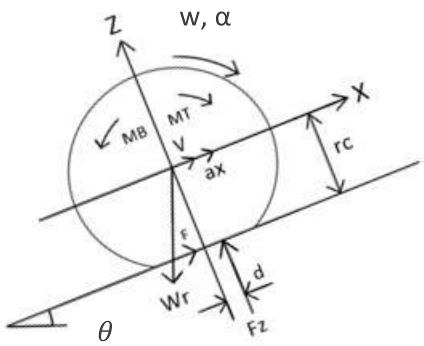

Figure 20. Sketch of the forces and moments involved in a vehicle's wheel.

Last equation of motion, although useful in terms of conceptualization, can be found in any vehicle engineering reference. The analytical challenge of the thesis is, therefore, transforming the equation into a single expression that could describe the linear acceleration of the cart, considering the rotational inertia of all the components of the transmission, its efficiency and the lineal inertia of the lifting platform and counterweights. In the **Appendix A: Dynamic Calculations**, a deep description of the calculation procedure can be found. The achieved equation has the following shape, in the case of the plastic oil pan:

$$a_x = \frac{\frac{\frac{D_{Pulley\,1}}{D_{Pulley\,2}} \cdot (m_{LP} + m_{POP} - m_{CW}) \cdot g \cdot r_{gear}}{r_{RW}} - \mu \cdot (m_{SPC} + m_{POP}) \cdot g}{(m_{SPC} + m_{POP}) \cdot (1 + \frac{2}{(m_{SPC} + m_{POP}) \cdot {r_{rw}}^2} \cdot (I_{RW} + I_{FW} \cdot \varepsilon_{FW}^2 + I_T \cdot \varepsilon_T^2 + I_{RP} \cdot \varepsilon_{RP}^2) + (m_{LP} + m_{CW} + m_{POP}) \cdot \frac{\varepsilon_j \cdot r_{gear}}{r_{RW}}}$$

4.1.4 Analysis results

Once the final expression has been found, several counterweights will be introduced in the equation to compute the resulting acceleration in order to select a suitable counterweight value that may be lifted when going forward, but also able of moving the cart backwards by lifting the platform.

Table 7 shows the result of these calculations, starting with the backward motion as it has to be checked first what is the minimum counterweight value that is able to move the cart back to the starting point, and then it will be checked if that value or values of counterweight may be lifted when going forward. The counterweight (CW) values that yield positive accelerations in both directions are the ones suitable to be selected.

Table 6. Time and speed parameters of possible counterweights.

Backward motion		Forward motion			
Empty Lifting-platform		Plastic Oil pan		Metal Oil pan	
CW (kg)	A (m/s^2)	CW (kg)	A (m/s^2)	CW (kg)	A (m/s^2)
15	-0,06429273	15	0,20969054	15	0,28062947
16	-0,04403642	16	0,18777708	16	0,26019914
17	-0,02387192	17	0,16577245	17	0,23968904
18	-0,00379862	18	0,1436761	18	0,2190987
19	0,01618412	19	0,12148743	19	0,19842766
20	0,03607689	20	0,09920587	20	0,17767543
21	0,0558803	21	0,07683085	21	0,15684155
22	0,07559496	22	0,05436176	22	0,13592552
23	0,09522146	23	0,03179801	23	0,11492685
24	0,11476039	24	0,00913901	24	0,09384507
25	0,13421234	25	-0,01361586	25	0,07267967

As it can be observed in the previous table, backward acceleration turns positive from 19 kg counterweights. Thus, this is the minimum value that ensures that the cart will go back to its initial position. Then, the forward acceleration values have also been computed for both, plastic and metal oil pans, providing a maximun counterweight that the weight of the lifting platform, together with the oil pan, are able to lift, by checking values that yield positive acceleration. The maximum counterweight that provides a positive acceleration and then lets the cart move forward is 24 kg for the plastic oil pan. As the selected counterweight has to be appropriate to work with both pans, the maximum acceptable counterweight is 24 kg. The range of values of counterweight that fulfill the requirements for the backward and forward motion are therefore from 19 to 24 kg.

Finally, an appropriate counterweight has to be selected in order to work with both oil pans providing acceptable operation parameters, this is, speed and time values that fulfill the station needs. Table 8 shows the calculated speed and time parameters corresponding to the suitable range of counterweights.

Table 7. Time and speed parameters of the range of suitable counterweights

Counterweight (kg)	Backwards Time (s)	Backwards Speed (m/s)	Forward Time (s)		Forward Speed (m/s)	
			Plastic	Metal	Plastic	Metal
19	19,9	0,321	7,3	5,670	0,880	1,125
20	13,3	0,480	8,0	5,992	0,796	1,065
21	10,7	0,597	9,1	6,377	0,700	1,000
22	9,2	0,694	10,8	6,851	0,589	0,931
23	8,2	0,779	14,2	7,450	0,450	0,856
24	7,45	0,856	26,4	8,245	0,241	0,774

By analyzing the obtained values can be said that a 24 kg counterweight is ideal for the backward motion, as it yield the minimum time possible 7,45 seconds, and the maximum speed possible 0,856 m/s. In the other hand this would be problematic when going forward with the worst scenario, the plastic oil pan, as the cart would spend 26,4 seconds to travel between lines, and reaching a final speed of 0,241, which is unacceptable for our station.

On the contrary, selecting a 19 kg counterweight would provide slower backwards parameters, spending 19,9 seconds to travel between lines and reaching a final speed of 0,321 m/s. In contrast to what happened with the 24 kg counterweight, the forward speeds and time are the highest possible, spending 7,3 seconds and reaching 0,880 m/s for the plastic oil pan, and 5,670 seconds and reaching 1,125 m/s for the metal one. Although these forward parameters are desirable, again, extremely low parameters, in this case at the backward motion, don't permit this counterweight value to be a real option to be implemented in the station.

As a conclusion, it is recommended to use a 22 kg counterweight, as the forward-motion parameters are still acceptable for both oil pans, permitting a return acceptably fast.

4.2 Resistance evaluation

After the mechanical analysis had yielded the maximum value of the counterweight that could be used, it was possible to estimate the forces acting on the structure (Figure 21). As no strength information was provided by the suppliers, the team found especially necessary to assess the resistance of the most critical beams, which had been dimensioned to provide a lightweight design, enhancing the performance of the cart but could also compromise its integrity.

4.2.1 Considerations

Observation of the design of the structure and the direction of the forces acting on the system motivated the study of the flexion of the horizontal beams and the buckling effect on the pillars. Regarding flexion, the selection of the studied bar was done according to the following criteria:

- Section: All profiles have the same section shape diameter.
- Length: a_1, a_2, b_1 and b_2 are the longest bars (shown in the image below).
- a_1 and a_2 are the horizontal bars that must resist highest values of transversal force: The weight of the oil pan, the oil-pan tray, four of the roller conveyors and their own weight, separately.

Considering this, and assuming a symmetric distribution of the forces applied to a_1 and a_2, only the flexion of a_1 will be studied. In the case of buckling:

- The slenderest beams, which also present a high proportion of forces applied in the direction of its axis, are the most susceptible to suffer this phenomenon.
- The longest bars, with longitudinal forces applied are the pillars (d_1, d_2, d_3 and d_4), which must resist the weight of all of the components that are not placed in the wheeled base.

Between the four pillars, a symmetric distribution of the forces has also been assumed. Not taking into consideration the slope of the fixed platform, which would introduce forces into the pillars at slightly different heights. The studied beam in this case will therefore be d_1. However, it needs to be mentioned that some simplifications have been assumed before calculating the acting forces:

- The only vertical force introduced by the transmission system into the structure has been its weight. Force and torque originated by transmission losses have not been considered, as an accurate efficiency figure on 3D-printed components can be arduous to achieve and its value (traditionally around 5% of transmission forces) has been assumed to be negligible.
- The weight of the oil pan, its tray and roller conveyors has been applied as a distributed load along the a_1 beam. Ideally, these forces should be applied only in the points of the beam where roller conveyors are attached. However, as number and position of conveyors is susceptible to vary during the prototyping process, this simplification has been admitted.
- The squared beams of the wheeled base have not been studied, as loads are applied close to the position of the wheels (supports), in a direction that cannot significantly affect the integrity of the profiles.

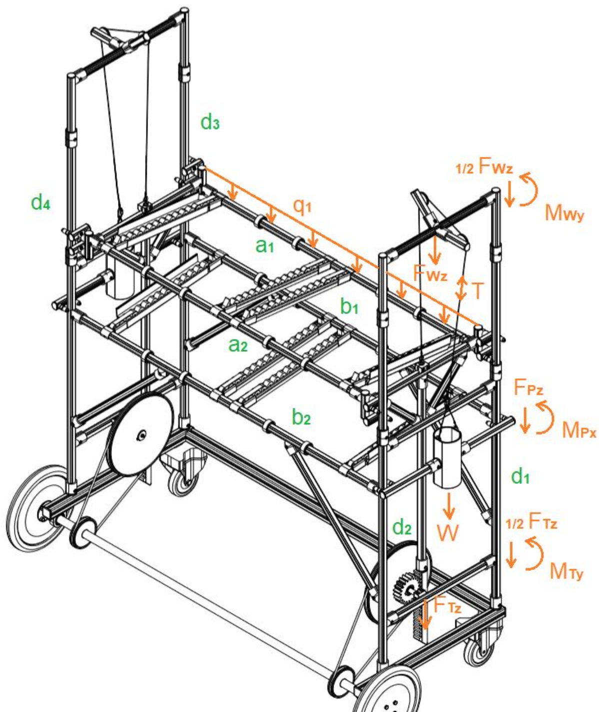

Figure 21. Nomenclature of the main forces acting on the most critical beams.

4.2.2 Loads estimation

The value of the forces acting on the two beams selected above, shown in the previous figure, have been estimated according to basic theory of resistance of materials. Joints between bars have been considered as fixed (full transmission of torque) and transmission of forces has only been calculated previous to the deformation of the beams (first order calculation).

Most values of weight have been obtained from technical datasheets and estimations from the CAD model. Selecting the highest value of acceptable counterweight from the mechanical analysis and the heaviest oil pan, which would represent the most unfavorable situation in terms of structure's resistance, calculations are as follows:

$$q_1 = \frac{Lifting\ platform\ weight^{*} + Oil\ pan\ weight + Oil\ pan\ tray\ weight}{2\ \times Lenght\ of\ a_1}$$

$$q_1 = \frac{(9.98 + 15 + 1.5) \times 9.81}{2 \times 1.5} = 76.78\ N$$

*Considering only the components supported by a_1 and a_2 beams.

