Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Ocean Operations and Civil Engineering

Armand Misund

A System Engineering approach to automation of sorting crates

Master's thesis in Product and System Design
IP501909 MSc thesis, discipline oriented
Supervisor: Henrique M. Gaspar
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Preface

This report is a master's thesis and is the final part of my master's degree in Product and System Design at NTNU Aalesund. This is based on a 3-year bachelor's degree in Mechanical Engineering - Product and system design also at NTNU Aalesund.

The subject of this thesis is given by Currence Robotics and is to analyse the sorting process of the reusable plastic crates IFCO6420 and IFCO4314, with a goal of automating the process with technology from Currence Robotics. To perform the analysis, Systems Engineering is used as a method, and 3 cases have been developed to explore different degrees of automation of the sorting process.

The subject was chosen to gain a deeper understanding of the process behind automation of production and sorting. This task is completed by observing the current process and interviewing selected stakeholders. There has been a good collaboration with Currence Robotics, and H.I. Giørtz Sønner AS, which is responsible for the sorting.

Abstract

Automating a manual process is an open task with many angles of incidence and solutions to choose from. By using a tool such as Systems Engineering to map the process and a selection of solutions, it is possible to compare several predefined KPI values.

The starting point for this thesis was a manual sorting process that was to be automated by Currence Robotics. The process involved quality check and sorting by size and quality of two different plastic crates, the IFCO 6420 and 4314.

Currence Robotics has already created an automatic solution for sorting pallets named “Sort” and wanted this technology to be considered for the sorting of crates. To gather information about the manual process, company visits were made where the process was observed, and the time of various sub-processes that were identified was measured. Interviews were also conducted with the operators performing the process, and engineers from Currence Robotics. In the same way, the automatic sorting machine "Sort" was observed in operation to map behaviour and structural elements. Together with interviews with the engineers behind the machine, this formed the basis for the mapping of available technology at the client.

In addition to this, a literature review was made of automatic sorting processes from various industries, with focus on the process and technical solutions.

With the literature review of Systems Engineering, a method was created to map the manual process and various solution proposals based on a set of KPIs.

The solution proposals, called change cases, were based on the manual process and an increasing degree of automatic solutions were implemented. In change case 3, the sorting process is completely automated with technology from Currence Robotics.

In collaboration with Currence Robotics, a set of KPIs was defined and used in the assessment of all cases, including the manual one. These are Opex [NOK], Capex [NOK], Reliability [Stops over time], Robustness [%, Probability of consequence], and Efficiency [crates per. hour].

The time it took to sort a given number of crates decreased with increasing implementation of automation through the various change cases. With reduced time consumption the efficiency and number of crates per hour increased, from 300 in the manual case, to 1200 in the fully automated case, change case 3.

The increase in automation also resulted in increased costs, both capital- and operating costs. If we look at the cost increase in relation to the capacity increase, the cost per sorted crate decreases by about 50%.

The manual process sorts 300 crates per hour, and if we look at the cost per sorted crate, the fully automated case must sort 600 crates per hour to have the same cost as the manual per crate. The interesting thing is that the fully automated case has a capacity of 1200 crates per hour and is profitable already after 600 crates per hour compared to today's manual solution.

Acknowledgements

I would like to show my gratitude to my supervisor Henrique M. Gaspar who has given good feedback and helped me through the process of writing this thesis.

I would also like to thank Currence Robotics for an interesting scope, and especially Rodrigo Urbina, Design Engineer, for answering all my questions during this period.

Finally, I would like to thank my wife who has made it possible for me to spend as much time as a master's thesis requires over the last six months. You have been a good supporter, as always. This also includes my two children who are patiently waiting for all of us to be together on afternoons and weekends again.

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Abbreviations / symbols

SE	Systems engineering
MBSE	Model Based Systems Engineering
PBS	Product Breakdown Structure
NIR	Near-infrared
PET	Polyethylene terephthalate
KPI	Key performance indicators
HSE	Health, Safety, and Environment
NOK	Norsk krone (With reference to ISO 4217)

1 Introduction

1.1 Problem

H.I. Giørtz Sønner AS is a grocery distributor supplying grocery stores with food. The food is transported to the grocery stores on pallets and in various reusable plastic crates. Upon delivery, they also take used pallets and crates back, and deliver these to a sorting department. All pallets and crates are visually inspected for damage and defects, before being sorted by type. These are then shipped to H.I. Giørtz Sønner AS for reuse.

Currence Robotics has designed, manufactured, and assembled an automated machine called "Sort" which performs quality control and sorts pallets based on type. This is in use at the sorting department and now they want to develop a similar solution that can sort the reusable crates.

There are several models of crates in use, but Currence Robotics wants this thesis to focus on a model that comes in two sizes, the IFCO6420 and IFCO4314 (half size). They also want to look at how their existing technology can be reused for sorting crates.

Figure 1-1 Reusable crates returned from grocery stores.

Figure 1-2 Sorted crates IFCO6420

Figure 1-3 Unfolded crate IFCO6420

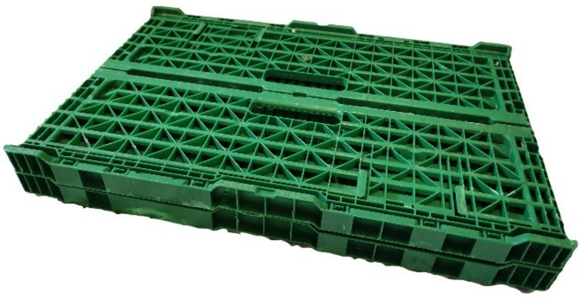

Figure 1-4 Two crates folded and stacked.

1.2 Motivation

Automation can have several beneficial consequences. Reduce routine tasks, increase efficiency and at the same time reducing costs in the long run. This can provide benefits for suppliers and distributors, but also for customers with, for example, better flow of goods that avoids empty store shelves.

Automation of logistics operations is today a growing industry in Norway, and to be part of this development is exciting and useful.

1.3 Objectives

The goal of this task is to be able to simulate the benefits of automating a currently manual process. The method will be Systems engineering and using this method all sub-processes will be identified. Based on the findings, a gradual automation of the process is implemented, and the results are evaluated with tools from Systems engineering.

1.4 Scope of work

Used crates are collected at grocery stores and brought to the sorting plant. Here they are checked for defects, sorted, and put in stock until they are to be transported out to grocery suppliers. Several different types of crates are used for different products.

This process involves many stages, and this thesis will focus on the sorting stage of one of the crates, which comes in two different sizes, IFCO6420 and IFCO4314. By using system engineering techniques, the different sub-processes in the sorting stage will be identified and simulated in a process/time graph.

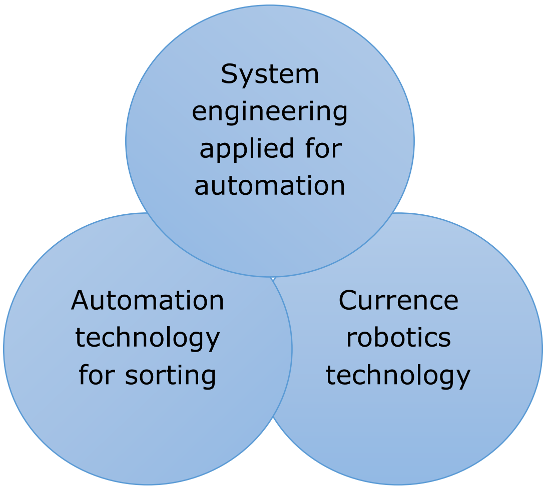

Figure 1-5 Scope graphical presentation

1.5 Research questions

- RQ1: How can we apply system engineering to organise the product, and the process for the automation of sorting?
- RQ2: How can we use Currence robotics technology to propose a solution?
- RQ3: How can we quantify efficiency (time), and cost by using Currency Robotics technology on the sorting process?

1.6 Structure of report

This report is structured with an introduction, literature review, methodology, analysis of the sorting process, discussion, and concluding remarks.

Literature review covers Systems Engineering theory, technology for automatic sorting, and Currence Robotics technology for sorting.

The methodology chapter (chapter 3) presents a method for testing an increasing degree of automation and different technology on the current process.

In chapter four, three different cases are presented and analysed using the method described in the methodology chapter.

The results are discussed in Chapter 5, concluded in Chapter 6, before the thesis ends with Chapter 7, where further work is reflected on.

2 Literature review

2.1 Systems engineering applied for Automation

2.1.1 Five aspect taxonomy

In (Rhodes and Ross, 2010) there is introduced a five aspect framework for the engineering of complex systems. This is a continuation of the model-based systems engineering (MBSE) approach, which mainly focused on the structural and behavioural aspects of a system. Rhodes and Ross do not take credit for, but they see the need to address three additional aspects: contextual, temporal, and perceptual. This due to their contribution in engineering value robust systems, systems that despite shifting times continue to deliver value to stakeholders.

2.1.1.1 Structural

The logical and physical aspects of a system with interrelationships, loos, and tight couplings, in both vertical and horizontal structures, makes the structural aspect of a system. (Rhodes and Ross, 2010) This include all structural, thermal, electrical, and signal interfaces as well as the human-system interfaces. (NASA, 2007)

By using a Product Breakdown Structure (PBS) it is possible to visualize the structure or the form of the system. Starting at the top and breaking it down in smaller pieces, relevant properties or functions for different parts and interrelationships is identified.

2.1.1.2 Behavioural

The behavioural aspect is the behaviours resulting from the logical and physical parts described in the structural aspect, and their response to stimuli. To understand how the system will perform, the emergent behaviours resulting from complex interconnections can be modelled.

2.1.1.3 Contextual

By understanding and mapping the complexities and uncertainties that define the external environment that are relevant for stakeholders in which the system operates, the contextual aspect is shown. These external factors may be related to seasons, shifts in workload, political, economic, cultural, and market factors. Systems with long life spans are more likely to meet shifts in context, but as all systems exist in a dynamic world, they must consider changes over time.

In a descriptive way the contextual aspects can be illustrated in system context diagrams and described in various documents like operational concept document or capability description documents.

2.1.1.4 Temporal

To characterize changes over time and time-based properties within the system, the temporal aspects is necessary. *"The temporal aspect of systems is critically important, but remains undertreated in the practice of engineering complex systems."* (Rhodes and Ross, 2010)

The most typical method in system engineering to illustrate temporal effects is to develop scenarios. Here one or more scenarios is developed around the system mission or purpose, all within the system boundary. To communicate the overall picture of the working system in its environment, these scenarios can be useful.

(Rhodes and Ross, 2010) describe several methods used in assessing the temporal aspects, like Boardman's systemigram, Richey's Morphological analysis, Monte Carlo simulation, and Rhodes and Ross Epoch-Era analysis.

The Epoch-Era analysis consider how the system deliver value to stakeholders in the context of a dynamic world. In Epoch-Era analysis the life span is divided into time periods, called epochs. For each significant change during the lifespan, a new epoch is created. To create a long-term view, multiple epochs following each other in time, can be linked together to create an era or scenario. Each Epoch is evaluated in regard to the current context before a path analysis across a series of epochs can identify system evolution strategies.

2.1.1.5 Perceptual

Perceptual aspects consider how the stakeholders preferences affect the system, and how these preferences may change over time due to context shifts. What stakeholders' value can change with external factors like economic changes, available technology or treats as seen in 2020/2021, a worldwide pandemic. Since needs are judged subjectively, meeting stakeholders' needs is perceptual. To identify this aspect, interviews with stakeholders can tell how they interpret the system in current and shifting contexts.

2.2 Automation technology for sorting

Automatic sorting takes place in several different industries, typically industries with hight volumes like food processing (sorting), parcel sorting, and waste management. Although much robotic technology is already developed, the true integration in sorting is still in its infant stage. There are some specialized solutions that can be bought off the shelf, and this selection increases, but still many solutions are special made. While most of the system is made of standardized parts, the integration of all the parts, the software that controls the system and in many cases the grippers, are special made for each case. (*Automated parcel sorting - An introductory guide*, 2021)

In food processing, automation is found in hight volume sorting jobs, like finding and picking small pits or stalks in fruits and nuts. Increasingly, they are also used in fruit and vegetable harvesting, where robots can select perfectly ripe fruit accurately and fast. (*Industrial automation : TOMRA*, 2021)

In waste management sorting is often done for recycling purposes, where the different waste types can be carboard, electronics, organic, metal, different types of plastic, and glass, and among these there is a large variation in sizes and shapes. (Bonello, Saliba and Camilleri, 2017)

2.2.1 Structural

Regardless of the type of product that is sorted, there are many common features to the structural structure. In general, the structure can be divided in three main areas, movement of objects to be sorted, sensors, and gripping/handling technology.

Movement of objects

The most used technology for transporting objects in a production and sorting environment are belt conveyor or roller conveyor.

Belt conveyor systems are some of the most universally used and recognized machines in any industrial setting. (*Conveyor Types & Configurations*, 2021) The belt conveyors use a series of powered pulleys to move a continuous belt. This belt can be made of natural or synthetic fabrics such as polyester or nylon. In extreme temperatures or aggressive parts, a wire mesh or fiberglass belting can be used. In the modular belt conveyors, the belting is made of individual, interlocked segments, usually made of hard plastic. These are easier to repair than flat belts models, easier to wash, and more resilient to sharp, abrasive, or otherwise problematic materials. Conveyor belt systems can be configured with back-lit belts for visual inspection and quality control, and vacuum belts for holding flat products to the belts surface. (*Conveyor Types & Configurations*, 2021)

Roller conveyors are a series of rollers supported within a frame where objects can be moved either manually, by gravity, or by power. (*Conveyor Types & Configurations*, 2021)

Because of their adaptability roller conveyors are used widely in numerous industries, but mostly in logistics and manufacturing.

Gravity roller conveyors are useful as they use gravity force to move objects by putting the conveyor at a decline angle.

This is a cost-effective solution, requires no power source which reducing the cost of operation, the need for maintenance, and time in maintaining the conveyor. This also provides a more environmentally friendly solution compared to a powered roller conveyor.

It is generally harder to control the conveyor speed, especially with heavy objects on the conveyor.

Powered roller conveyors are more suitable when transporting object over a longer distance, there is a need to control the speed, or split the conveyor in zones with different speeds. The motion can also be controlled by sensors.

Powered systems are more expensive and needs more maintenance than passive systems.

Sensors

In automatic sorting, different sensors are used, either alone or in combination. The choice of sensors is dependent on what feature to identify, material, shape, or colour. A combination of sensors can identify both material and colour/shape of the same object. In the (MRF) material recovery facility in Marsaskala, Malta, they combine a NIR sensor (Near-infrared) with visual imaging (2D) to identify PET plastic and to differentiate between withe and clear versions. Near-infrared (NIR) spectroscopy is effective, and a common technology to identify various materials like paper, cardboard, metallic objects, plastic, and various foam products. (Bonello, Saliba and Camilleri, 2017)

Gripping

While the technology used for gripping is known, how it is used, in which combination and in what shape, can differ from project to project. Often the grippers are specially made for the object(s) to be handled, and even a combination of technologies is used like the universal gripper design proposed in (Bonello, Saliba and Camilleri, 2017) and seen in the picture below. Here both mechanical jaws and a retracting vacuum tube is used both individually and simultaneously, depending on the object to be lifted.

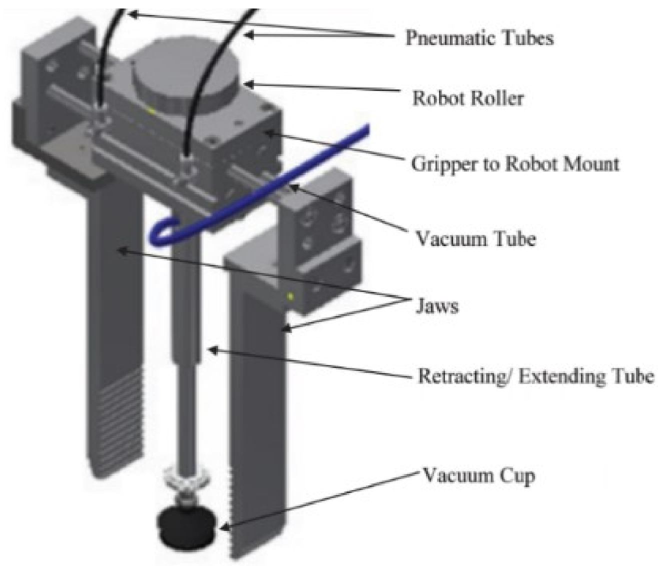

Figure 2-1 Gripper with vacuum and jaws (Bonello, Saliba and Camilleri, 2017)

To extract the metallic objects, magnets or electromagnets can be used on ferrous objects, while eddy current separation technology sorts out 90% of non-ferrous metallic objects. (Bonello, Saliba and Camilleri, 2017)

Some objects can be sorted by air stabilization systems that pins the object to the conveyer and allows it to exit through dedicated outlets.

In some cases, a cooperation between man and machine is a good solution, where some objects can be extracted manually to increase sensing precision.

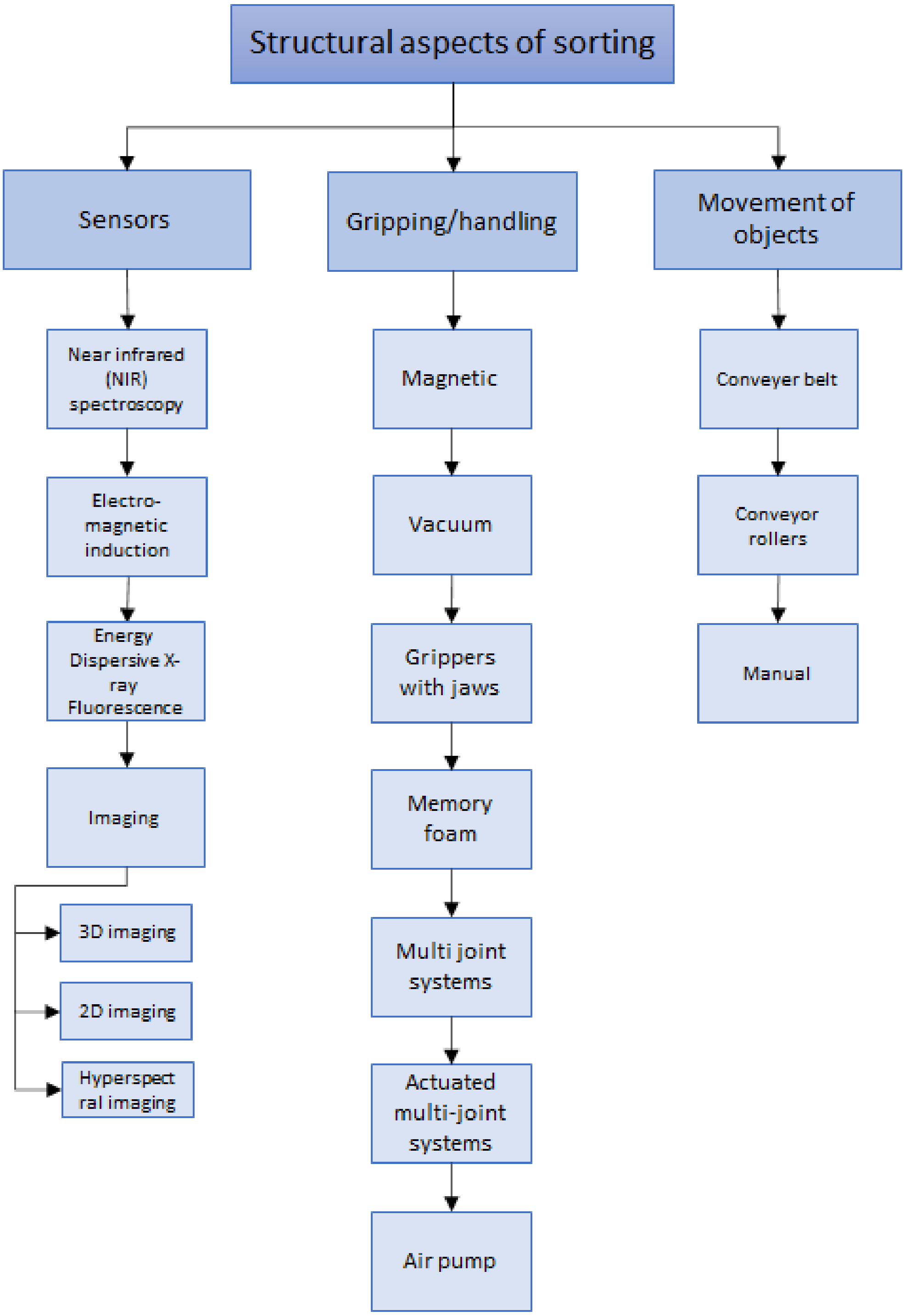

Figure 2-2 General product breakdown of the structural aspects in automated sorting.

2.2.2 Behavioural

This work breakdown structure visualising the sorting process found at the (MRF) material recovery facility in Marsaskala, Malta.

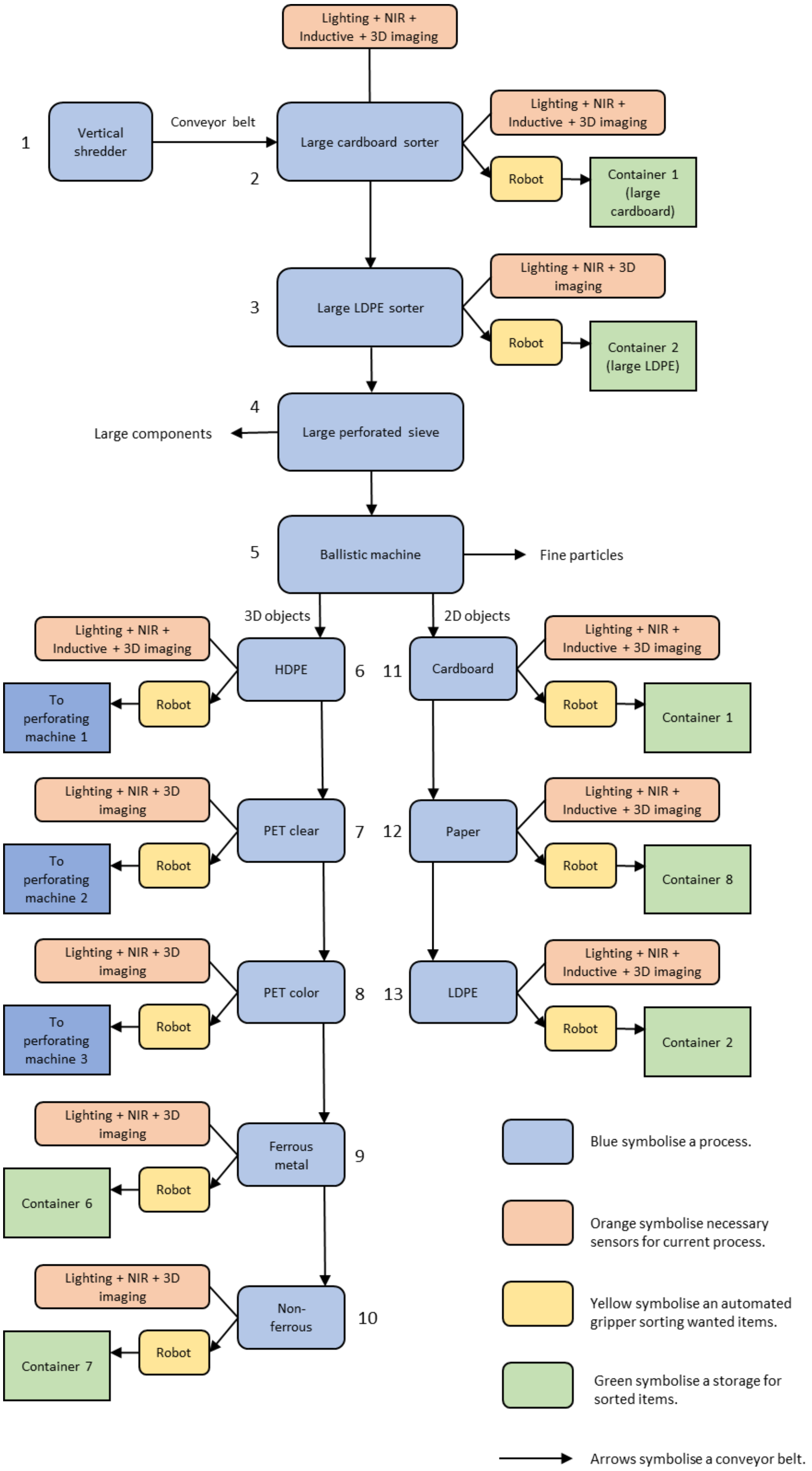

Figure 2-3 Behavioural block diagram

(1) The vertical shredder crushes all the material that is added to the process. This is done to disassemble composite objects and makes it easier for sensors to differentiate different parts. (2) The first sorting is of cardboard, this to clear out the largest parts first. A combination of different sensors such as near infrared, 3D imaging, and inductive in combination with a lot of light is used to identify the cardboard. (3) In step three, large LDPE (plastic) parts are sorted out for the same reason and with the same sensors as in step 2. In step 4, other large parts are sorted out of the waste stream so that the next machine will be as efficient as possible. (5) And this machine is an important step for the further sorting. Here, 3D objects are separated, i.e., bottle, jugs, and metal objects, both magnetic and non-magnetic. 2D objects such as cardboard, paper, and various plastic materials and finally fine particles that can be a combination of everything. Here, the waste stream is divided into 3D materials and 2D materials, and there is then a parallel process of differentiating the different materials the waste stream consists of.