Understanding the lifting platform total weight as the weight of the platform itself, plus the heaviest oil pan on it and its tray:

$$F_{Wz(max)} = \frac{Lifting\ platform\ total\ weight + Maximum\ counterweight}{2}$$

$$F_{Wz(max)} = \frac{(16.96 + 15 + 1.5 + 22) \times 9.81}{2} = 272.03\ N$$

This force is assumed to be applied in the middle of the beam, and therefore transmitted to a_1 as $F_{Wz(max)}/2$. Likewise, the generated torque is, according to the theory of structures for a beam fixed on the extremes:

$$M_{Wy} = \frac{F_{Wz(max)} \times Lenght\ of\ the\ crossbar}{8}$$

$$M_{Wy} = \frac{272.03 \times 0.5}{8} = 17.00\ Nm$$

Analogously:

$$F_{Pz} = \frac{Weight\ of\ the\ fixed\ platform + Weight\ of\ the\ tray}{4}$$

$$F_{Pz} = \frac{(7.15 + 1.5) \times 9.81}{4} = 21.21\ N$$

$$M_{Px} = \frac{F_{Pz} \times Lenght\ of\ b_1}{4}$$

$$M_{Px} = \frac{21.21 \times 1.5}{4} = 7.95\ Nm$$

$$F_{Tz} = Weight\ of\ the\ transmission = 1.77\ \times 9.81 = 17.36\ N$$

$$M_{Ty} = \frac{F_{Tz} \times Lenght\ of the\ crossbar}{8}$$

$$M_{Ty} = \frac{17.36 \times 0.5}{8} = 1.09\ Nm$$

4.2.3 Finite Element Analysis

After loads were determined, a FEM analysis was performed, in order to obtain valuable data regarding the maximum displacement produced in the beams and the factor of safety achieved, applying the von Mises Stress failure criterion, traditionally used in metallic, ductile materials such as aluminium. The type of mesh used in the simulation was curvature-based, made of second-order elements, which means that the elements' shape and size was automatically adjusted, depending on the complexity of the solid on each point. A curvature-based mesh has, therefore, permitted the team avoiding the use of mesh controls in the grooves of the aluminum beams.

4.2.3.1 Flexion analysis of horizontal bars

In the case of the studied horizontal bar of 1500 mm, the external load was introduced as a distributed force on the upper surface of the beam. Fixtures consisted on simple embedded ends, applied on the portion of the beam that would be covered by the actual joints. The size range of the elements generated in the mesh was: 4.22 mm – 21.10 mm.

Figure 22 shows the results yielded by the factor-of-safety simulation. A minimum value of 1.78 is reached next to the embedded joints. However, the value obtained in the middle of the beam, 3.77, has been considered to be the most representative of its real behavior as, according to the theory of FEM analysis, it is usual that singularities are introduced by the supports, these peak values that occur right at the connection are not of interest (Plos, 2014). In the case of the resultant displacement study shown in Figure 23, the maximum value obtained, due to the flexion of the beam, is 1.07 mm on the middle of the bar, as expected.

It can be concluded that, in terms of flexion of the horizontal beams, the structure is resistant enough for the working conditions, as a factor of safety over 3 is considered acceptable in most engineering applications. Automobiles tend to use values around 3.0 and buildings commonly apply a less restrictive condition of 2.0 for each structural member (Burr & Cheatham, 1995). On the other hand, a vertical displacement of 1.07 mm can be considered to be between the acceptable margins, as the beam will not be deformed permanently and the deflection suffered when the loads are applied will not compromise the functioning of the cart, apparently, confirming it in the prototyping phase.

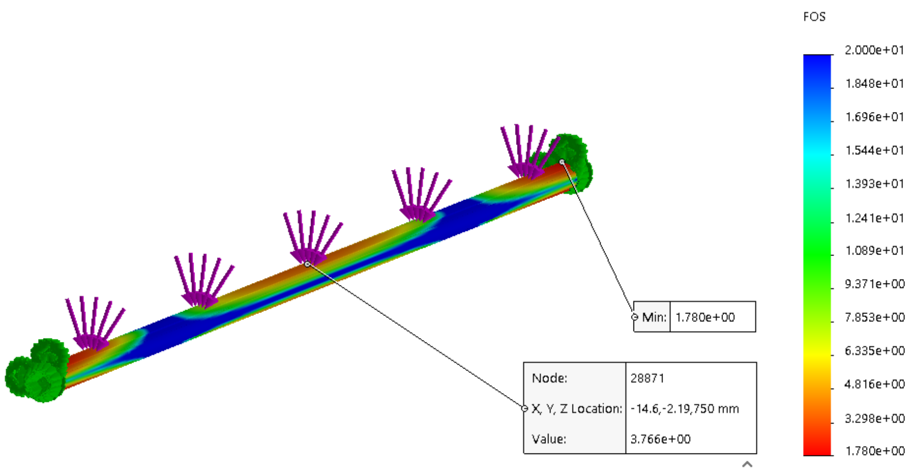

Figure 22. FEM results for a_1 beam. Factor of safety.

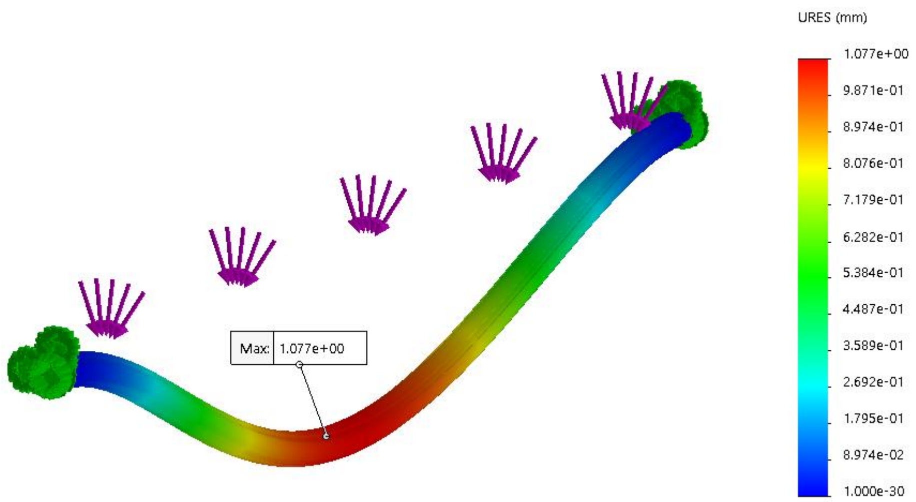

Figure 23. FEM results for a_1 beam. Resultant displacement.

4.2.3.2 Buckling analysis of pillars

In the case of the buckling simulation of d_1 pillar. Forces and torques were introduced, again, distributed in the surface of those portions of the beam corresponding to the contact of the joints, which in this situation act as supporting elements and simultaneously introduce loads into the bar, except from the bottom linkage of the pillar, that has been simplified as an embedded constraint. The size range of the elements generated in the mesh was: 4.61 mm – 23.06 mm. Figure 24 shows that the load factor obtained is 0.35, with mode shape of 1, meaning a high chance of experiencing buckling in the pillars. To conclude, this figure would be taken into consideration in the prototyping phase, so that if the effect was observed in the final prototype, extra supporting bars would be added in order to prevent it.

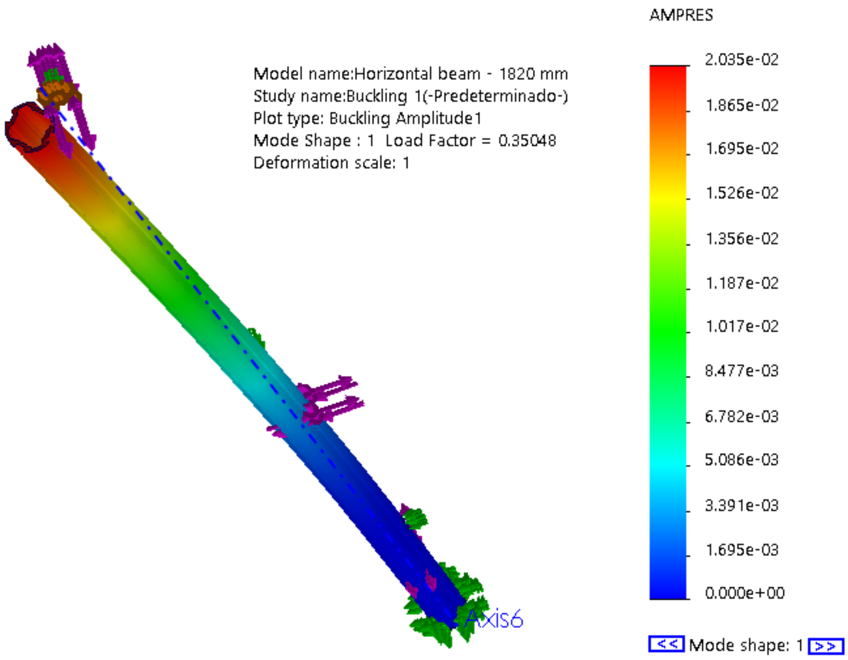

Figure 24. FEM results for d_1 pillar. Buckling effect.

4.3 Ergonomics assessment

Once the main dimensions of the SPC (self-propelled cart) have been set, based on the boundary conditions and the functioning requirements brought up by the mechanical analysis, it has to be verified that they are equally correct from an ergonomics perspective, according to the current *Volvo Ergonomics Directive* (Volvo Group, 2017).

4.3.1 Consideration of anthropometric diversity

In order to validate Volvo's directive, its consideration of anthropometric data has been compared with a study carried out in 2008, which compiled anthropometric information of Swedish population from a total of 367 subjects, 105 males and 262 females (Hanson, 2008).

The following figure shows the different body measures considered in the directive, on which its ergonomics regulations are based, which "correspond to the situation of a worker wearing shoes (equivalent to 30 mm)" (Volvo Group, 2017).

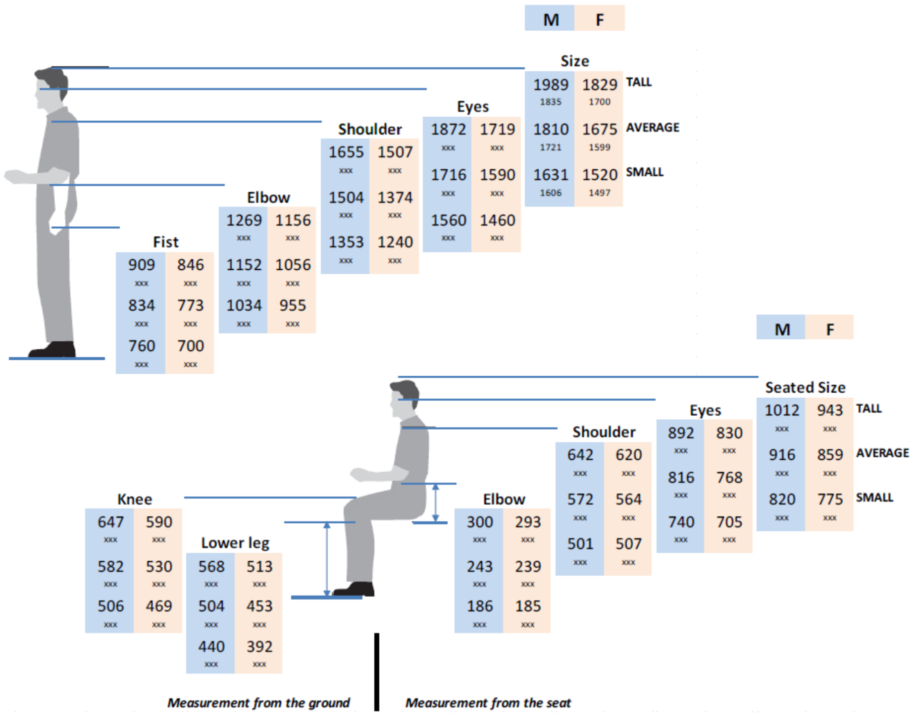

Figure 25. Anthropometric data (Volvo Group, 2017).