All sorted materials are compressed and packed on pallets for transport to recycling.

2.2.3 Contextual

Contextual aspects describe the inn- and outputs of the system. How rules and regulations from governments could change the systems prerequisites and make limitations and boundaries for the system, but also new possibilities. The same factors can also come from Constraints set by the management, and the work force.

Sustainable waste management systems are needed to handle the increasing amount of household waste across the globe. A sustainable waste management system involves several shareholders and some of their interests can be:

- Reducing environmental impact.
- Assuring public health.
- Economically realistic waste management and sorting.
- Organising appropriate infrastructure for waste collecting

The motivation to build and sort waste often comes from regulatory provisions from the authorities. These are often in line with the expectations of the inhabitants and companies of a country. The increased waste production will probably set stricter requirements for regulations from the authorities in the future. A growing environmental focus is seen both from private households, but also companies who wants to appear sustainable for customers and the stock market. This sets higher demands on recycling facilities, and their capabilities to handle both the volume and the different materials that needs to be differentiated.

Sorted waste has several forms of value. Waste that cannot be recycled and is harmful to the environment must be treated and stored properly for the future.

Recyclable materials have value in the form of sales value to recycling companies. Here, sorting quality will have a direct impact on the value, better sorting with less interference of other materials, the higher the final price. The sales value can also vary depending on market forces, access to raw materials for new production and regulations from governments.

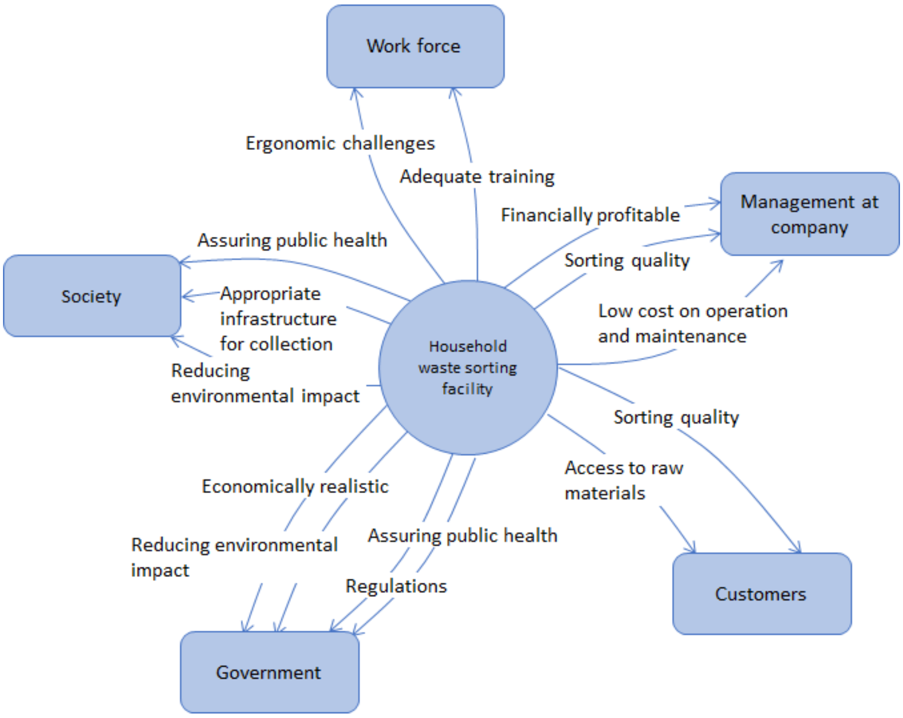

Figure 2-4 System context diagram

2.2.4 Temporal

Based on the temporal section, a simplified time schedule for the sorting process is made and presented in a Gantt-chart.

	Task	Sum duration	Duration sec.	Unit
1	Vertical shredder	0	138	sec.
2	Large cardboard sorter	138	25	sec.
3	Large LDPE sorter	163	35	
4	Large perforated sieve	198	93	
5	Ballistic machine	291	180	
6	3D HDPE	471	26	
7	3D PET clear	497	32	sec.
8	3D PET color	529	32	sec.
9	Ferrous metal	561	20	NOK
10	Non-ferrous metal	581	240	NOK

Tabell 2-1 Time schedule for each sub process.

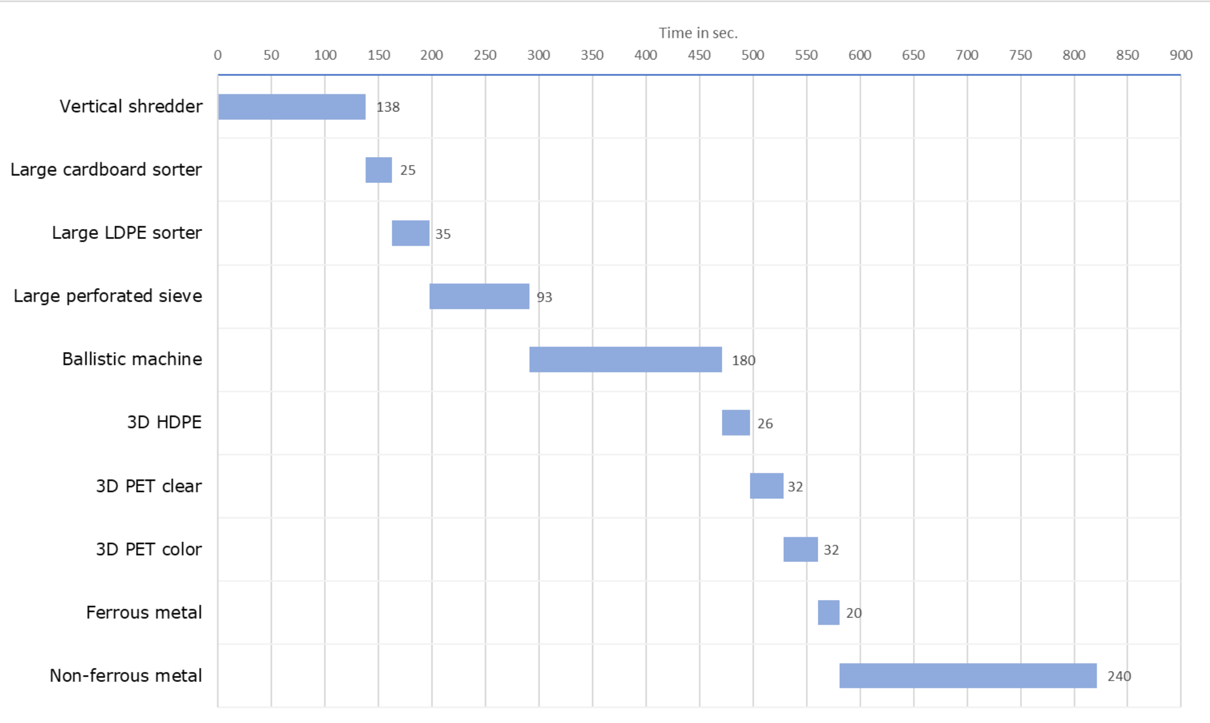

Figure 2-5 Time schedule for each sub process.

The automated sorting is a continues process, which is constantly feed with unsorted waste. Since sorted objects are separated along the way, this timeline illustrates a given amount of unsorted waste, and the time before this is finished sorting. This representation does not show how multiple sorting processes happens simultaneously. Although some processes occur simultaneously, they must also be run sequentially. This is to constantly minimize the number of objects that must be analysed by the sensors.

2.2.5 Perceptual

Perceptual aspects consider how the stakeholders preferences affect the system, and how these preferences may change over time due to context shifts.

- Main stakeholder one, government
  - Rules and regulations
    - Limitations and boundaries
    - New possibilities
    - More customers
    - More waste to sort

The increased waste production and environmental focus/demands from private persons and companies will probably set stricter regulations in the future. Can also lead to new types of waste being sorted and recycled, which must be handled by the system.

- Main stakeholder two, customers:
  - Sorting quality, purity of sorted objects.
  - Market forces
  - New raw material pricing
  - Regulations from the authorities

Different regulatory requirements from the authorities may give different demand for different types of sorted waste. Global access to raw materials and associated pricing can also give a rise or fall in the price of sorted material.

2.3 Currence Robotics technology for sorting

Currence robotics has developed a robotic pallet sorting system called Sort. This system is now coming out of beta and is ready for production. Sort is a modular and scalable system, making it suitable for both small warehouse hubs and regional district centres. Sort can handle a variety of pallets, Euro-, plastic-, eco-, half sized- and quarter sized pallets. Sort can process about 180 pallets per hour today, working 24 hours a day. The future goal is 400-500 pallets per hour. This reducing the need for manual handling and physical labour done by people. (*Currence robotics*, 2021)

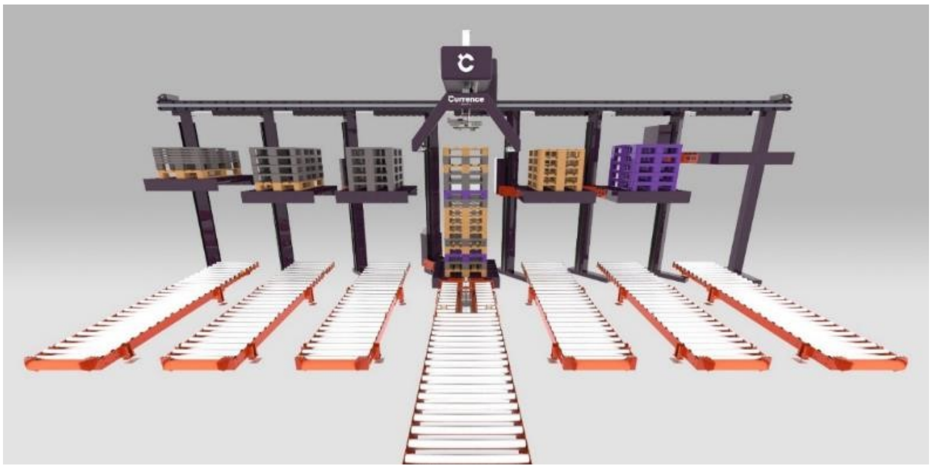

Figure 2-6 "Sort" front view

2.3.1 Structural

The machine is built up from five main parts, the infeed conveyor system, infeed tower with vision equipment, all the output towers, robot with gripper, and outfeed conveyors. The machine can be controlled from the main cabinet, located next to the machine.

One of these five main parts is the outfeed towers, one for each type of pallet to be sorted. It is these output towers that make the system modular, the ability to add more towers as needed, and in this way handle new types of pallets. What is called the robot, grabs, lifts, and moves the pallets to the correct outfeed tower. This is based on the assessment made by 3D vision sensors. This robot moves between the output towers on a horizontal travers crane mounted on top of the towers.

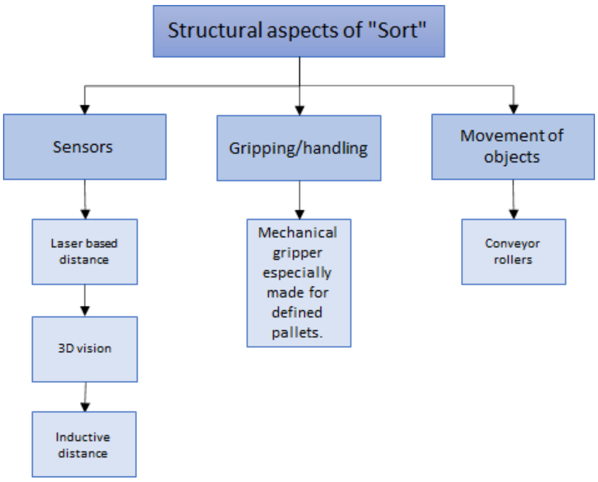

Figure 2-7 General product breakdown of the structural aspects in "Sort".

2.3.1 Behavioural

Movement of pallets

Stacks of unsorted pallets are transported to the sorting area by trucks. These stacks are picked up by forklifts and moved in to the "Sort" buffer area, pallet infeed. The infeed buffer is made of roller conveyors. These conveyors are slightly lifted at one end, giving it a slight slope towards the machine, making the pallets travel to the machine due to gravity. A mechanical stopper holds back the next stack of pallets, so the robot gripper can work with the front stack. In the same way, the output conveyors are sloped from the machine, making the pallets slide to the end of the roller conveyor. Her the mechanical stopper prevents the stack from sliding forward, until the stack has reached its predefined height with 17 pallets. At the end of these output conveyors, forklift pick up the stack of pallets, moves it to the storage area where it is wrapped in plastic for stabilisation before it is placed on storage.

Sensors

The first sensor to detect new pallets are the laser based top limit sensor at the infeed tower. This is to prevent the stack of pallets from being higher than the machine can handle. The most important sensors on "Sort" are the six 3D vision cameras. They are all placed in the infeed tower and are used to examen and evaluate all the pallets, one by one. The pallets are then picked up by the robot and placed in the correct outfeed tower. In each of these output towers there are inductive limit sensors to detect the stack hight. When the stack contains 17 pallets, it is released and will slide down the outfeed conveyor. The number of stacks on the output conveyor is monitored by a laser-based outfeed sensor. There are absolute encoders in all motors on the robot and the towers, this to know the exact position of the robot.