The body dimensions that better represent the ergonomics of the self-propelled cart have been chosen to be stature, shoulders height and arm length, in a standing position. Table 8 gathers the values obtained by the previously mentioned article in terms of percentile:

Table 8. Anthropometric descriptive statistics of Swedish population (Hanson, 2008).

	Male (mm)			Female (mm)		
Body measure	5th	50th	95th	5th	50th	95th
Stature	1669	1779	1902	1562	1673	1789
Shoulder height	1333	1459	1548	1252	1357	1468
Elbow height	1020	1108	1181	957	1044	1130

As it can be observed, if the 30 mm, corresponding to the shoes of the operators, are added to each measure, the range of dimensions of Swedish population between 5th and 95th percentile is considered by the directive taken as a reference, which means that its regulations can be described as correct, in terms of anthropometric diversity.

4.3.2 Workstation accessibility and dimensions

According to *Volvo Ergonomics Directive*, regarding the pedestrian access to the workstation:

- The width of the walkway that the operator uses to reach the workstation must be of, at least 800 mm.
- The width of the area in front of the workstation must be of at least 1000 mm.
- If the operator turns his back on a corridor where vehicles are likely to pass through, previous measure must be increased up to at least 1500 mm.

Regarding level changes, in case of a ramp, If the maximum height of the ramp is over 250 mm and its climbing frequency is bigger than 20 times per hour:

- The slope must be lower than 15°
- The minimum width of the ramp must be bigger than 1200 mm.
- It should always be highlighted with black and yellow stripped paint.

Regarding level changes, in case of stairs, its dimensions must always respect the following formula:

$$600\ mm \leq G + 2H \leq 660\ mm$$

Where G represents the step tread depth, with an optimal dimension of 290 mm and H represents the height of the steps, with an optimal dimension of 150 mm.

Regarding the dimensions of a standing workstation, some of the regulations of *Volvo Ergonomics Directive*, retrieved from the standard *ISO 14738:2002* (Swedish Institute for Standards, 2002)*,* are:

- The height of the operator's hands, stated as one of the critical elements of the ergonomics of a workstation, must be of at least 1000 mm, when freedom of the upper limbs is required.
- An extra space for the operator's feet must be included beneath the workplace. Its dimensions must be of at least 150 mm of height and 130 mm of depth inside the working bench.
- The horizontal width of the working surface should be of at least 480 mm and must be of at least 1170 mm, for standing, repetitive work.

4.3.3 Working posture

Most regulations under this heading refer to the frequency of the activity that is being carried out. In this case, by observing the cycle time of the assembly of one oil pan at the main assembly line, it can be assumed that the frequency of each task in the material handling line will be of 10 to 30 times per hour. Considering this, the main norms that concern our case are:

- Flexion of the trunk should not exceed 20° and must never reach 45° (0° straight position) If the operator's trunk is not supported.
- Hands of the operator should be able to reach most frequently used objects within a radius of 200 mm, less frequently used objects within a radius of 300 mm and 400 to 500 mm only in exceptional cases.
- Frontal lifting of the arms should be under 60° and must never exceed 90° for the calculated lifting frequency.
- A maximum of 12 kg can be lifted within the zone A shown in the figure below, 7 kg in zone B, and never reach zone C, under the estimation made on the lifting frequency.

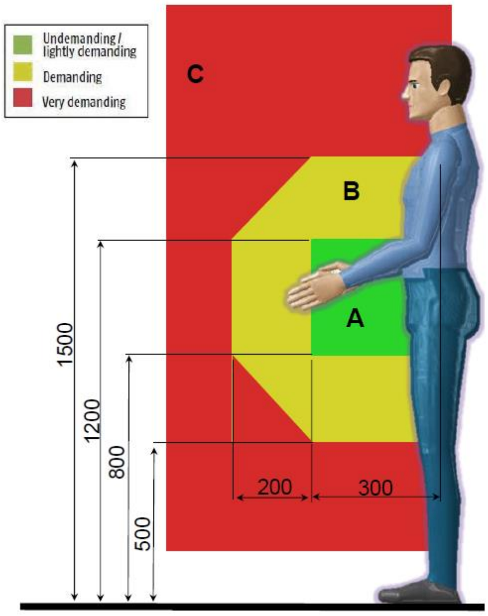

Figure 26. Workplace allowed lifting areas chart (Volvo Group, 2017).

4.3.4 Regulation of kitting trolleys

As the design of the self-propelled cart reveals similarities with a kitting trolley, the following standards have been considered to be relevant:

- Placement of the parts inside the trolley must minimize manipulation movements such as turning or rotation.
- The cart should be designed to be compatible with lifting device if needed.
- Parts inside the kitting cart must be placed stable and secured. Extra fixation might be needed to prevent the parts from falling during the transport.
- Prevent including sharp edges in the design of the cart, which would be considered as a cutting hitting risk.
- Minimize the total height of the cart to prevent overturning.

Handling and push/pull forces have not been considered, since the transport function of the self-propelled cart is automatic.

4.3.5 Ergonomics considerations, incompatibilities and possible solutions

The current design of the self-propelled cart (SPC) shows some incompatibilities with *Volvo Ergonomic Directive* (VED) regulations that must be considered:

- Regarding workstation accessibility, the current space has been checked to meet VED requirements. As the design of the SPC is made for a batch of a single oil pan, its dimensions are narrower than the existing cart, which means that the surrounding work areas would not be reduced.
- In terms of workstation dimensions, the rear axis of the SPC would represent an obstacle for operators' feet, as the clear space beneath it does not meet VED requirement of 130 x 150 mm.
- In relation to the lifting postures, the current design would force most operators to lift their arms over the limit of 90°, placing the oil pan over the B zone shown in the

figure above. Furthermore, the oil pan must be turned upside-down before being placed in the SPC and the weight of the metallic one exceeds the 7 kg limit (zone B).

- Concerning safety, lateral roller conveyors present sharp edges that could cause injuries in case of an impact. Secondly, the oil pan must be placed in a high point to be able to propel the cart, which might increase the risk of overturning. Finally, the SPC is designed to cross over a walkway automatically without an emergency braking system, which would represent a risk for the pedestrian and vehicles traffic.

Likewise, conceptual possible solutions and measures to be taken have been generated and will be left for further study:

- Placing a platform in front of the SPC for the operator to step on would eliminate the problems regarding the excess of lifting height and the need of clear room for the operator's feet. A sketch of the concept is shown in Figure 27.
- As it has been mentioned under previous headings, the existence of the current lifting device must be considered, which would highly reduce the load and ease the general handling of the oil pan.
- Stability of the SPC during the transport can be easily improved by displacing the rear axis backwards, which would increase the overall wheelbase, if needed. Likewise, although it is not desirable, the weight of the wheeled base could be augmented for this purpose.
- Sharp edges of roller conveyors can easily be reduced to rounded corners maintaining their functionality.
- Light-signalling devices and right-of-way regulations can be implemented to enhance traffic safety while the SPC is crossing over the walkway between lines.

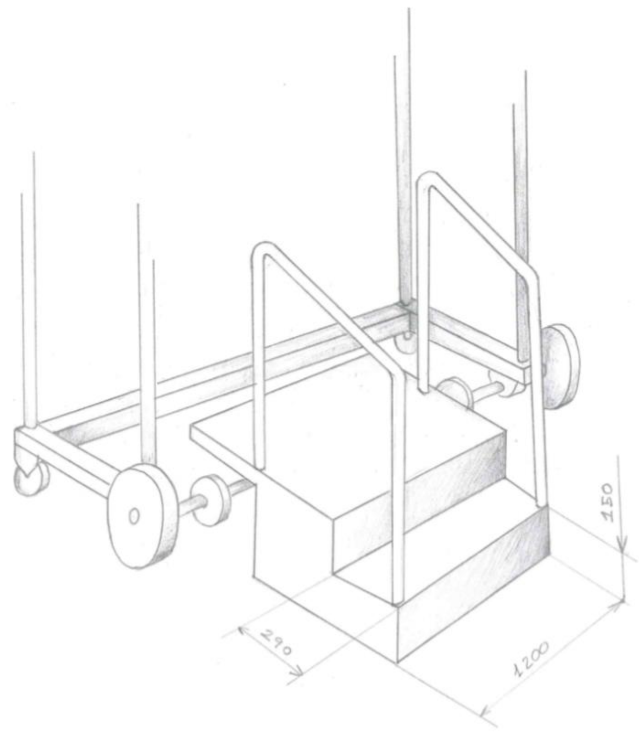

Figure 27. Concept sketch of stepping platform.

4.4 Prototyping. Proof of concept.

The prototyping phase started with the realization of an alternative, simplified CAD model, which would arrange all the components that would be used in this preliminary prototype, widely differing from the ones that will be used in the final product. Majorly, the use of cheap, heavy, steel profiles and joints involved the need of improvised redesign. An overview of the result is shown in Figure 28.

Figure 28. Proof of concept. Perspective.

A brief description of the decisions made during the process, shown in Figure 29, would be:

- Specific transmission components like the racks, pinions gears and pulleys were decided to be manufactured using 3D printing, as they are cheap, lightweight, and their dimensions are easily adjustable. The 3D printer has a maximum printable size and long printing times, so the transmission reduction was limited by the available printing space even though some components were redesigned and printed into several pieces that would afterwards be assembled. The material used (PLA), the fill material percentage inside the component and their shape, played a major role when defining the correct parameters with which to print the parts correctly. In some cases, it was observed sudden material contractions, called warping, that apparently happened when the plastic cooled down faster than desired and the part that was being printed bent up from the build plate, especially in the corners. This problem was mostly solved by printing an adhesion 'raft' under the printings that helped to dissipate heat in a controlled manner.

- Bending of the rack and the bar to which it is attached caused the transmission to dismount and interrupt the needed transmission of radial forces between racks and gears. A guiding system made with two big bearings and washers was built in order to maintain in place the rack satisfactorily solving the problem.

- Although steel profiles were over dimensioned and their resistance exceeded the needed in most of the structure, triangular reinforcements had to be introduced to assist the alignment of the joints, as they were not designed to cope with relatively high torsional forces.

Figure 29. Proof of concepts. Details.

4.5 Proof-of-concept evaluation.

After first prototyping phase was accomplished and the self-propelled cart had proven to be able to move in both forward and backwards directions, the need of evaluating the performance of the prototype was agreed. This evaluation was based on the variation of working loads and counterweight values, metallic wastes from the sand jetting system that hardens the surface of engines blocks, as depicted in Figure 30.

Figure 30. Use of metallic sandbags for varying and measuring working loads.

As a starting point, in order to clarify the working boundaries of the system, the minimum counterweight (hereinafter CW) that would make the cart move backwards (at a minimum speed) was measured. This limit was set on 14 kg (including CW buckets and guiding systems). The minimum load that would be able to lift this CW and start propelling the cart forward was observed to be 10 kg (weight of the lifting platform not included).