Gripping

When unsorted pallets are fed the system through the infeed buffer, the 3D vision sensors do the quality assurance and sort identification before the robot with gripper grips and lifts the pallet. The 3D vision sensors do a second inspection from underneath, before the robot transports the pallet to the correct tower, sorted by type or due to damage. The gripper is made by Currence robotics, and can handle seven different types of pallets, Euro, NLP, half NLP, 1/3 NLP, chip, half chip, blue plastic pallet.

Figure 2-8 "Sort" robot with gripper

2.3.2 Contextual

The contextual aspects of the pallet sorting system are based on interviews of engineers at Currence Robotics.

There are seasonal variations in the amount of work in pallet sorting. It is high season from November to mid-January. There is also an increase in work in the summer, but not as much as in the winter. The various holidays throughout the year also provide extra work to do right before and after. The pallets are delivered by truck, and all sorting takes place indoors, so there are no seasonal variations in connection with weather and climate.

As mentioned, "Sort" can handle seven different types of pallets Euro, NLP, Half NLP, 1/3 NLP, Chip, Half chip, and blue plastic pallets.

There are regulations regarding design of pallets, this has not been changed for a long time and it is Currence Robotics impression that this system is set in stone.

In relation to regulations and laws, the ordinary working environment law for factories also applies here.

This is a large machine that requires a lot of space. In addition, there must be sufficient space in the front for the access of the forklifts. Pallet handling generally requires a lot of space, but such a machine will take up a lot of space.

This system is designed as a modular system, at any given point there can be added more towers for different types of pallets. By adding towers and types of pallets to sort, the output will decrease because it is still only one robot to do the sorting.

2.3.3 Temporal

The table below shows the sub-processes, and the time it takes. Processes 1, 2and 8 are manual, and are performed with a forklift. Processes 3 through 7, marked with bold text, are automatic and are performed by the machine.

	Task	Sum duration	Duration sec.	Unit
1	Pick up from the delivery truck by forklift	0	60	sec.
2	Deliver stack of pallets on the infeed buffer (17 pallets)	60	12	sec.
3	**3D scan of paller from top side (17 pallets)**	72	34	sec.
4	**Gripper move in and grab pallet (17 pallets)**	106	60	sec.
5	**Lifting crate (17 pallets)**	166	20	sec.
6	**3D scan of pallet from below (17 pallets)**	186	34	sec.
7	**Automated sorting by type and quality, placed on pallet (17 pallets)**	220	60	sec.
8	Pick up stacks of sorted crates, put on storage.	280	60	sec.
	Total duration	**340**		sec.

Tabell 2-2 Duration of each sub-process "Sort"

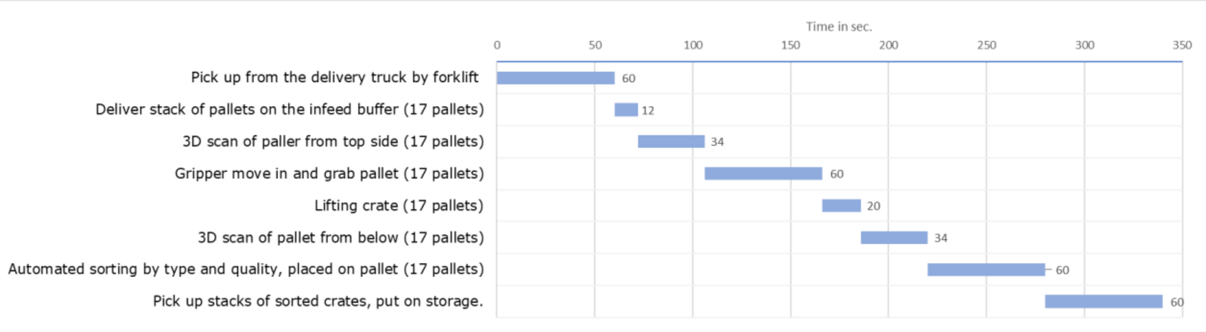

Figure 2-9 Duration of each sub-process "Sort"

2.3.4 Perceptual

There are several different stakeholders to this process.

Currence Robotics who develop the machine with their engineers, assembly team, and maintenance team. Where the engineers want a simple and good system, the assembly team wants a system that is easy to assemble and does not require as many tools, and the maintenance team wants a system that is available for maintenance so they can do their job.

The company that owns and rents out the pallets. They are interested in sorting out defective pallets, something such a system does better than a manual alternative where the quality assessment takes place from the forklift.

The company that sorts pallets. They experience seasonal variations and must staff accordingly. Such a machine will be able to take care of the load peaks in the high season, and there may be a permanent basic staff that manages to handle the job.

Forklift drivers. Today there is a lot of pressure on the drivers who must both sort pallets by type and at the same time assess the quality. There is essentially no time to get out of the forklift, so everything takes place from it. But something must be done by hand, and that is hard work. This machine will therefore relieve the operators both physically and mentally.

3 Methodology

3.1 Assumptions and Limitations

To limit the overall process according to the given time and scope for this thesis, the most important objectives and the limitations must be identified. This will be based on the presented theory, literature reviews, interviews with company engineers, and discussion/dialogue with my supervisor.

In close dialog with Currence Robotics, we are looking into their current process of sorting reusable plastic crates. In that perspective we are focusing mostly on the actual sorting, not the necessary processes before and after. This process will be automated, as they have done with the sorting of pallets.

- Using System Engineering to identify the different sub processes involved in sorting crates.
- Preferably use existing state of the art technology and knowledge in the company when proposing automated scenarios for the sorting of crates.
- Key performance indicators (KPIs).
    - 1200 crates per. hour [Efficiency]
    - Robustness [%, Probability of consequence]
        - To measure robustness to the process, three levels of failure with increasing consequence will been defined
    - Reliability [Stops over time]
        - This indicator gives an average number of stops in the process per unit of time.
    - Installation cost (capex)
    - Maintenance cost. (Opex)
- The stakeholders and the purpose with the process is fixed, system must be adaptable/modular.
- Company representatives are considered sufficient to assess the process.

3.2 Overall Process

This thesis builds on a step-by-step procedure that involves Systems Engineering. The procedure is designed to ensure a thorough understanding of the different steps and ends up in the case studies and the evaluation of these. The procedure is illustrated in the following figure.

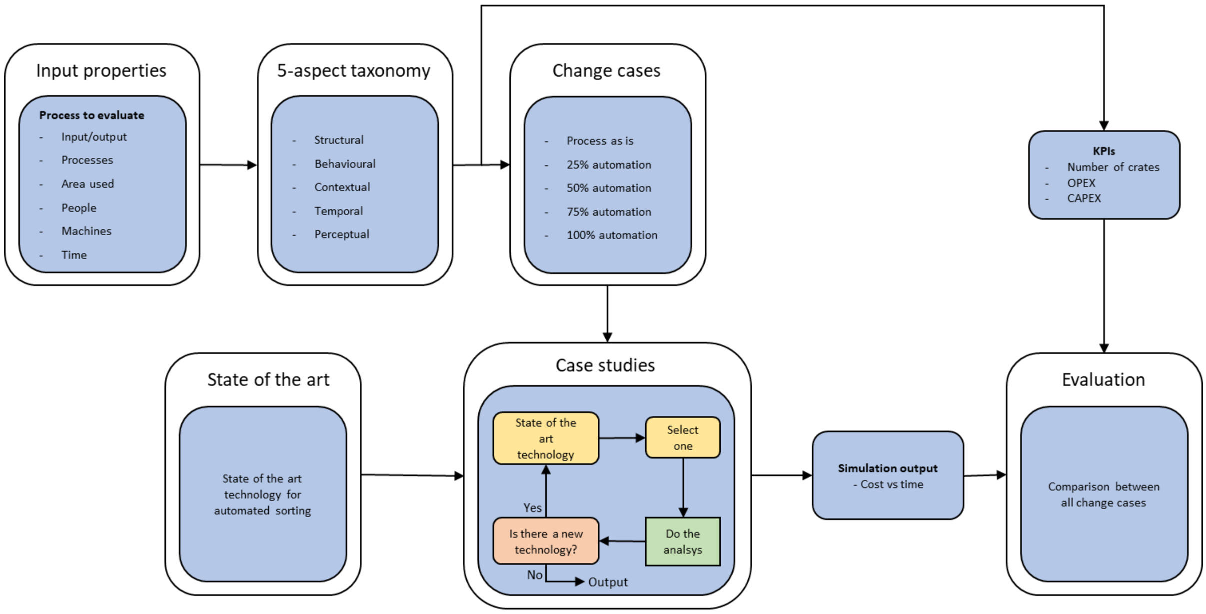

Figure 3-1 Procedure overview

The following chapters will explain the different steps in the procedure.

3.2.1 Input properties / Process to evaluate

The sorting of crates consists of several processes, but this thesis will only focus on the main sorting process.

To take full advantage of the 5-aspect taxonomy later in the procedure, the selected process must be thoroughly mapped and described to understand the background, objectives and being able to present the input and output of the process. This is done by interviewing operators, engineers, and observing the process. From this a step-by-step description is made with time indication for the different steps, and the necessary workspace is calculated. Based on these interviews, human aspects to the process have also been identified.

3.2.2 5-aspect taxonomy

To understand the sorting process as good as possible, the 5 -aspect taxonomy is used. The 5 taxonomies are: Structural, Behavioural, Contextual, Temporal, and Perceptual.

Structural taxonomy

The structural taxonomy is applied for a detailed mapping of all structural components involved in the process and eventual sub-processes. The process and its associated components are identified by observing the current procedure. Interviews have been conducted with the operators who carry out the process, and with engineers responsible for the process. To formalise the structural taxonomy, a product breakdown structure is made, showing the logical and physical aspects of a system with interrelationships, with loos and tight couplings in a hierarchic order.

Behavioural

The behavioural aspect is the behaviours resulting from the logical and physical parts described in the structural aspect, and their response to stimuli. On basis of the observations, a timeline will be made, divided in the different subprocesses and timed.

Contextual

By understanding and mapping the complexities and uncertainties that define the external environment that are relevant for stakeholders in which the system operates, the contextual aspect is shown. This can be rules and regulations from the Working Environment Act, constraints set from the management, and work force limitations, but also seasonal differences. Periods of holidays, affect the amount of work to a great extent, where amounts and time must be identified and described.

Temporal

Based on the timeline from Behavioural Aspects, a Gantt chart will be developed, structured according to sequential and / or parallel sub-processes. The purpose is to be able to document the effects of any changes in the process.

Perceptual

Perceptual aspects consider how the stakeholders preferences affect the system, and how these preferences may change over time due to context shifts. There are many stakeholders connected to this system. From the company developing the automated machines, pallet sorting company, pallet owner company and operators working with the automated solutions. In such a system, it will be both consistent and changing preferences over time. The ease of maintenance, robustness, and operability for the operators will always be importance factors, but the type of crates and how many sorted per. hours can change several times.

3.2.3 System performance (KPIs)

The key performance indicators (KPIs)are agreed with selected shareholders based on conversations and interviews. This KPIs focuses mainly on number of sorted crates per. hour (time), Installation cost (capex), operational cost (Opex) etc. With the selected process, the KPIs will be calculated based on findings from the 5-aspect taxonomies.

3.2.4 Change cases

The selected process is presented in detail, as it is now, over time, based on the findings in the Behavioural taxonomy. This will be the basis for three different cases with gradually implementation of automation. The three cases will have increasingly use of automation to solve the process and the third case will be 100% automated.

3.2.5 State of the art technology for sorting

The main goal is to improve the process based on selected KPIs in chapter 3.2.3. An increasing degree of automation using various technologies based on previous literature review will be suggested. Based on the current and manual process, the implementation of automation will take place in three steps, where the third step is completely automatic.

3.2.6 Case studies

In the case studies, the change cases, which are the selected process with three degrees of automation implemented, will be matched with the state-of-the-art technology for sorting. The change cases will be matched with technology one by one, and the process is repeated for all change cases. There will be made a Gantt-chart for every change case, which displays the cost over time.

3.2.7 Evaluation

Along with the results from the 5-aspect taxonomy, KPI calculations for the current change case are presented in a Gantt chart.

4 A System Engineering approach to automation of sorting crates

This chapter involves the case study of the master thesis, and uses the procedure described in chapter 3, to evaluate the chosen process.

4.1 Process to evaluate

Currence Robotics design and builds automated sorting machines for pallet sorting. They are primarily aimed at food suppliers, and those who rent out the pallets. In addition to Euro pallets that are sorted with the machine "Sort", foldable and reusable plastic crates are widely used. These crates come in several different versions, but this thesis will only look at one type, the IFCO 4314 and 6420 crates.