Once minimum values of load and CW that would produce motion were recorded, it was observed that, obviously, this load baseline would variate if CW value is increased, so the working limit could be better represented by a curve of load-CW combinations than by a single point. These values are shown in Figure 31:

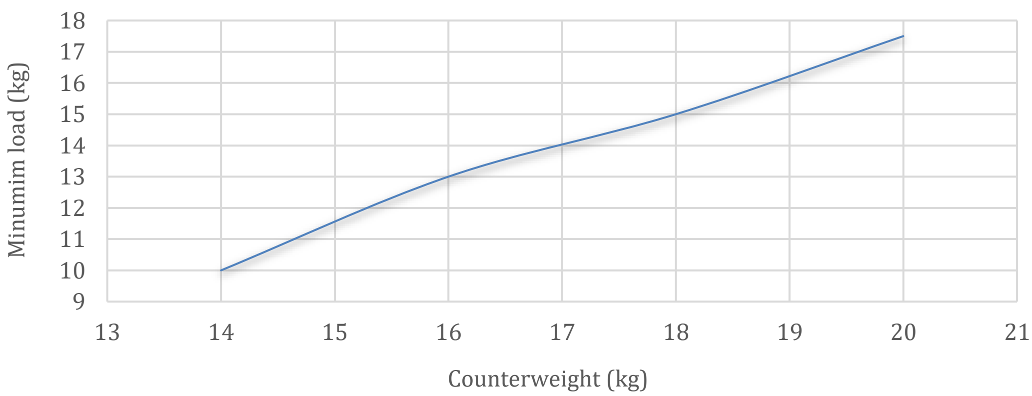

Figure 31. Values of counterweight (X axis) and minimum working load (Y axis).

After the functional baseline was set, the actual performance of the cart was assessed within two speed tests. Firstly, the average speed of the backward movement for different values of CW were calculated, based on the travelled distance and the delivery time. Results are shown below:

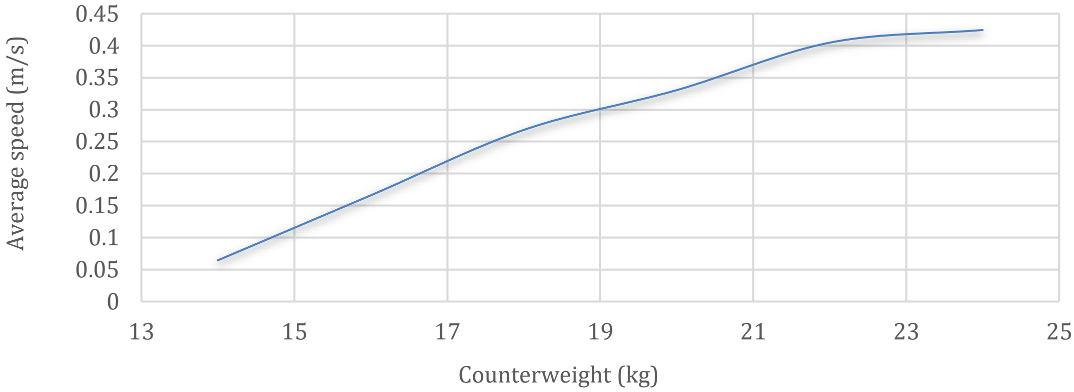

Figure 32.Values of average speed (Y axis) and applied counterweight (X axis).

Finally, a CW of 16 kg was selected as the minimum value for 'acceptable' backward motion. Fixing this parameter, the average speed of the forward movement could be measured based, again, on the delivery time and the distance travelled, varying the transported load. Results are the following:

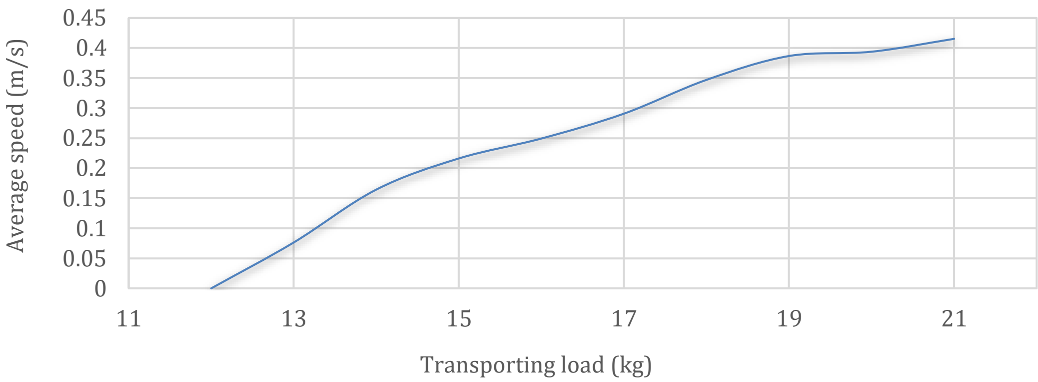

Figure 33. Values of average speed (Y axis) and applied load (X axis).

After accomplishing the different tests carried out, the following observations must be mentioned:

- The horizontal displacement of the cart was 1.91 meters, determined by a vertical displacement of 0.275 meters on the lifting platform, which was limited by the length of the 3D printed racks. The goal is to reach 3.20 meters, approximately. This could be achieved by either extending the length of the rack, which would have a negative impact on the operational ergonomics, or increasing the reduction of the transmission system, declining its speed and augmenting minimum working load and CW.
- The surface finish of the floor has a considerable impact in the movement of the cart. Small amounts of dirt or discontinuities in the paving can cause the system to brake completely, specially at the beginning of the displacement. Values of minimum counterweight and load to produce motion were observed to be significantly different

when testing the cart in the prototyping workshop and the assembly line. The curves shown above correspond to values obtained in the assembly plant.

- An asymmetric application of the load on the lifting platform does not have a relevant impact on its functioning, apparently, which is highly satisfactory, considering the weight asymmetry of the oil pans to be transported.
- The speed of the cart increases over reasonable limits closer to the end of the movement, and it suddenly brakes once the rack has reached its functioning limit, causing the wheels to drift over the paving and displacing the cart from the desired transport path. A braking system, which would preferably accumulate the kinetic energy lost, such as regular or torsional springs, is desirable to be introduced in the next prototype.
- Curvature of the line charts shown above resemble a non-lineal behavior when the speed of the cart increases above 0.4 m/s, approximately. This phenomenon can potentially occur because of the appearance of an aerodynamic resistance that can no longer be negligible. Likewise, efficiency of the transmission system might decrease for relatively high values of load and speed.

5 Sprint 3

5.1 Risk assessment

As part of the analytical phase of the beginning of the third sprint, a risk assessment was elaborated. It was carried out trough observation of the prototype built during the second sprint and the workplace where the cart would be implemented. The task was performed in collaboration with safety experts within Volvo, who provided the group with the risk-assessment layout that is currently being used in the plant. The assessment result can be found the **Appendix B.**

The layout shown in the appendix includes a list of all the possible risks that the cart can represent towards its users, followed by an estimation of their probability of occurrence and their severity, rated from 1 to 5. A multiplication of these two values automatically yields a risk index that is linked to a color and provides the urgency of taking safety countermeasures (Red: The risk requires direct action. Yellow: The risk requires action in the near future. Green: Continuous improvement.)

Right after the preliminary assessment, all the planned safety countermeasures were also included in the layout and the soring was repeated, yielding satisfactory results. Most of these countermeasures will be left for further development. They will be taken once the self-propelled cart concept is approved for its implementation.

5.2 Failure modes and effects analysis (FMEA)

Besides the risk assessment, a functional analysis of the cart was also needed before the prototyping phase of the third sprint. This stage, in the shape of a FMEA, would provide valuable information regarding the functional inconsistencies that the previous prototype showed, their impact on its performance and possible solutions that, again, will be implemented on the final prototype or left for further development, according to availability of resources and complexity of the countermeasures.

The FMEA chosen layout is based on the well-known Six Sigma techniques, described on *The Design for Six Sigma Memory Jogger* (Ginn, 2004). As it is shown in the **Appendix C**, it lists the different subsystems of the mechanisms that might be susceptible of failure, followed by the description of the possible effects of those subsystems failing. These failure modes are evaluated and rated in terms of severity, continuing with a list of the potential causes of these failures and a second rating based on its likelihood. Likewise, the current controls that are used to identify these failures are described and their effectiveness is also punctuated. Finally, an index called Risk Priority Number (RPN) is calculated by multiplying the three previous scores, providing a ranking of the urgency of solving the different functional inconsistencies of the design.

According to the results, the priority would be to reinforce the SPC pillars, as they were estimated by the FEA to suffer buckling effect; changing the 3D-printing material to nylon, which provides higher values of resistance and flexibility than PLA and would be appropriate for full production; and reinforcing the axis of the counterweight pulleys, which tend to bend under regular working loads, causing the tensioning cables to leap out of the pulleys' grooves and abruptly stopping the mechanism.

5.3 Prototyping. Refinement.

The second and final prototype (Figure 34) was built using the 3D-Mock-Up model developed in the first sprint as a reference, introducing the purchased aluminum components from a karakuri specialized supplier. The methods used to build the second prototype were similar to the ones followed in the previous model, making use of the wide variety of tools available in Volvo's maintenance workshop.

Figure 34. Refined prototype overall perspective.

With the objective of achieving a final prototype closer to the target specifications with respect to the previous one, several upgrades were made (Figure 35) in order to enhance the operating parameters, the mechanical efficiency of the transmission, the ergonomics, safety, etc.

- Specialized, aluminum profiles composed the entire frame. Many of these beams presented specific section shapes for easing the coupling of aluminum-casted joints or provided grooves for the adjustable fixation of tensioning-cable pulleys and rolling wheels. The aluminum-manufactured frame provided a much lighter cart, which considerably improved its performance in comparison with the previous cart, but also the ease of assembly, as the majority of the components were smartly designed to be easily mounted.

- Regarding the arrangement of the transmission, racks and spur gears were modified. The main improvement was the use of nylon filament instead of PLA in the 3D-printing of the gears, providing a remarkable resistance improvement, close to the one needed in components usable in full production. This decision was made after noticing that the previous PLA gear started to show wear in the point of contact with the rack teeth. Changing the material and sanding the surface of the rack teeth finally increased the smoothness of the transmission working, reducing the losses and improving its efficiency.

- Furthermore, the rack length was extended. The previous prototype rack length was 27,5 cm, providing a total of 2 m of horizontal displacement of the cart. This was decided to avoid problems of travelling longer distances and focusing on demonstrating the basic principle of the cart. Now that this target was accomplished, the rack length was extended to the corresponding longitude that provides the actual horizontal distance between stations, 3,19 m, this is, a total of 53,1 cm of rack length. The parts used for the previous rack were reused, and extra mid-parts were printed and introduced.

- In addition, the flexion of the transmission axis caused by the mounting tension of belts has a considerably negative impact, as maintaining a parallel contact of the teeth of the gear with the ones of the rack ensures a correct transmission of the forces. Therefore, in order to reduce this bending, the tube to which pulleys and gears are attached was shortened, minimizing the misalignment.

- In terms of resistance, as FEM analysis predicted, critical buckling was experienced on the pillars of the structure. As it might be expected, the aluminum profiles provided a lightweight design, at the expense of its rigidity. The issue was rapidly solved by introducing triangular reinforcements.

- Regarding safety, some of the improvements described in the risk assessment were included, such as handlers or striped warning stickers to avoid the operators putting their hands in the guiding pillars.

- Finally, in an attempt to improve the energetic efficiency of the cart, longitudinal springs were introduced at the end of the travel of the lifting platform, helping the cart to break on its way forward but also providing it with an initial impulse that would decrease the counterweight needed for the forward motion.

Figure 35. Improvements performed trough prototyping.

5.4 Final evaluation.

Once the prototyping phase of the project had concluded, in favor of comparability, it was decided to assess the unit analogously to the previous prototype. First, the search of the minimum counterweight able to move backwards the cart to its initial position yielded a value of 11 kg, and the corresponding minimum load able to lift it was 7 kg. Again, the next step was finding the corresponding values of minimum transporting loads to several heavier counterweights. The result is the following.

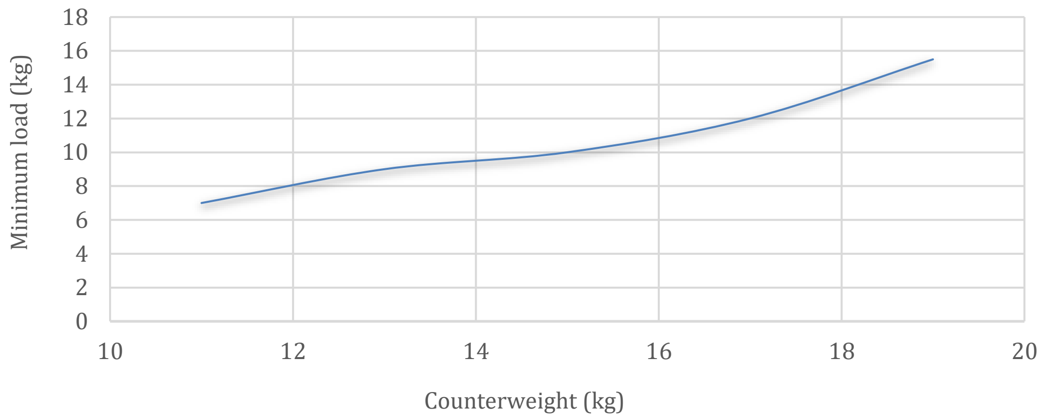

Figure 36. Values of counterweight (X axis) and minimum working load (Y axis).

As it may be observed in Figure 37, a frame made of aluminum reduced the minimum counterweight able to move backwards the cart in 3 kg, as well as the minimum load needed to lift it when going forward. The second test, average backwards speed – counterweight values, also provided the expected results from a lighter cart, which could also take advantage of the impulse generated by the installed braking springs, travelling at higher speeds:

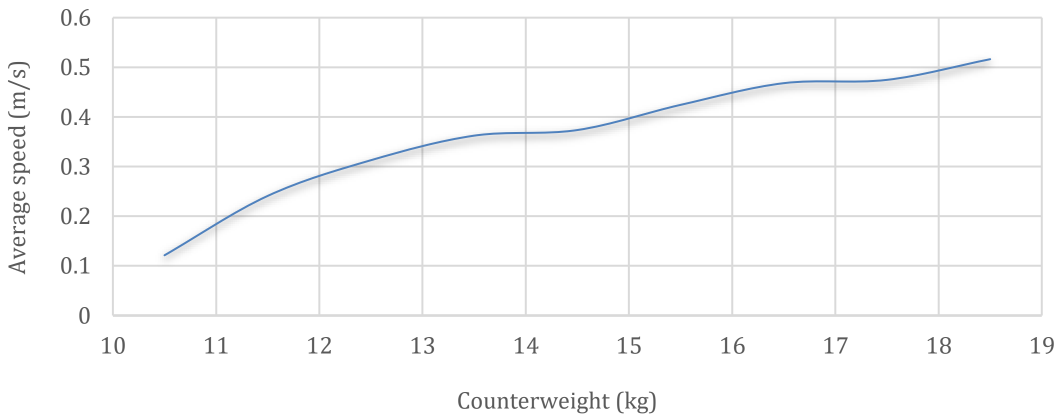

Figure 37.Values of average speed (Y axis) and applied counterweight (X axis).

Finally, the forward performance was reviewed with increasing values of load. For this to happen a counterweight value had to be fix, for all the load values. The counterweight chosen weighed 13 kg, as it provided an acceptable backwards speed even if it was not the minimum value. The load-time plot that this third test yielded was the following:

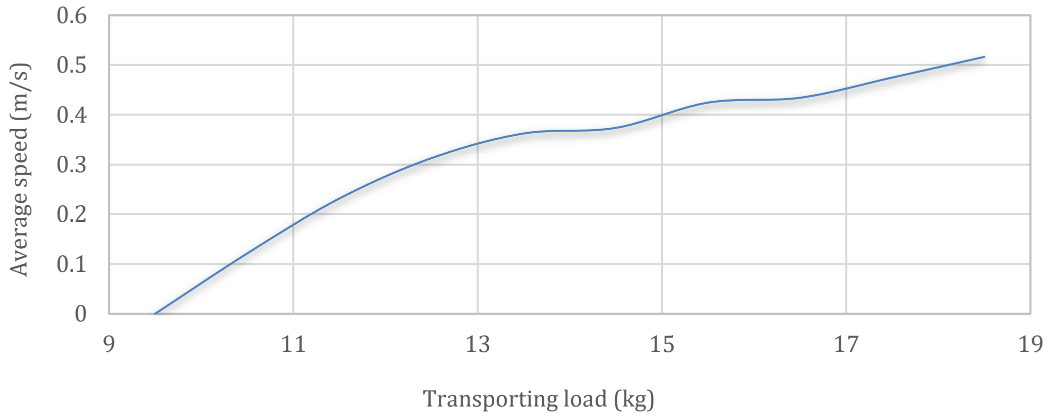

Figure 38. Values of average speed (Y axis) and transporting load (X axis).

As expected, the average speeds upgraded from the last prototype. As an example, for a 15 kg load, the first prototype reaches an average speed of 0,23 m/s, while the second reach an average speed of 0,37 m/s. To finalize, some observations must be mentioned:

- Despite travelling a longer horizontal distance, there is an obvious influence of the improvements described under the previous heading on the dynamic behavior of the cart (Figure 39). The refined prototype is now able to transport the plastic oil pan, which was the most energetically restrictive with acceptable values of speed, target that was not achieved with the previous configuration.

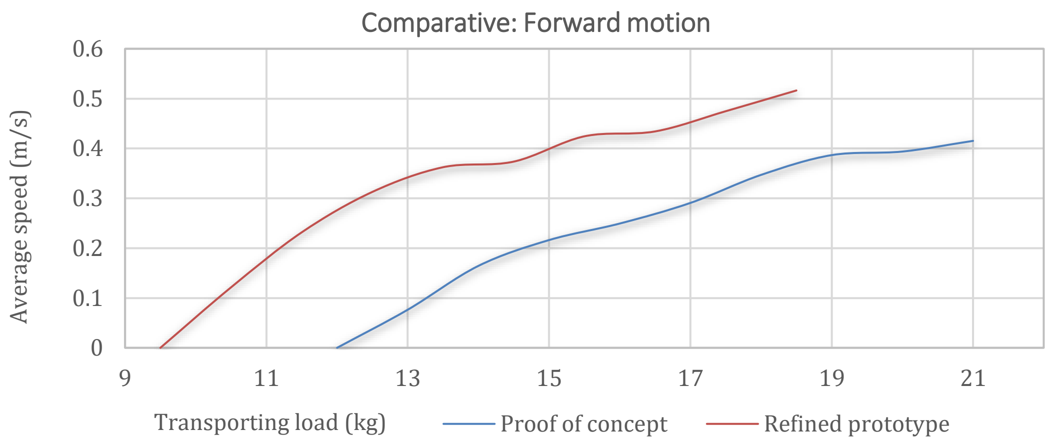

Figure 39. Comparative of the performance of prototypes.

- As it was stated before, in order to simulate the floor conditions of the assembly facilities, several metal sheets were placed in the floor to provide a clean and smooth surface to travel. The result is a paving with a finish surface slightly better than the actual working conditions, which has to be taken into consideration.

- As it happened with the previous prototype, the curves show a non-linear behavior when reaching certain speeds, which may have its origin, as it was stated in the previous evaluation of the concept, in the aerodynamic resistance and/or the system efficiency for high loads and speeds. Whether one or the other reason is the most likely must be assessed further.

6 Implementation plan

Under this heading the reader will find a brief description of what an implementation plan for the self-propelled cart should include. The plan is based on Volvo's current procedures, when introducing new technology into the assembly stations, which describe the proper sequence to elaborate operating standards at the workstation, ensuring quality, safety and efficiency.

- Elaboration of the Standard Operating Procedure (SOP): Once the prototype has been iteratively tested and refined so that it fulfills production requirements, a multidisciplinary team must arrange a session to test the cart and elaborate the standard operating procedure that will be used as a reference when handling it. This team should include, at least, some of the operators belonging to the modified station, quality and safety experts and, in the case of the implementation of new technology, such as the SPC, the engineers who developed the new system. Together, they must agree on establishing tentative standards that are satisfactory in terms of productivity, safety and quality. The engineers developing the system play a crucial role in this session, as they will be in charge of sharing the acquired knowledge of the cart functioning to all the parties involved. Figure 40 shows an example of the layout containing the tentative standards of an SOP belonging to the assembly of an oil pan.

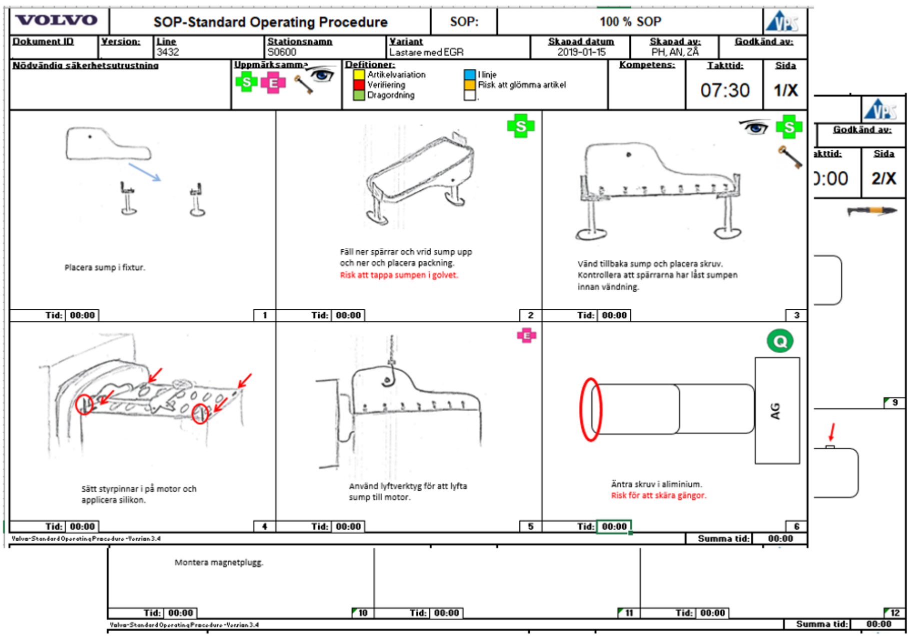

Figure 40. SOP layout example.