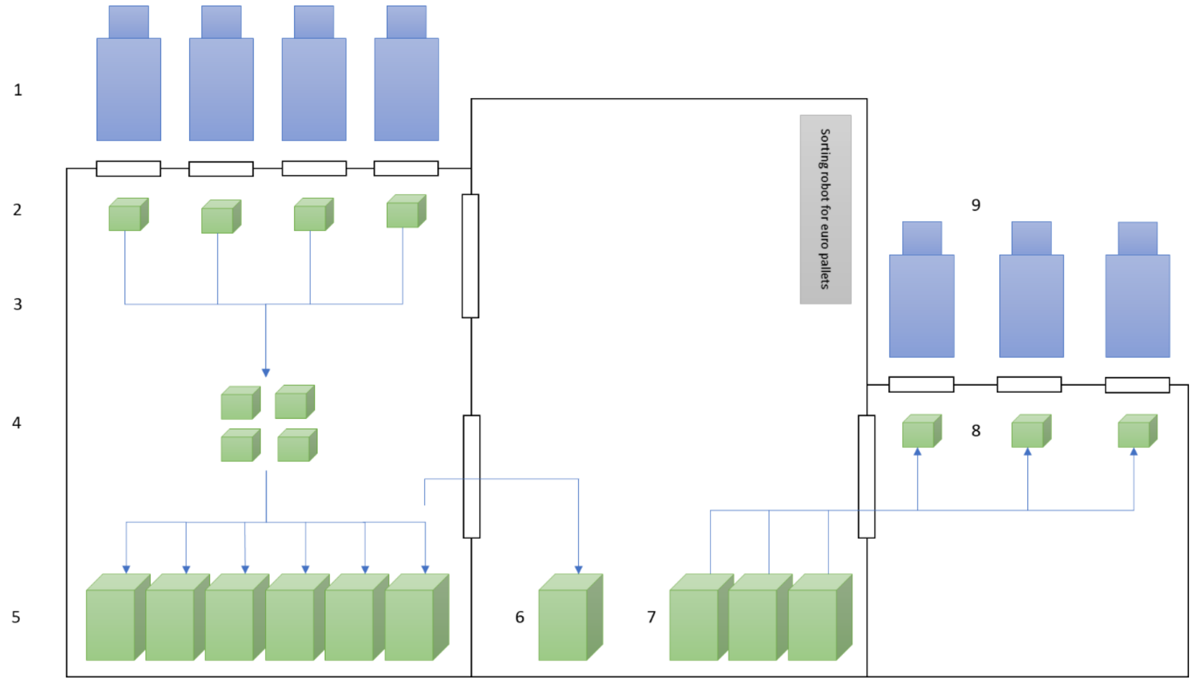

Figure 4-1 Overview of sorting process of crates.

1. Truck with unsorted crates and pallets from grocery stores.
2. Pallets with crates unloaded from trucks.
3. Move pallets with forklift to sorting station.
4. Sorting station
5. Pallets with sorted crates by type and size.
6. Pallets with sorted crates wrapped in plastic.
7. Storage.
8. Pallets with sorted crates ready for shipping.
9. Trucks transporting sorted crates to grocery suppliers.

Trucks collect pallets and crates at grocery stores and bring these to the sorting facility. The different crates arrive mixed and stacked on Euro-pallets.

Truck drivers collect the pallets and bring them to the sorting area. Here the different crates are separated and stacked on new euro-pallets. When the stacks have reached the desired height, they are wrapped in plastic film for safety, and put in stock.

The process to be investigated is the sorting, and not the processes before and after.

4.2 5-aspect taxonomy on manual case

Structural taxonomy

The product delivery from this process is both the sorted and quality-controlled stacks of crates, the storage, and the distribution of crates when needed, number 7, 8 and 9 in figure above.

Figure 4-2 Structural taxonomy- product

This process is mostly manual today, with the help of forklifts to move pallets full of crates. The manual solution is working well if the volumes is moderate. When the volumes increase, which they do frequently, the manual solution becomes the problem. It simply takes too long to sort all the crates that arrive in a day, and overtime must be used to solve the challenge.

The structural elements of this process are therefore limited, and consist of the forklift, the pallet with crates, and the crates themselves.

Behavioural

The process of sorting crates, is visualized in a work breakdown structure (WBS), showed in the figure below. This figure is created on the basis on the current process and is based on observations and interviews. The process is described in detail with reference to the numbering in the figure below.

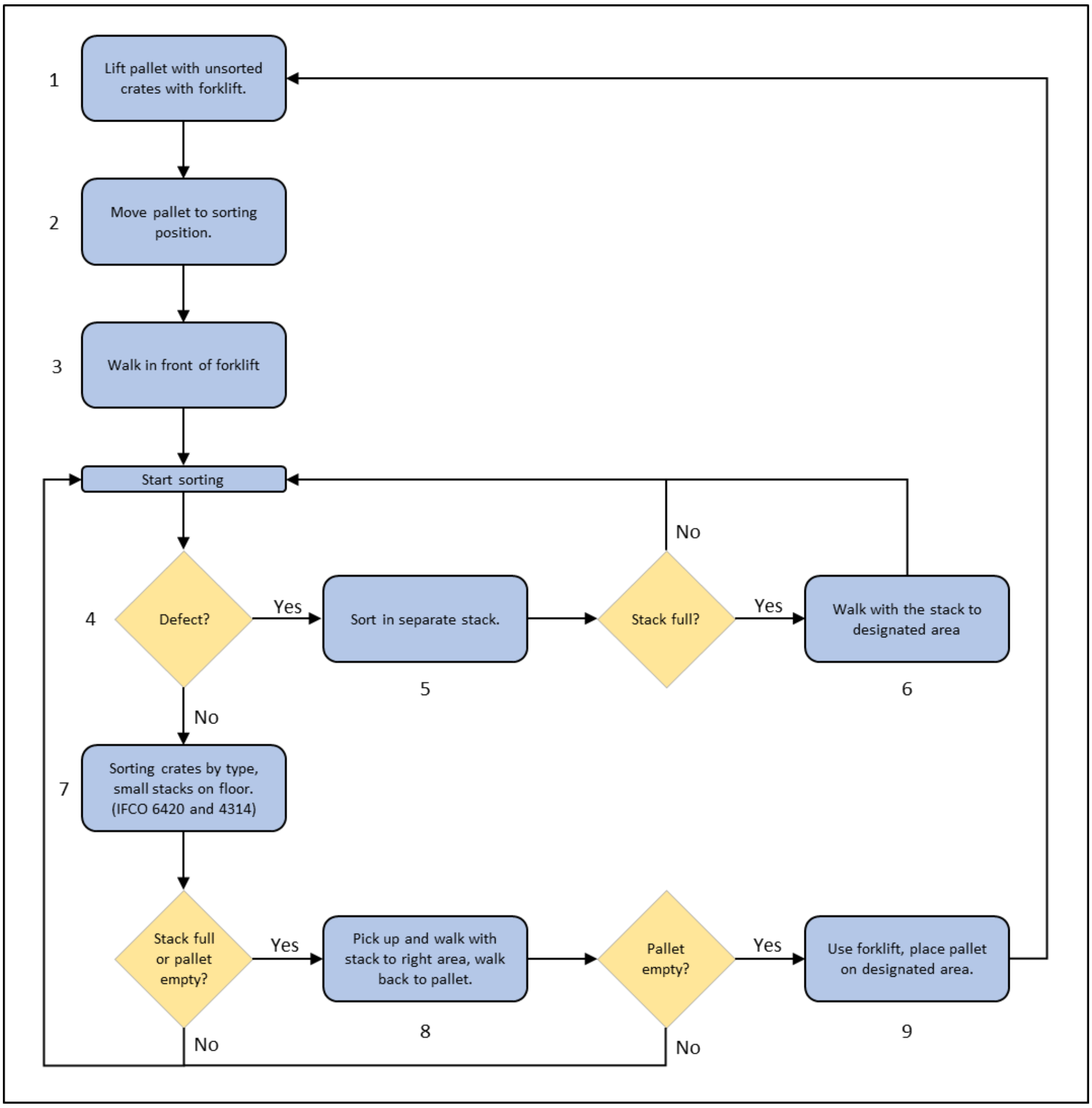

Figure 4-3 Behavioural work breakdown structure

Whit a forklift, one person picks up the pallet with unsorted crates (1) and drive as close to the pallets with sorted crates as is convenient (2). Here the person walks in front of the forklift and pallet (3) and starts to sort the crates by type and stack them on the floor in small and manageable stacks (7). All times while the person is collecting and sorting crates, the quality and functionality of the crates must be considered (4). Defect crates are sorted out (5) As the pallet with unsorted crates is empty, and there are several small stacks on the floor, the small stacks are then picked up by hand, and place on top of the already sorted crates (6 and 8). On each pallet there are 4 by 60 IFCO 6420 crates, and 8 by 60 IFCO 4314 crates (half size). The now empty pallet is then driven by forklift and placed on the designated place (9). The process then repeat itself, until all crates are sorted.

Contextual

The contextual aspects of the sorting system are based on interviews of engineers at Currency Robotics and workers at the sorting facility.

There are clear seasonal variations in the amount of work at the sorting station. The period just before and after various holidays is extra demanding with a large amount of work. Two shifts are often necessary to get the job done on time. In general, the period from November to mid-January is considered high season, they experience peaks in the amount of work during the summer months as well, but not as much as the periods mentioned. There are also variations during a week. Extra crates are collected on Mondays due to the weekend, which in turn generate work for Monday and Tuesday. Wednesdays and Thursdays are often a bit calmer before the workload builds up on Friday.

The crates are stored indoors, at the grocery stores, in the sorting station and they are transported I closed trucks. Seasonal differences in weather conditions and temperature, will not affect the crates, and therefore not the sorting process.

All pallets and crates discussed in this thesis are strictly regulated and standardized in terms of design and function. It is Currence Robotics' impression that this is "set in stone” and will not be changed in the foreseeable future.

Temporal

Based on the Behavioural section, the time schedule for each sub process is presented in a Gantt-chart. The time estimate for the sub processes is based on interviews and observations of the processes. Although the processes are relatively simple, time variations for the different sub-processes can vary from person to person and from day to day. Stated values are based on an average of observations, or estimates made by various stakeholders.

Pallets returned from grocery stores contain a mix of different crates, the IFCO 6420 and 4314 is one the most common, and all the pallets contain a varying amount of these. On average, there are 51 pieces of both sizes in total on each pallet. This number of crates will therefore be used in the further calculations in this, and the next sections.

	Task	Sum duration	Duration sec.	Unit
1	Drive to, choose, lift pallet with unsorted crates, forklift.	0	11	sec.
2	Move pallet to sorting position.	11	9	sec.
3	Walk in front of forklift.	20	5	sec.
4	Visual inspection (51 pcs. * 5 sec.)	25	255	sec.
7	Sorting crates by size, stacks on floor (51 pcs. * 4,25 sec.)	280	217	sec.
8	Walk with stack to right area, walk back (4 times * 19,5 sec.)	497	78	sec.
9	Use forklift, place empty pallet on designated area.	575	37	sec.

Tabell 4-1 Time schedule for each sub process.

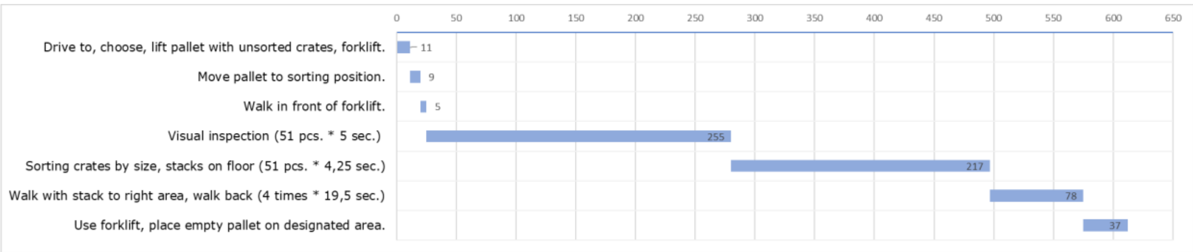

Figure 4-4 Time schedule for each sub process.

Tabell 4.1 and figure 4.4 shows how much time the operators spend on each individual operation.

The first two operations are performed with a forklift and are easy to carry out. The third operation is, as we see, the most time-consuming. Here, each individual crate must be visually inspected for defects. Since the crates are collapsible and flat-packed, each crate must be lifted in a special way that allows them to open slightly, so that it is possible to inspect the entire construction. The fourth operation is a continuation of the third, and the execution takes barely one second. Operation five completes the sorting by placing the sorted crates on the specified area. The pallet with unsorted crates is placed close to this area in point two, so the distance to the stacks of sorted crates is short. During the observations, the now empty pallet was always moved with the forklift.

Perceptual

Main stakeholders in this sorting process are the clients, those who perform the sorting, those who own and rent out the crates, and the food suppliers who use the crates. The problem today is that people make mistakes, and defective crates are returned to food suppliers. The company that owns and rents out the crates is interested in sorting out defective crates. They do not get paid for defect crates, and their customers are not helped by these.

Other stakeholders are the operators who perform the sorting, and the company these work for.

By automating the sorting process, some new stakeholders are introduced. Currence Robotics develops, assembles, and maintains the automated solution, and therefore has several relevant stakeholders. This can be the assembly team, the maintenance team, and the design team with engineers.

Important features of an automated solution may look different depending on the perspective. For major stakeholders, those who perform the sorting, a cost-effective system is important. This is a system that is both inexpensive to purchase, requires little maintenance and performs sorting very well. Time and cost are often the most important characteristics of a system, and in this system, time is also crucial. Due to large seasonal variations, it is desirable that an automated system can handle the peaks without the operators having to work overtime or other costly measures.

For the operators who perform the sorting, an automated system will remove much of the physical load. Most of the work can be done using the forklift.

As mentioned in the Contextual chapter, all pallets and crates discussed in this thesis are strictly regulated and standardized in terms of design and function. And it is Currence Robotics' impression that this is "set in stone” and will not be changed in the foreseeable future. The main stakeholders believe that the development over time will lead to an increase in the volume of pallets and crates. So, they want an automated system to be able to handle increased volumes, i.e., be flexible and expandable.

Currence Robotics is currently not aware of any special rules or regulations that apply to sorting machines in particular. They estimate that these machines are subject to the same regulations as all other machines in a workplace, and that it will be HSE considerations that must be complied with.

A Challenge with such types of machines is the space it requires. The machine itself requires a lot of space, as it must handle large stacks of crates, and there must be enough space to use a forklift to feed the machine and retrieve sorted crates.

4.3 System performance (KPIs)

The key performance indicators (KPIs) are agreed with selected shareholders based on conversations and interviews. As the Perceptual chapter shows, important characteristics will vary with who decides, but the main stakeholder decides which KPIs are used in this thesis. And for all the processes examined in this thesis, the following KPIs will be measured.

The manual process is based on the time it takes to sort 51 crates, which is the average of IFCO- 4314 and 6420 on a pallet with several types of unsorted crates. This is then multiplied up to find the number of crates sorted per. hour.

For the forklifts, which are included in all cases, the purchase price is divided by the estimated useful life, plus service and operating costs for the same period. The operators driving the forklifts is also to varying degrees included in all cases and here salaries, personal protective equipment, work clothes, sick leave, injuries are included in the various KPIs.

Opex [NOK]

Operating costs is the day-to-day expenses necessary for the process. This includes maintenance of equipment, and salary for the operators. The maintenance costs are divided into working time cost and material cos.

Capex [NOK]

Capital cost are major purchases designed to be used over a long term, included the installation. This is different for the different processes, especially the manual one in relation to those where automation is implemented to different degrees.

For the manual process, the forklifts are responsible for the capital cost, as these are the only machines in use.

For the three subsequent processes, the increased implementation of automated solutions will increase the capital cost for the processes.

The installation costs will also increase with the amount of install equipment through the various cases, these costs are divided into working time cost and material cos.

Reliability [Stops over time]

In this context, a reliable process is a process with few stops and if a stop occurs, the process starts again quickly. This indicator gives an average number of stops in the process per unit of time. A lower number equals a more reliable system. As previously mentioned, this average number is based on interviews of the main stakeholders, experiences made by the operators.

Robustness [%, Probability of consequence]

System robustness is the ability to remain functioning under a range of disturbances. (Mens *et al.*, 2011)

To measure robustness to the process, three levels of failure with increasing consequence have been defined. The probability of the different failures for each case is then stated in percent.

Failure 1 is a simple failure that can be quickly corrected without stopping the process or the process restarting in seconds. This can be a box or crate falling on the floor, and an operator uses one or two second picking it up and continues the process.

Failure 2 is a medium failure. This can be equipment that fails and needs to be replaced, either within a few minutes or within a few hours. Standardized equipment in stock is replaced within minutes, while many spare parts are currently in centralized remote warehouses in the county and can be delivered within a few hours.

Failure 3 is a large failure. This type of error stops the process for a long time, often several days. This can be caused by major errors that require service personnel and ordering and waiting for parts. A larger or smaller fire in the plant will be able to stop the process for a long time and is considered a major fault.

Efficiency [crates per. hour]

The efficiency indicator tells us how many crates are sorted per hour. There is today a desire to sort approx. 300 crates per. hour, but all main stakeholders agree that a system must handle more than this in the future. An automatic sorting process must handle 1200 crates per hour.

4.4 Change cases

All change cases will contain different degrees of automation, the last one being fully automated according to Currence Robotics technology. All will be compared with the manual sorting described in the chapter 4.1 and 4.2.

In change case 1, technology will be introduced to automate the visual quality assessment. As stated in chapter 4.2 Temporal, this is the sub-process that takes the most time. In addition to the use of time, the quality of this process is also important. The number of errors in the manual sorting process is not known but as stated in chapter 4.2 Perceptual, it is an important factor.

Change case 2 builds on case 1 by automatically sorting the crates according to the quality control. The crates are then ready to be transported to the designated area.

In change case 3, full automation for the sorting process is implemented. This may seem like a big step in relation to case2, which it also is, but it may appear natural, especially when we look at it in more detail in chapter 4.6

4.5 State of the art technology for sorting

In addition to using state of the art technology, it will also focus on available and what technology is used by Currence robotics today.

From chapter 2.2 Automation technology for sorting, we have that technology for sorting can be divided into three main areas. Transport of what is to be sorted, sensors, and gripping technology.

To transport pallets with crates over relatively short distances of 5 -6 meters, and at the same time act as a buffer for the automatic sorting process, a roller conveyor will be a robust, simple and good solution. As a buffer, there will be room for 5- 6 pallets of crates on a roller conveyor used today. If a larger buffer is needed, the roller conveyor can easily be expanded. The pallets with crates have enough weight that gravity roller conveyors can be used. The pallets that are waiting are held back with stop blocks integrated in the roller conveyors, which are controlled by sensors.

Different sensors are used for different tasks. To detect the stacking height, both laser and inductive sensors are currently used at Currence Robotics. But the most important and mes allside sensors are the 3D vision cameras. Several 3D vision cameras, all of which are located in the infeed tower, are used to verify both type and quality.

4.6 Case studies

All change cases will be based on and compared to the manual process from chapter 4.2, this chapter will therefore start with a visual and descriptive presentation of the manual process to make it easier to compare later.

4.6.1 Manual case

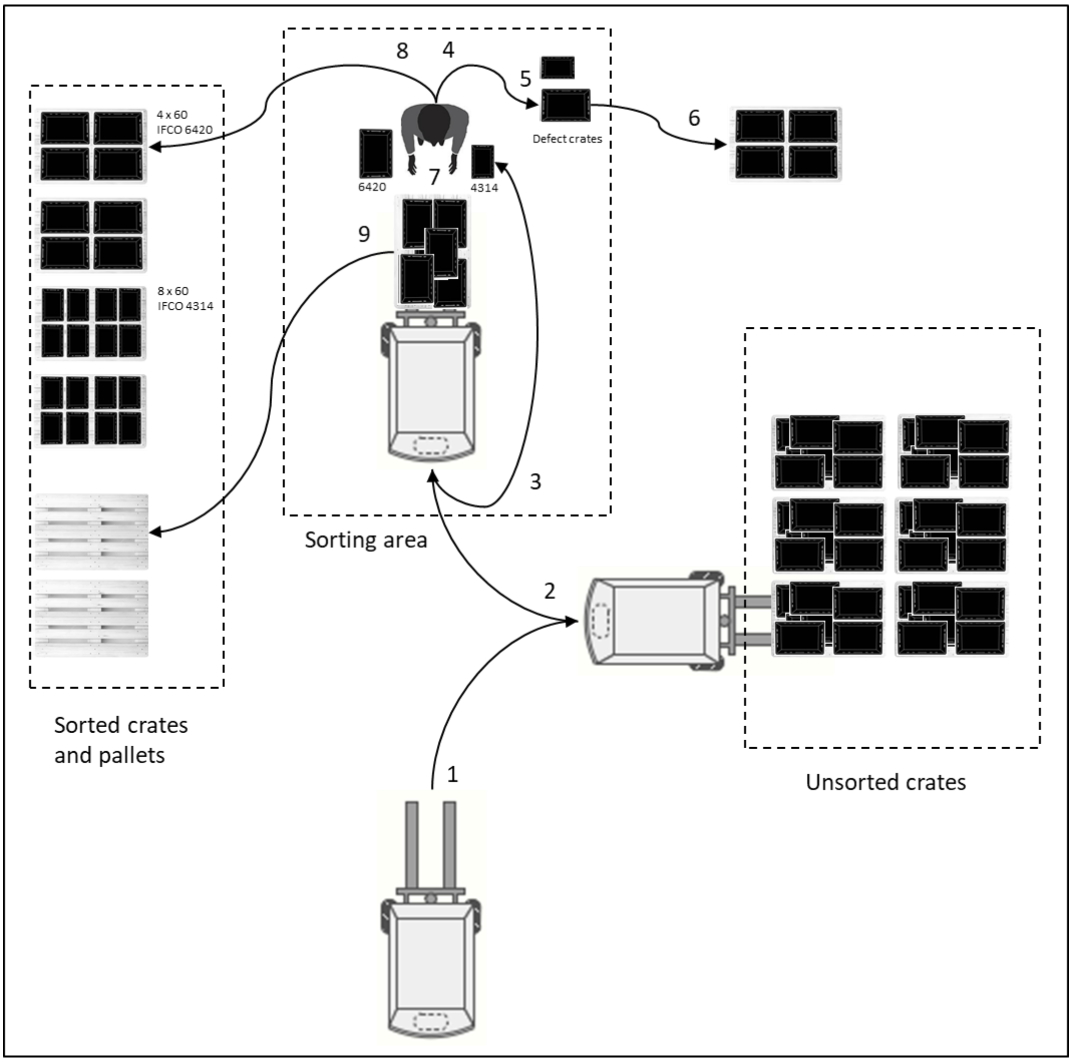

Figure 4-5 Block diagram of manual sorting case

(1) Whit a forklift, one person picks up the pallet with unsorted crates (2) and drive as close to the pallets with sorted crates as is convenient. Here the person walks in front of the forklift and pallet (3) and starts sorting the crates by type and quality and stacking them on the floor in small and manageable stacks (7). All times while the person is collecting and sorting crates, the quality and functionality of the crates must be considered (4). Defect crates are sorted out (5) As the pallet with unsorted crates is empty, and there are up to 4 small stacks on the floor, the stacks are then picked up by hand and place on top of the already sorted crates (6 and 8). On each pallet there are 4 by 60 IFCO 6420 crates, and 8 by 60 IFCO 4314 crates (half size). The now empty pallet is then driven by the forklift and placed on the designated place (9). The process then repeat itself, until all crates are sorted.