- Analysis of the Job Cover Matrix: Once the initial SOP session has been accomplished and the tentative standards are set, the Job Cover Matrix, containing the assigned tasks for each operator has to be carefully analyzed to decide which are the workers susceptible to be trained in the functioning of the cart, and indicate it in the matrix to be able to visualize it. Figure 41 contains a typical Volvo's JOB Cover Matrix.

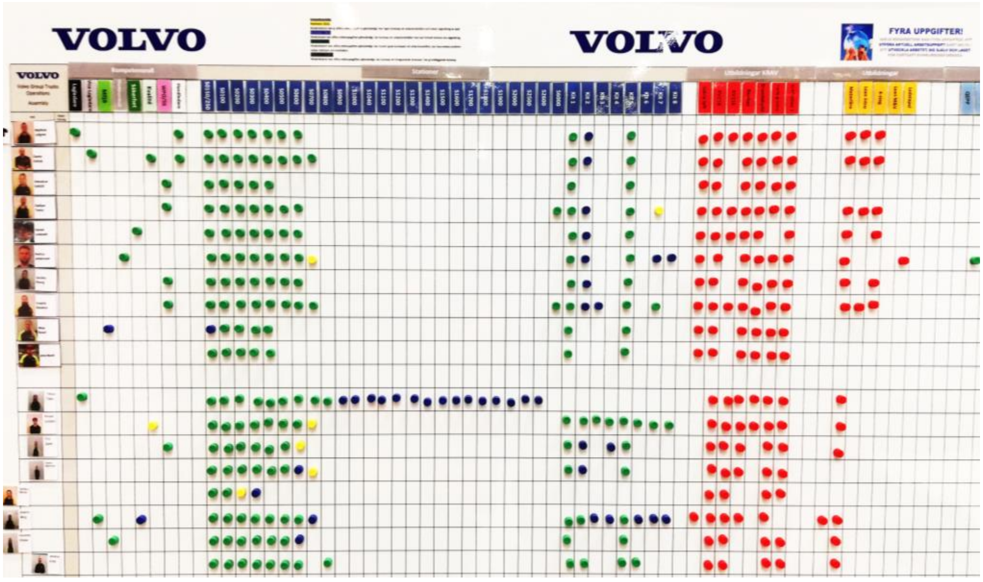

Figure 41. Example of a Job Cover Matrix.

- Training with 4 step method: Finally, selected operators must be trained by the responsible engineers or team leaders following a method that eases the assimilation of the procedures stated in the SOP. This is done through four steps, consisting of an introduction and detailed oral explanation of the standards, followed by a demonstration of the use of the cart, a practice phase where the trainer is allowed to interact with the operator and a final follow up stage, reviewing that all standards are satisfactory accomplished without the need of interaction.

- SOP audit: If operators have been successfully trained, the final, iterative stage is to perform SOP audits, which means that the responsible engineers must periodically revise the effectiveness of the established standards trough close observation of the cart functioning in the assembly line. For new products, it is recommended to perform an SOP audit right the day after the cart has been implemented, a second audit the week after, and repeating the process weekly up to five times. During this trial time it is also needed to have a backup plan in case of unexpected failure, otherwise the malfunctioning of the self-propelled cart can lead to a costly production interruption. Storing the previous manual-cart model close to the station to be able to quickly replace it is highly advisable.

7 Conclusions and discussion

The completion of the thesis work depicted in the present report, together with its appendixes and the interaction with the collaborating company has led to the accomplishment of the following objectives:

- Successfully introducing into the company insights of the potential of the karakuri philosophy as a low-cost alternative to automate assembly operations. This knowledge transmission has been carried out trough continuous internal presentation of results (up to 7), in the presence of representatives of all stakeholders.

- It has hereby been proved that Scrum, a methodology traditionally used for software development, is capable of enhancing design of production equipment, especially when complex, pragmatic solutions are needed to be presented within tight deadlines. The main differentiation with traditional stage-gate methodologies has been found to be the requirement of constant delivery of solutions that get defined iteratively through the process.

- A correct station selection for the introduction of karakuri has been achieved, providing the company with useful insights of the ideal conditions to implement karakuri solutions in the future.

- A satisfactory, functional prototype has finally been achieved after three loops of iterations. The unit is mechanically capable of transporting the required components within the dimensional boundaries, respecting, to a mayor extent, ergonomics and safety limitations. If this product is finally implemented into Volvo's production is unknown. However, the demonstration of its functioning, the use of standardized parts from karakuri suppliers and the type of constructive arrangements that have been discovered has set a precedent in Volvo's assembly plant and will be considered as an example for future development of material handling solutions.

- In general, documentation generated through the developing process has successfully become the main contribution made so far to a global project within Volvo, beyond the scope of this thesis, designated GTO RAE: Increase KARAKURI Knowledge.

After defining the goals achieved, it is also relevant to describe the weaknesses that the project presents, which mostly have to do with the pre-study phase:

- Prior to the start of the project, a design method, Scrum, and development philosophy, karakuri, were settled by the company. Although these two concepts have been found to be highly valuable for the fulfillment of the company requirements, the thesis lacks further investigation of other alternatives and a clear statement of the advantages of the selected strategies over the others existing.

- Tight deadlines and long shipping times of supplies have forced the assumption of solutions quite early in the development process. Otherwise, a broader view of existing karakuri concepts and a deeper benchmarking of suppliers' constructive arrangements would have been beneficial. In terms of the adopted solution, dealing with the alternatives presented in the concept generation phase in a more exhaustive way would have led to the prototyping of the most promising ones. Reaching this stage with various alternatives would have provided valuable information towards concept evaluation, being, for example, able to compare self-propelled focused concepts with fixed-structure inspired ones.

To finalize, if the product were finally decided to be implemented, further development is needed in the aspects listed below:

- There is a mayor need of enhancing the efficiency of the cart. Even though a refinement of the transmission dimensions and components could improve its mechanical performance, an energetic balance would report that most of the kinetic energy reached during the transport is lost when the cart breaks at the extremes of the walkway. The last prototype, however, introduces small springs at the end of the lifting platform's travel that accumulate some of the kinetic energy and provides an impulse that assists the beginning of the backward motion. Furthermore, the implementation of purchased torsional spring would improve this energy recovery, acting on the whole displacement of the cart and balancing its speed.

- Solving the compatibility with the rig system that collects the oil pans would also be necessary. Elements such as stoppers that would automatically release oil pans when reaching the destination, sub-transport of screws and guiding devices to avoid the accumulative deviation of the cart must be designed.

- Fully developing the alternatives described to meet the ergonomics requirements stated in the assessment is advisable, before putting the cart into production.

- Adapting the design to the future, heavier oil pan that will be assembled in the main line, together with the ones already considered, is mandatory. Although the flexibility of the current design should be able to cope with its dimensions, it must be formally reviewed.

- Finally, if previous design issues get solved, preparation of the documentation needed for the introduction of full production equipment into the plant will be necessary: Manufacturing plans, a bill of maintenance materials and a statement of the maintenance procedures, ending up in a registration of the cart in Volvo's economical system for further follow up of its costs.

To conclude, it is important to describe general aspects of the work performed in relation to ethics. Designing systems to enhance the efficiency of production, as well as products that involve a significant reduction of the environmental impact and fulfil the upcoming necessities of the society, is an inherent responsibility to the design profession's role. The solution developed aims to embody the potential of *karakuri* towards production streamlining, by creating motion out of the most sustainable source of energy, gravity. From the human perspective, it constitutes an alternative to heavy automation that enables an equilibrium between automated systems and blue-collar work.

Karakuri allows the engagement of executives, engineers and operators in the pursuit of a leaner, inclusive and sustainable production.

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Appendix A
Dynamics Calculations

1 Initial data

The data set from the boundary conditions, depicted in the main body of the report of this thesis is the one shown in the following table:

Table 1. Input data of the mechanical analysis.

Weight data		
Weight of the Cart	64.49	kg
Plastic Oil Pan Weight	6.00	kg
Metal Oil Pan Weight	15.00	kg
Lifting-Platform Weight	16.47	kg
Geometric dimensions of the transmission		
Rear Wheel Radius	0.1	m
Front Wheel Radius	0.05	m
Radius Pulley 1	0.05	m
Radius Pulley 2	0.15	m
Radius Gear	0.05	m
Distances of the workplace		
Distance to Delivery point	3.19	m
Displacement of the lifting platform	0.53	m
Friction coefficients		
Rolling resistance coefficient nylon - concrete	0.004	Adim.
Inertias (calculated by the CAD software)		
Inertia Rear Wheel (Nylon 101)	0.0053	kg·m2
Inertia Front Wheel (Nylon 101)	0.0026	kg·m2
Inertia Transmission (Pulley 2 & Gear)	0.0118	kg·m2
Inertia Pulley 1 (Fasteners included)	0.0003	kg·m2
Transmission relation values with respect to the rear wheels		
Transmission Relation, Front Wheel (FR)	2.50	Adim.
Transmission Relation, Transmission (T)	0.33	Adim.
Transmission Relation, Pulley 1 (P)	1.00	Adim.
Efficiency values for gears and pulleys		
Gears Efficiency	95.00	%
Pulleys Efficiency	95.00	%
Power loses for the bearings used in the cart		
Bearing Model	7200 BECBP	
Quantity	30	Adim.
Loses per bearing (N·m)	0.0029	N·m
Total losses (N·m)	0.0870	N·m

Transmission dimensions have been selected with the aim of making the cart move the necessary horizontal distance (3,19 m between the main assembly line and the secondary line) with the minimum vertical displacement of the lifting platform, respecting manufacturability constraints (3D printing).

2 Mathematical background of the acceleration expression

As stated in the report, the essential equation of Motion of the Self-propelled cart can be described as:

$$F_t - R_a - R_r - R_d - R_g = m \cdot a + \frac{I_{wr} \cdot \alpha_r}{r_{cr}} + \frac{I_{wf} \cdot \alpha_f}{r_{cf}}$$

2.1 Definition of each term

Let us develop each term and neglect all zero terms. Traction force can be described as:

$$F_t = F_f + F_r = \frac{M_{Tf} - M_{Bf}}{r_c} + \frac{M_{Tr} - M_{Br}}{r_c}$$

Where:

M_{Tr}= Traction moment in the rear wheel (N·m).
M_{Br}= Braking moment due to brake force (F) in the rear wheel (N·m).
M_{Tf}= Traction moment in the front wheel. (N·m).
M_{Bf}= Braking moment due to brake force (F)in the front wheel. (N·m).
r_c= Effective Radius (m).

As the cart is propelled by the rear axis and there is no braking system:

M_{Br} *and* $M_{Bf} = 0\ N \cdot m$; $M_{Tf} = 0\ N \cdot m$, this is $F_f = 0\ N$

Then we have:

$$F_t = \frac{M_{Tr}}{r_c} = \frac{M_T}{r_c}$$

The aerodynamic resistance is usually described as:

$$R_a = \frac{1}{2} \cdot \rho \cdot c_x \cdot A_f \cdot V^2$$

Where:

ρ= Air density (kg/m^3).
c_x= Aerodynamic Coefficient.
A_f= Frontal Area (m^2).
V^2= Horizontal Speed (m/s).