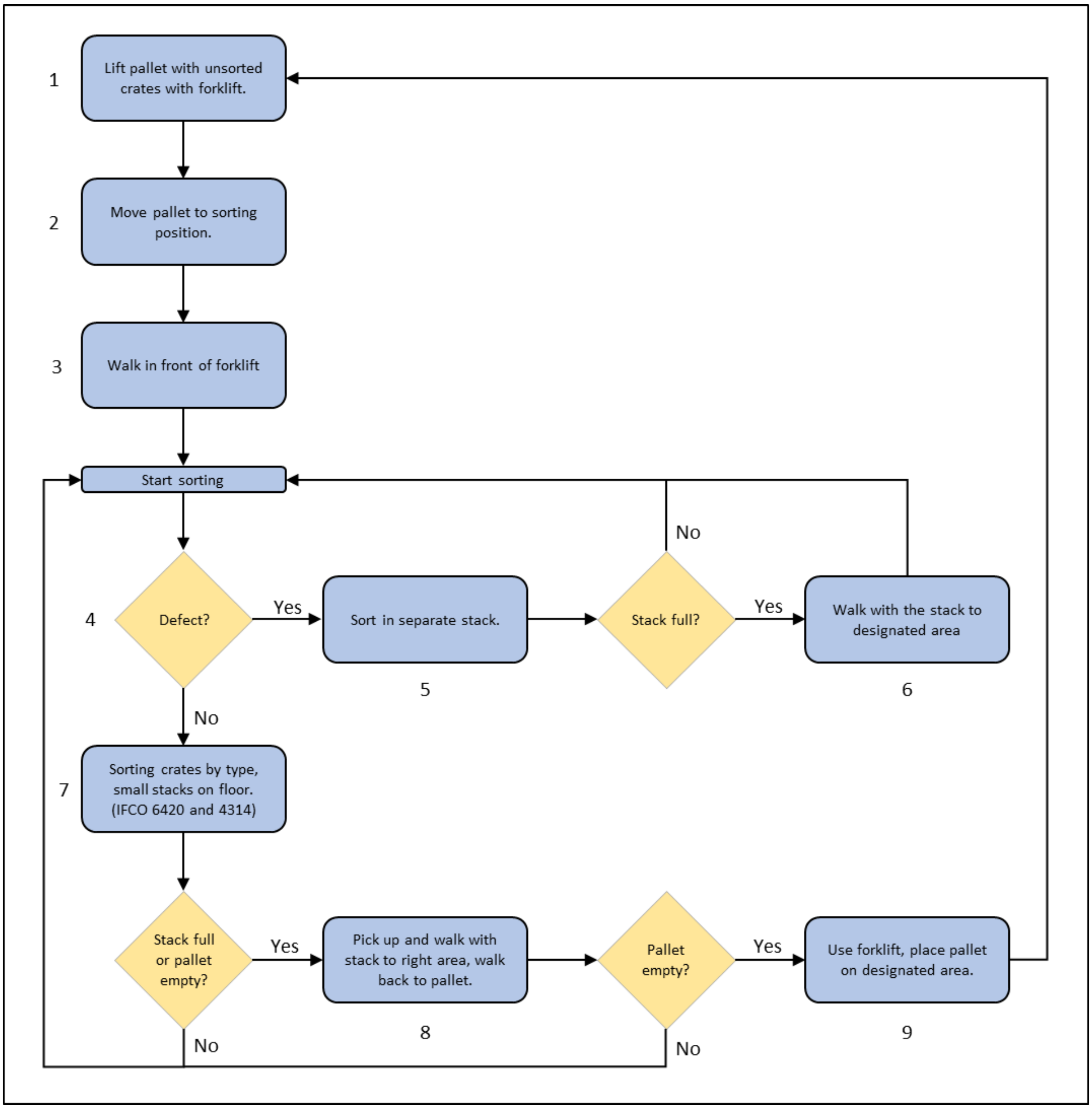

Figure 4-6 Flow chart of manual sorting case.

The figure above shows the logical workflow of the manual case. The numbering corresponds to the numbers in the previous block diagram and paragraph. The gradual implementation of automation in the next cases will be made visible in a new corresponding flowchart for each individual case.

The table below shows all operations visible in the flowchart above in sequential order, matched with the time to execute the individual operations. The bottom five rows show the values for the KPIs described in Chapter 4.3.

Task	Sum duration	Duration sec.	Unit
Drive to, choose, lift pallet with unsorted crates, forklift.	0	11	sec.
Move pallet to sorting position.	11	9	sec.
Walk in front of forklift.	20	5	sec.
Visual inspection (51 pcs. * 5 sec.)	25	255	sec.
Sorting crates by size, stacks on floor (51 pcs. * 4,25 sec.)	280	217	sec.
Walk with stack to right area, walk back (4 times * 19,5 sec.)	497	78	sec.
Use forklift, place empty pallet on designated area.	575	37	sec.
Opex (NOK per hour)		675	NOK
Capex (NOK per hour)		26	NOK
Reliability (Stops per hour)		0,13	Stops per hour
Robustness (%)			
Probability of failure 1		85	%
Probability of failure 2		20	%
Probability of failure 3		1	%
Efficiency (crates per. hour)		300	crates per. hour
Cost per sorted crate (Sum Capex + sum Opex/ 391)		2,34	NOK per crate

Tabell 4-2 Duration of each sub-process, and KPI values for manual sorting case.

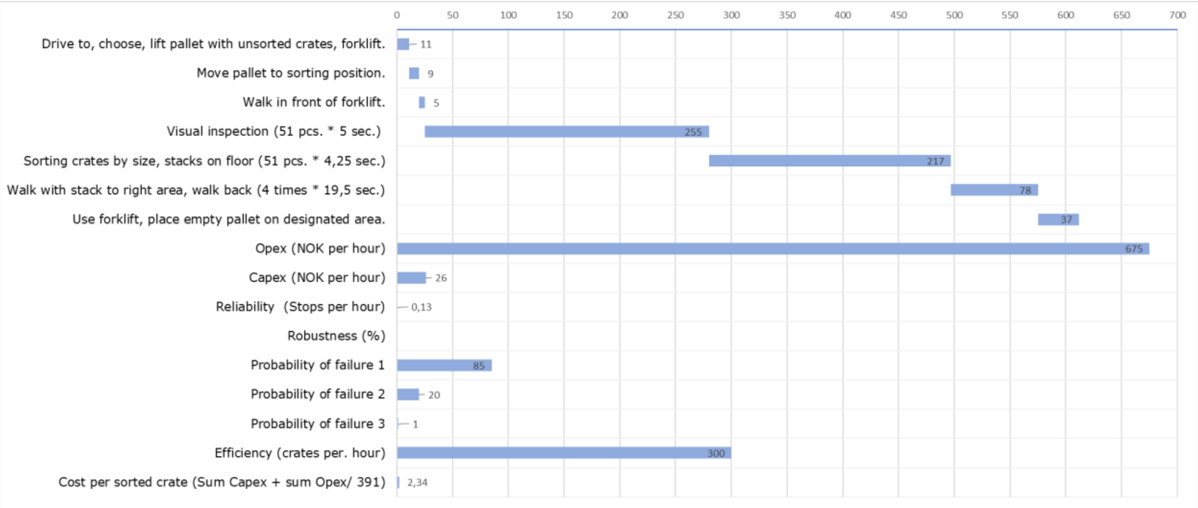

Figure 4-7 Duration of each sub-process, and KPI values for manual sorting case.

KPI calculations

Opex

To indicate operational costs for the process, expenses for salaries, sick leave, maintenance of equipment, personal protective equipment and work clothes are summed and divided by the number of working hours during a year.

Capex

There are not many items within the cost of capital for the manual sorting process, and to simplify, only the forklift, which is the only machine in use, is included.

Reliability (Stops per hour)

During the observations of the manual sorting process, there was no stop. However, from the interviews with the operators, it was said that despite good personal safety equipment, there could be a small cut from time to time that needed washing and a band-aid. Occasionally one of the forklifts ran out of power and had to be charged. There is always one on charge so this rarely created major problems, but it would cause a short stop in the process.

To make the comparison as realistic as possible, there will be one stop a day in the manual sorting process.

Robustness (%)

Failure 1 is a simple failure that can be quickly corrected without stopping the process or the process restarting in seconds. Small accidents happened from time to time, this is because the operators were inattentive, or worked a little too fast. These small mishaps could be losing a stack of sorted crates on the floor on the way to placing them in the right place, which meant they had to be stacked and picked up again. Such small misses of various kinds happened almost daily, but there was no damage, and the process continued quickly.

Failure 2 is a medium failure. Not as often as previous errors, but occasionally, accidents occurred with the forklift. These consisted of crashing into the pallet with crates that could lead to many crates plunging across the floor. This rarely led to damage to equipment, but some work to clean up. A little abrupt manoeuvring could also lead to crates falling off the pallet. Again, there was rarely material damage, but some extra work. This did not happen very often but could occur once or twice a week.

Failure 3 is a large failure. This type of error stops the process for a long time, often several days. The manual process is completely dependent on forklifts. These are electric and they charge every night. A power outage that meant that these were not charged and ready for use will stop the whole process. The pallets with crates are heavy and cannot be carried by humans. Lifting a certain number of crates from the pallets and then carrying them in place is possible but will take so long that you do not get enough sorted. In practice, this will stop the process. All forklifts charging at the same place in the factory. Should there be a fire in a forklift or charger, it will easily spread to the other forklifts. This will, for the same reason as previously mentioned, stop the whole process. Fortunately, major accidents rarely happen, but when they do, the process can stop for several days.

Efficiency [crates per. hour]

Based on Table 4.3 and Figure 4.7, we can see that it takes 612 seconds to sort 51 crates, which gives 300 crates per hour. There are two people who work about 4 hours a day with the sorting, these also perform other tasks because of the process. In addition, there are other processes in which they participate. If there is a desire to sort more crates per day, more people must be hired.

System performance indicators (KPIs) - Manual process							
	Unit price	Operators	Days per year	Hours per day	Calculation	Sum	Unit
Opex							
Sallary	472 680	2	239	4	472 680 *2/ (239*4*2)	494	NOK per hour
Sick leave	247	2	20	4	(247*2*20*7,5)/239	165	NOK per hour
Maintenance forklift	8 000	2	239	8	(8 000*2)/(239*8)	8	NOK per hour
Personal protective equipment	4 000	2	239	8	(4 000*2)/(239*8)	4	NOK per hour
Work clothes	3 000	2	239	8	(3 000*2)/(239*8)	3	NOK per hour
Sum						**675**	**NOK per hour**
Capex							
Purchase price forklift	250 000	2	239	8	(250 000*2)/(239*8*10 years)	26	NOK per hour
Sum						**26**	**NOK per hour**
Reliability							
Stops in production (One stop per day)						0,13	Stops per hour
Robustness (Probability of consequence)							
Probability of failure 1						85	%
Probability of failure 2						20	%
Probability of failure 3						1	%
Efficiency							
Crates sorted per hour				(51 crates / 469 sec.) * 3600 sec/hour		300	Crates per hour
Cost per sorted crate					Sum Capex + sum Opex/ 391	2,34	NOK

Tabell 4-3 KPI calculations for manual sorting case.

4.6.2 Change case 1 – Automatic quality control

The first step towards a fully automated process is to implement an automatic quality control of the crates. This is a consequence of the results from Table 4.3 and based on the KPIs. Table 4.3 and figure 4.7 show that it takes an average of 255 sec to inspect 51 crates. This is the sub-process that takes the longest time to complete manually and both time use, and workload will hopefully benefit from automation.

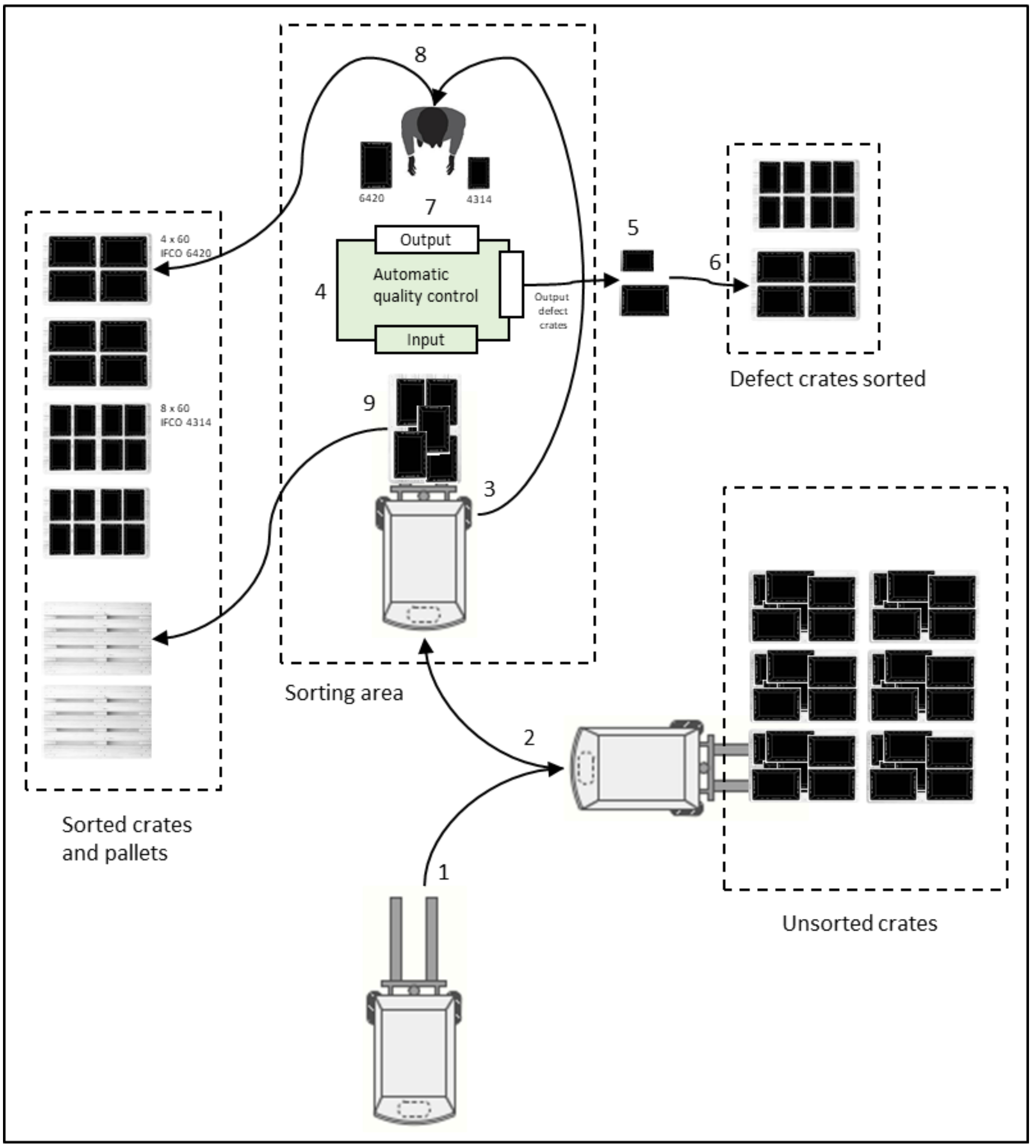

Figure 4-8 Block diagram of change case 1.