As the structure of the cart uses thin bars, the frontal area of the cart, A_f, is negligible. Likewise, the cart will reach low speeds, around 1 m/s, which makes this term also negligible.

The expression results in:

$$R_a = \frac{1}{2} \cdot \rho \cdot c_x \cdot 0 \cdot 1 = 0\ N$$

The rolling resistance is.

$$R_r = \mu \cdot m \cdot g$$

Where:

μ= Rolling resistance coefficient. (according to nylon wheels suppliers, μ= 0,004).
m= Mass of the cart (kg).
g= Gravity Acceleration (m/s^2).

The drawbar load resistance, as it was stated in the assumptions, in our case is zero as there is no drawbar or load attached to the cart and all the masses introduced (oil pans) in it, will be added to the mass of the cart. In terms of gravitational resistance:

$$R_g = m \cdot g \cdot sen(\theta) = m \cdot g \cdot sen(0) = 0\ N$$

As θ is 0^0 due to the flat surface where the cart is moving the gravitational resistance force is also 0. Likewise, the two first resistance forces are negligible, and the only existing resistance force is the rolling resistance force due to the friction between the wheels and the ground. Moreover, the generic term corresponding to acceleration and inertias is:

$$m \cdot a_x + \frac{I_{wr} \cdot \alpha_r}{r_{cr}} + \frac{I_{wf} \cdot \alpha_f}{r_{cf}}$$

Where:

m= Mass of the cart (kg).
a_x= Acceleration in the X axis (m/s^2).
I_{wr}= Inertia of the rear wheel (m^4).
α_r= Angular Acceleration of the rear axis (rad/s^2).
r_{cr}= Effective rear wheel radius (m).
I_{wf} = Inertia of the rear wheel (m^4).
α_f = Angular Acceleration of the front axis (rad/s^2).
r_{cf}= Effective front wheel radius (m).

The inertia term may be written in function of the traction moment referred to the wheel, necessary to accelerate the wheels and the transmission elements:

$$m \cdot a_x + \frac{M_T}{r_c}$$

Knowing that he relation between any transmission component (j) speed and the wheel speed is:

$$\varepsilon_j = \frac{\alpha_j}{\alpha_w} = \frac{w_j}{w_w} = \frac{M_w^T}{M_j^T}$$

Traction moment may be written as:

$$M_T = \Sigma I_{wheel} \cdot \alpha_{wheel} + \Sigma_{j=1}^{n} I_j \cdot \alpha_j \cdot \varepsilon_j = \Sigma I_w \cdot \alpha_w + \Sigma_{j=1}^{n} I_j \cdot \alpha_w \cdot \varepsilon_j^2 = I_w \cdot \alpha_w + \Sigma_{j=1}^{n} I_j \cdot \alpha_w \cdot \varepsilon_j^2 = \\ = \frac{a_x}{r_{rear\ wheel}} (\Sigma I_w + \Sigma_{j=1}^{n} I_j \cdot \varepsilon_j^2)$$

Thus, the right term may be written as:

$$m \cdot a_x + \frac{M_T}{r_{rear\ wheel}} = m \cdot a_x + \frac{M_T}{{r_{rear\ wheel}}^2} \left(\Sigma I_w + \Sigma_{j=1}^{n} I_j \cdot \varepsilon_j^2\right) = \\ = m \cdot a_x \cdot \left(1 + \frac{1}{m \cdot {r_{rear\ wheel}}^2} (\Sigma I_w + \Sigma_{j=1}^{n} I_j \cdot \varepsilon_j^2)\right) = m \cdot a_x \cdot \gamma$$

Where γ is the equivalent mass factor. Finally, the preliminary, essential equation of motion of our cart results in:

$$F_t - F_r = m \cdot a_x \cdot \gamma$$

Let us now compute the value of γ:

$$\gamma = 1 + \frac{1}{m \cdot {r_{rear\ wheel}}^2} \left(\Sigma I_w + \Sigma_{j=1}^{n} I_j \cdot \varepsilon_j^2\right) = \\ = 1 + \frac{2}{m \cdot {r_{rear\ wheel}}^2} (I_{RW} + I_{FW} \cdot \varepsilon_{FW}^2 + I_T \cdot \varepsilon_T^2 + I_{RP} \cdot \varepsilon_{RP}^2)$$

Where:

I_{RW}= Inertia of the rear wheel (driving wheel).
I_{FW}= Inertia of the front wheel.
ε_{FW}= Transmission relation between front and rear wheel.
I_T= Inertia of the transmission (Gear + Pulley 2).

ε_T= Transmission relation of the transmission.
I_{RP}= Inertia of the rear axis pulley (Pulley 1).
ε_{RP}= Transmission relation of the rear axis pulley (Pulley 1).

2.2 Calculation of the Rear Wheel Traction Force

The torque in the driving wheel depends on the vertical force the platform is generating in the transmission gear teeth.

The vertical force depends, at the same time, on the motion of the cart, this is, forward or backwards, as the weight acting on the gear is different in each case as the weight of the platform includes the weight of the oil pan when going forward, but not when going backwards, as it has already been delivered. The vertical force in each case is:

Forward:

$$F_{V\ Forward} = \left(m_{Lifting\ Platform} + m_{Oil\ Pan}\right) \cdot g$$

Backward:

$$F_{V\ Backwards} = m_{Platform} \cdot g$$

Thus, the torque in the rear axis is, from the transmission relation:

$$\frac{M_{RW}}{M_{Transmission}} = \frac{D_{Pulley\ 1}}{D_{Pulley\ 2}} = \frac{1}{3} \rightarrow M_{RW} = \frac{D_{Pulley\ 1}}{D_{Pulley\ 2}} \cdot M_{Transmission}$$

From now on we will call transmission to the assembly of the gear and the pulley 2, attached to the same axis.
Also:

$$M_{Transmission} = F_V \cdot r_{gear}$$

The we have:

$$M_{RW} = \frac{D_{Pulley\ 1}}{D_{Pulley\ 2}} \cdot F_V \cdot r_{gear}$$

In order to get the traction force in the rear axis:

$$F_t = \frac{M_{RW}}{r_{RW}}$$

As we have two different vertical forces for both motions the we have to different traction forces:

Forward:

$$F_t = \frac{\frac{D_{Pulley\ 1}}{D_{Pulley\ 2}} \cdot F_{V\ Forward} \cdot r_{gear}}{r_{RW}}$$

Backwards:

$$F_t = \frac{\frac{D_{Pulley\ 1}}{D_{Pulley\ 2}} \cdot F_{V\ Backwards} \cdot r_{gear}}{r_{RW}}$$

2.3 Calculation of the Lifting Platform and Counterweight Acceleration

Now the acceleration of both, the counterweight and the lifting platform will be computed, in order to calculate the linear inertias for both forward and backward motion. As they are both joined by ropes, the move with the same acceleration, this is:

$$a_{Lifting\ Platform} = a_{Counterweight}$$

First the relation between linear acceleration and angular or rotational acceleration is the following:

$$a = \alpha \cdot r$$

Where:

a= Linear acceleration (m/s^2).
α= Angular or rotational acceleration (rad/s^2).
r= Radius (m).
It can be stated that:

$$a_{LP} = a_{CW} = \alpha_{Transmission} \cdot r_{gear} \rightarrow \alpha_{Transmission} = \frac{a_{LP}}{r_{gear}}$$

Likewise:

$$a_x = \alpha_{RW} \cdot r_{RW} \rightarrow \alpha_{RW} = \frac{a_x}{r_{RW}}$$

As the pulley 2 and the gear are attached to the same axis:

$$\alpha_{gear} = \alpha_{Pulley\ 2} = \alpha_{Transmission}$$

From the transmission relation of the table:

$$\frac{\alpha_{Transmission}}{\alpha_{RW}} = \frac{W_{Transmission}}{W_{RW}} = \varepsilon_j = \frac{1}{3}$$

$$\alpha_{RW} = \frac{\alpha_{Transmission}}{\varepsilon_j}$$

Combining both expressions, we have:

$$\frac{a_x}{r_{RW}} = \frac{\alpha_{Transmission}}{\varepsilon_j} \to \alpha_{Transmission} = \frac{a_x \cdot \varepsilon_j}{r_{RW}}$$

Concluding:

$$\alpha_{Transmission} = \frac{a_{LP}}{r_{gear}} \to a_{LP} = a_{CW} = \frac{a_x \cdot \varepsilon_j \cdot r_{gear}}{r_{RW}}$$

2.4 Calculation of linear inertias of Lifting platform and Counterweights

The linear inertia for both, forward and backward motion and expressed in terms of acceleration, are the following:

When going forward the parts of the cart moving vertically and hence holding a linear inertia are the lifting platform, the counterweights, and the oil pan that is being transported, thus the inertia is:

$$I_{Forward} = m \cdot a$$

$$I_{Forward} = (m_{LP} + m_{CW} \cdot + m_{OP}) \cdot \frac{a_x \cdot \varepsilon_j \cdot r_{gear}}{r_{RW}}$$

When going Backwards the parts of the cart moving vertically and hence holding a linear inertia are only the lifting platform and the counterweights, as the oil pan has already been delivered, thus the inertia is:

$$I_{Backwaerd} = m \cdot a$$

$$I_{Backwards} = (m_{LP} + m_{CW}) \cdot \frac{a_x \cdot \varepsilon_j \cdot r_{gear}}{r_{RW}}$$

2.5 Essential equation of Motion, for Backward and Forward Motion.

Now that all the inertias to take into account and terms form the original equation have been defined, the complete expression will be assembled for each case, isolating the acceleration which is the variable to compute at the end, in order to dimension the counterweights, as it will be further explained later. The general expression for the essential equation of motion is the following:

$$a_x = \frac{F_t - R_r}{m_T \cdot \gamma + I_L}$$

Where:

$F_t = Traction\ Force\ (N)$
$R_r = Rolling\ resistance\ force\ (N)$
$m_T = Total\ Cart\ Mass\ (kg)$
$\gamma = Equivalent\ mass\ factor\ (adimensional)$
$I_L = Linear\ Inertia\ from\ the\ entire\ Cart\ (m^4)$

For the forward motion, as it was stated before, depending on the oil pan that is being transported, the vertical force in the transmission varies and hence the traction force. In the case of the plastic oil pan (POP):

$$a_x = \frac{\dfrac{\frac{D_{Pulley\,1}}{D_{Pulley\,2}} \cdot (m_{LP} + m_{POP} - m_{CW}) \cdot g \cdot r_{gear}}{r_{RW}} - \mu \cdot (m_{SPC} + m_{POP}) \cdot g}{(m_{SPC} + m_{POP}) \cdot (1 + \dfrac{2}{(m_{SPC} + m_{POP}) \cdot {r_{rw}}^2} \cdot (I_{RW} + I_{FW} \cdot \varepsilon_{FW}^2 + I_T \cdot \varepsilon_T^2 + I_{RP} \cdot \varepsilon_{RP}^2) + (m_{LP} + m_{CW} + m_{POP}) \cdot \dfrac{\varepsilon_j \cdot r_{gear}}{r_{RW}}}$$

In the case of the metal oil pan (MOP):

$$a_x = \frac{\dfrac{\frac{D_{Pulley\,1}}{D_{Pulley\,2}} \cdot (m_{LP} + m_{MOP} - m_{CW}) \cdot g \cdot r_{gear}}{r_{RW}} - \mu \cdot (m_{SPC} + m_{MOP}) \cdot g}{(m_{SPC} + m_{MOP}) \cdot (1 + \dfrac{2}{(m_{SPC} + m_{MOP}) \cdot {r_{rw}}^2} (I_{RW} + I_{FW} \cdot \varepsilon_{FW}^2 + I_T \cdot \varepsilon_T^2 + I_{RP} \cdot \varepsilon_{RP}^2) + (m_{LP} + m_{CW} + m_{MOP}) \cdot \dfrac{\varepsilon_j \cdot r_{gear}}{r_{RW}}}$$

For the backward motion:

$$a_x = \frac{\dfrac{\frac{D_{Pulley\,1}}{D_{Pulley\,2}} \cdot (m_{CW} - m_{LP}) \cdot g \cdot r_{gear}}{r_{RW}} - \mu \cdot m_{SPC} \cdot g}{m_{SPC} \cdot (1 + \dfrac{2}{m_{SPC} \cdot {r_{rw}}^2} \cdot (I_{RW} + I_{FW} \cdot \varepsilon_{FW}^2 + I_T \cdot \varepsilon_T^2 + I_{RP} \cdot \varepsilon_{RP}^2) + (m_{LP} + m_{CW}) \cdot \dfrac{\varepsilon_j \cdot r_{gear}}{r_{RW}}}$$

2.6 Mechanical losses from the gears, pulleys and bearings.

The expression that is being developed is ideal, this is, it doesn't take into account the mechanical losses from gears and pulleys. The estimated efficiency for both pulleys and gears is 95%, this value was determined taken as reference the different manufacturers available in the market. The way to introduce this loses (F_L) in the final equation is multiplying the percentage of loses with the traction force and detracting it from the numerator, as it may be observed in the following equations:

$$F_L = F_t * (1 - \varepsilon)$$

Where:

$F_L = Loses\ (N)$
$F_t = Traction\ force\ (N)$
$\varepsilon = Gears\ Efficiency * Pulleys\ Efficiency = \frac{95}{100} * \frac{95}{100} = 0{,}9025$

The final expression for the three previous equation is as follows:

$$a_x = \frac{F_t - F_r - F_L}{m_T \cdot \gamma + I_L}$$

Appendix B
Risk Assessment

Risk assessment from work environment perspective

The risk assessment concerns (machine, equipment, change etc..)
Karakuri self-propelled cart

Participant	Role	Participant	Role
Petrit Krasnigi	Safety Engineer	Andreas	Safety Engineer
Yanni	Engineer		
Arturo	Enigneer		
Henrik Eklund	Supervisor		

Department (Work station/Area of work/Geographic area)
HDE13 High volume

Person responsible (Name, phone)
Henrik Eklund, 072 86 23 447

Execution date	**Date of last update**
4/25/2019	4/26/2019

Conditions (e.g. protective equipment, work methods etc.)
Normal PPE. SOPs not yet existing, the execution date was done on prototype.

Other notes

Issued by (Name, phone)
Yanni Porteiro +34664676307

Place /Process /Activity	Description of potential risk situation - what could go wrong?	Impact on person	Risk existing S 1-5	Risk existing K 1-5	Risk existing Index	Action	Risk if the measure S 1-5	Risk if the measure K 1-5	Risk if the measure Index	Problem solver	Planned completion date	Was the risk managed?	Comment
S0950 to S0900 and aisle	Get finger stuck between rack and pinion. Operator might unintentionally manipulate the transmission.	Fingers get crushed.	3	4	12	Adding a protective cover around the transmission	1	4	4	Yanni Porteiro and Arturo Mateos	6/1/2019	Ongoing	Action will be taken when the prototype is implemented.
S0950 to S0900 and aisle	Get finger stuck between belt and pulley. Operator might unintentionally manipulate the transmission.	Finger cuts.	3	2	6	Adding a protective cover around the transmission	1	2	2	Yanni Porteiro and Arturo Mateos	6/1/2019	Ongoing	Action will be taken when the prototype is implemented.
Self-propelled Cart	Sharp edges might damage operators while manipulating the cart	Finger cuts.	4	2	8	Adding rubber tops	1	2	2	Yanni Porteiro and Arturo Mateos	6/1/2019	Ongoing	Action will be taken when the prototype is implemented.
S0950	Lifting oil pans	Back or shoulder stress injuries	4	3	12	Lifiting device and SOP.	1	3	3	Yanni Porteiro and Arturo Mateos	Done	ok	Lifting device is existing and SOPs and mandatory trainings are defined.
S0950 to S0900 and aisle	Small vehicles or operators walking trough the aisle getting hit by the moving cart.	Getting hit and/or cut by sharp edges	3	2	6	Establishing a right-of-way regulation	2	2	4	Yanni Porteiro and Arturo Mateos	Done	ok	The existing manually-driven cart has priority over the rest over the rest of operators and vehicles.
S0950 to S0900 and aisle	Hand placed on lifting-platform´s guiding system while the cart is moving.	Hand squeezed or pinched	3	2	6	Coloured pillar in warning colours. Adding handles to safely hold the cart if needed.	2	2	4	Yanni Porteiro and Arturo Mateos	6/1/2019	Ongoing	Action will be taken when the prototype is implemented.
S0950 to S0900 and aisle	Operator gets run over by the cart wheels	Foot squeezed or pinched	2	2	4	Mandatory use of safety shoes.	1	1	1	Yanni Porteiro and Arturo Mateos	Done	ok	Safety shoes are mandatory for everybody accesing shopfloor.
S0900	Upper or lower limbs getting pinched when the cart reaches the rigg.	Soft tissue damages in limbs	3	2	6	Establishing a right-of-way regulation, including a safety perimeter.	2	2	4	Yanni Porteiro and Arturo Mateos	Before implementation	Ongoing	An alternative way of solving the problem would be to drease cart's speed at the end of the movement by installing springs at the ends of the guiding system, which would also have a positive influence in the dynamic behaviour.
S0950 to S0900 and aisle	Cart overturns and hits operators causing damage.	Soft tissue damages in the lower body and/or small bone fractures	2	3	6	Establishing a right-of-way regulation, including a safety perimeter and improving cart stability.	1	3	3	Yanni Porteiro and Arturo Mateos	Before implementation	Ongoing	Height of the cart can not be reduced for functional reasons. Stability of the cart can be improved by augmenting the wheelbase or lowring the center of gravity of the system.
S0950 to S0900 and aisle	Erosion of tensioning cables prevoques the cable to brake and hit nearby operators.	Soft tissue damages in the upper body. Small eye impact.	2	2	4	Making periodic preventive maintenance on the tensioning cables.	1	2	2	Yanni Porteiro and Arturo Mateos	After implementation	Ongoing	Cables must be changed periodically. Erosion caused because of the friction with pulleys edges and safety metal plates can cause the cables to brake.
S0950 to S0900 and aisle	Lifting platform and oil pan suddently drops beacause a failure in the tensioning cable and hits the operator.	General soft tissue damages and small cuts	2	3	6	Making periodic preventive maintenance on the tensioning cables.	1	3	3	Yanni Porteiro and Arturo Mateos	After implementation	Ongoing	If cables brake counterweights stop transmiting force and the platform would dangerously increase its dropping speed.

Appendix C
Failure Modes and Effects Analysis (FMEA)

Subsystem	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Controls	Detection	RPN	Recommended Actions
Wheeled base	Cart overturns	Production will be stopped and the cart will be damaged when hitting the floor	9	Wheeled base is not big enough to provide the needed stability	1	No control	9	81	Increasing the distance between the rear axis and the front wheels if overturning is observed
	Cart brakes	Production is paused	6	Dirt particles in the floor causes the wheels to suddenly stop turning	7	Visual inspection	2	84	Preventive maintenance: periodically cleaning the transport path
Frame	Buckling on pillars	Displacement of the lifting platform will be disabled and production will be stopped untill pillars are replaced.	7	Selected pillars are too slender for the regular working loads	5	FEM analysis	5	175	Reinforcing pillars with transversal supporting beams (triangulation)
	Beams fall appart	Overall integrity of the cart is compromised	6	Joints of the structure tend to get loose, specially under maintained vibration	6	Systematic review of the tension of the bolts	3	108	Including Grower washers and performing preventive maintenance: periodically tensioning bolts
	Joints wear down	Sructure bends under horizontal loads (accelerating and breaking).	5	Cuadrangular arrangement of beams	6	Visual inspection when intentionally applying horizontal forces on the structure	3	90	Reinforcing pillars with transversal supporting beams (triangulation)
Lifting Platform	Guiding system fails in constraining the movement of the platform	Undesired horizontal displacement of the liftting platform	4	Rolling wheels of the guiding system tend to get loose, when receiving excessive horizontal loads during cart's acceleration.	6	Visual inspection consisting on checking that rolling wheels turn while vertically displacing the lifting platform	3	72	Substituting steel pillars by aluminum karakuri beams made with grooves to guide the rolling wheels
Tranmission	Transmission axis bends over	Rack is displaced from the pinion and becomes unable to properly transmit the movement.	5	Transmission axis bends over due to excessive applied forces.	7	Visual inspection	4	140	Reinforcing transmission axis (welding of joints or triangulating)
	Transmission belts break	Movement of the cart is interrupted untill belts are replaced, stopping the production.	8	Joints of the thermoweldable belts are susceptible to break under big loads and maintained functioning.	3	Trenght test. Joints must at least resist the nominal acceptable axial load recommended by the supplier (120 N) .	6	144	Purschasing professional equipment to perform the joints and periodically changing the belts, according to the lifespan recommended by the supplier
	3D printed components get erosioned or partly break	Efficiency of the transmission drastically decreases	6	PLA, 3D-printed components are not suitable for full-production equipment due to a lack of resistance.	7	Visual inspection of the surface of components and bending angles.	4	168	Changing 3D-printing material to Nylon
	Cart brakes	Transmission bearings get stuck	5	Bearings are exposed so they might accumulate dirt particles.	3	No control	6	90	Covering the exposed bearings and periodcally changing the bearings according to the supplier recommendations
Counterweight	Tensioning cables to leap out of the pulleys	Counterweight forces stop being transmitted and the cart is not able to move backwards. Production is paused.	7	Axis of counterweight pulleys undesirably rotate under regular working loads, as supports of the beams where counterweight pulleys are placed tend to get loose.	6	Visual inspection of bending angles	4	168	Reinforcing pulleys axis (welding of joints or triangulating)
	Tensioning cables brake	Counterweight forces stop being transmitted and the cart is not able to move backwards. Productions is stopped.	8	Undesired rotation of the pulleys also causes tensioning cables to get erosioned untill breakdown.	4	Visual inspection of the surface of the cables	4	128	Preventive maintenance: periodically inspecting tensioning cables and changing them if needed.
	Counterweight guiding joints collide against the guiding pillars	Surface of the guiding pillars get damaged	3	The guiding system of the Counterweight guiding system is not fixed to the pillars, causing undesired collisions when the cart accelerates.	3	Visual inspection of the surface of the pillars	3	27	Redesign of the guiding system, including soft protections in the inner faces of the guiding supports if needed