In the figure above, a sub-process has been added, marked with the number 4, which symbolizes the automatic quality control that is performed on all crates before sorting.

4.6.2.1 5-aspect taxonomy on change case 1

Change case 1 is based on the manual sorting case, and a 5-aspect taxonomy for the manual case was reviewed in chapter 4.2. This chapter will only refer to changes that the implementation of automatic quality control entails for the process.

Structural

The original process consisted of forklifts, pallets, and crates. There will always be a manual contribution to the various change cases, and in addition to the pallets with crates, the forklift will always be included. The structural elements that are new in this case are the parts that the automatic quality control consists of. This is a large implementation as it contains most of the sensors, the gripper for the crates and the electronics that control it all.

New structural element is laser based top limit sensor, several 3D-vision sensors to perform the quality control and a gripper handling the crates.

Behavioural

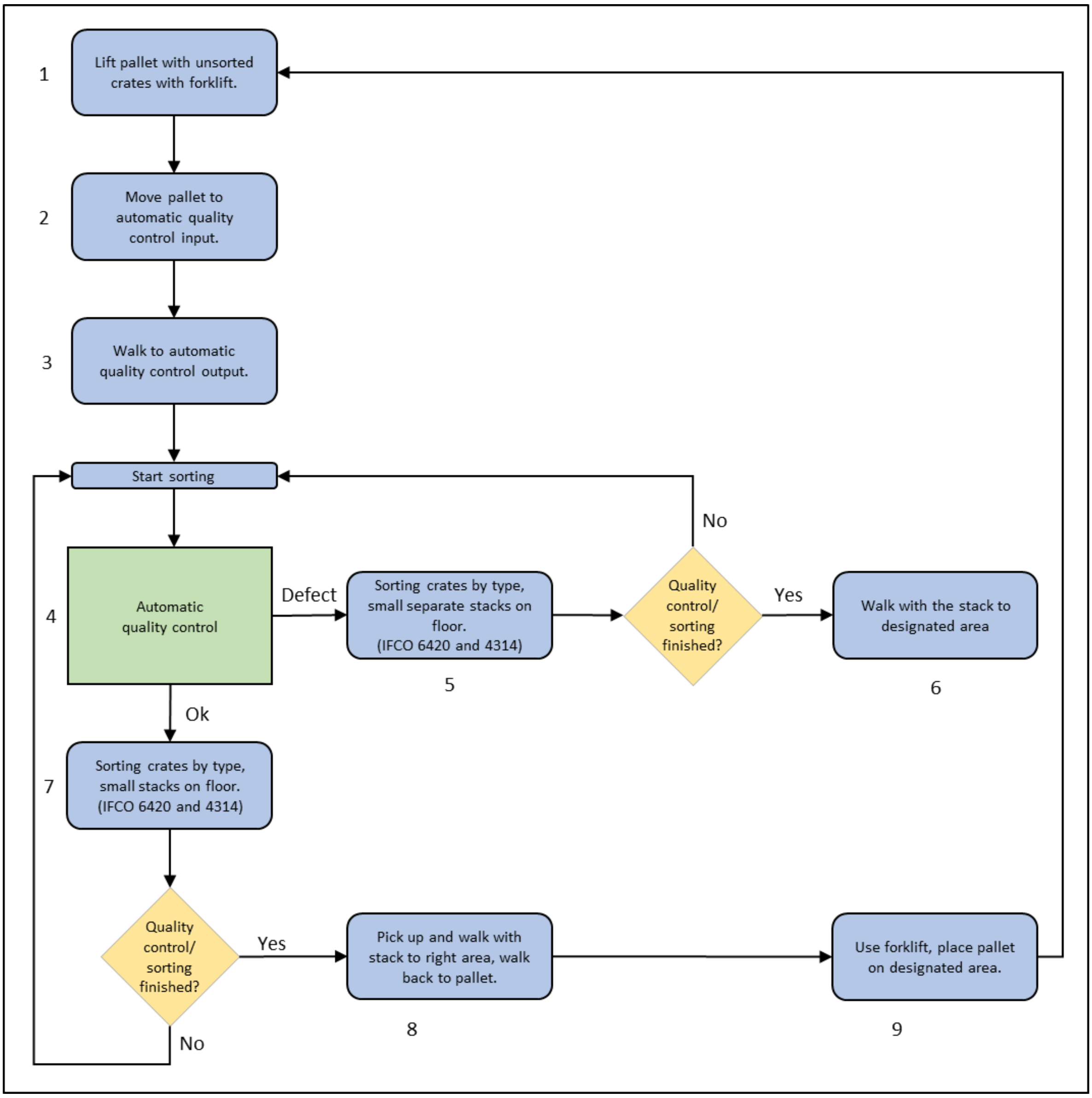

Figure 4-9 Flow chart of manual change case 1.

The new sub-process is also here numbered with the number 4 and marked in green, and inside the green box the new quality control takes place. After the manual subprocesses 1 and 2 are performed, while the operator performs process 3, the automatic process 4 starts.

The first thing that meets the pallet crates are the laser based top limit sensor at the infeed. This sensor prevents the stack of crates from being higher than the machine can handle. The quality assurance is done by the 3D vision sensors first from the top before the gripper lifts the pallet and the 3D vision sensors do a second inspection from underneath. The defect crates are then sorted out in a separate stack.

Contextual

Table 4.4 below, shows that the number of sorted crates has increased from 300 per hour to 409. This will help in the seasonal and weekly variations that take place. If it is not sufficient to relieve the operators significantly, it is a clear signal of what is achieved by implementing automation.

Temporal

Based on the Behavioural chapter, the time schedule for each sub process is presented in a Gantt-chart

	Task	Sum duration	Duration sec.	Unit
1	Drive to, choose, lift pallet with unsorted crates, forklift.	0	11	sec.
2	Move pallet to sorting position.	11	9	sec.
3	Walk in front of forklift and automatic quality control	20	5	sec.
4	**3D scan of crate from top side x 51 pcs.**	25	21	
5	**Gripper move in and grab crate x 51 pcs.**	46	25	
6	**Lifting crate x 51 pcs.**	71	25,5	
7	**3D scan of crate from below x 51 pcs.**	96,5	20,5	
8	Sorting by size, stacks on floor (51 pcs. * 4,25 sec.)	117	217	sec.
9	Walk with stack to right area, walk back (4 times * 19,5 sec.)	334	78	sec.
10	Use forklift, place empty pallet on designated area.	412	37	sec.
1	Opex (NOK per hour)		832	NOK
2	Capex (NOK per hour)		92	NOK
3	Reliability (Stops per hour)		0,13	Stops per hour
4	Robustness (%)			
	Probability of failure 1		70	%
	Probability of failure 2		20	%
	Probability of failure 3		1	%
5	Efficiency, crates per. hour (51 crates / 449 sec.) * 3600 sec/hour		409	crates per hour
6	Cost per sorted crate (Sum Capex + sum Opex/ 391)		2,26	NOK per crate

Tabell 4-4 Duration of each sub-process, and KPI values for change case 1.

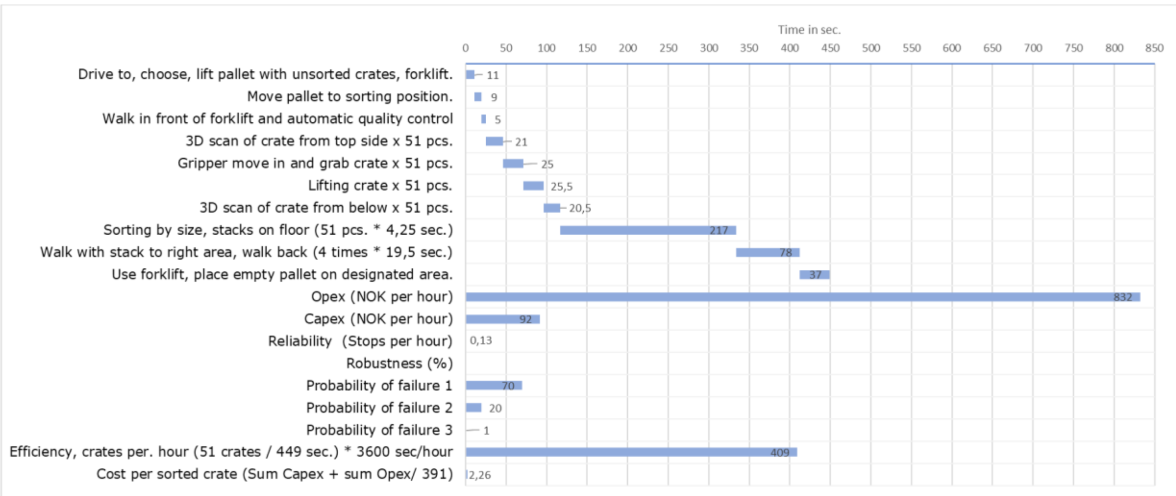

Figure 4-10 Duration of each sub-process, and KPI values for change case 1.

In bold, lines 4 to 7 in table 4.4, show the sub-processes in the automatic quality control. Compared to the manual process, the time to sort 51 crates is reduced by 163 seconds.

This gives an increase in the number of possible sorted crates from 300 to 409 pieces per hour.

Table 4.5 shows the KPI calculations for change case 1. Operational costs have increased from NOK 675 per hour to NOK 832 per hour. This is due to annual maintenance costs related to the structural parts of the automation. Currence Robotics has estimated a maintenance cost of NOK 1 million per year for a fully automated machine. To better compare the cases, this amount is divided between the different cases.

Capital costs increase from NOK 26 per hour to NOK 92 per hour. This is due to the purchase of the structural parts related to the automatic quality control of NOK 1,250,000. This in turn is based on statements from Currence Robotics regarding price. Their estimates show that a complete plant for sorting crates will cost approx. NOK 3.5 million. This sum is divided into the different cases for comparison.

As long as there are people involved in the sorting process, it is difficult to assess the number of stops per unit of time differently for this process. Experience from Currence Robotics' existing solutions shows that the machines have very few stops.

When it comes to faults in the process, the gradual elimination of human impact will reduce the probability of small errors such as failure 1. The probability of failure 2 and 3 is considered to be the same as before.

The efficiency of the process has increased by approx. 36% from 300 to 409 crates per hour. Not part of the initial KPIs, butt interesting to compare between the cases, is the cost per crate. Despite increased costs in both Opex and Capex, and that all costs associated with the operators are the same, the cost per sorted crate has been reduced from NOK 2.34 to NOK 2.26. So, a 36% increase in efficiency per hour, has resulted in a price reduction of 3.4% per sorted crate.

System performance indicators (KPIs) - Manual process							
	Unit price	Operators	Days per year	Hours per day	Calculation	Sum	Unit
Opex							
Sallary	472 680,00	2	239	4	472 680 *2/ (239*4*2)	494	NOK per hour
Sick leave	247,00	2	20	4,0	(247*2*20*7,5)/239	165	NOK per hour
Maintenance forklift	8 000,00	2	239	8	(8000*2)/(239*8)	8	NOK per hour
Personal protective equipment	4 000,00	2	239	8	(4000*2)/(239*8)	4	NOK per hour
Work clothes	3 000,00	2	239	8	(3000*2)/(239*8)	3	NOK per hour
Yearly maintenance Automatic quality control	300 000,00		239	8	300 000/(239*8)	157	NOK per hour
Sum						**832**	**NOK per hour**
Capex							
Purchase price forklift	250 000	2	239	8	(250 000*2)/(239*8*10 years)	26	NOK per hour
Automatic quality control	1 250 000		239	8	(1000 000*2)/(239*8*10 years)	65	NOK per hour
Sum						**92**	**NOK per hour**
Reliability							
Stops in production (One stop per day)						0,13	Stops per hour
Robustness (Probability of consequence)							
Probability of failure 1						70	%
Probability of failure 2						20	%
Probability of failure 3						1	%
Efficiency							
Crates sorted per hour				(51 crates / 469 sec.) * 3600 sec/hour		409	Crates per hour
Cost per sorted crate					Sum Capex + sum Opex/ 391	2,26	NOK

Tabell 4-5 KPI calculations for change case 1.

Perceptual

The main stakeholders who benefit most from this step in the automation are the operators who carry out the process, and the company that owns and leases the crates. The operators do not have to deal with a bottleneck in the process, and the company that owns the crates will only send out crates that are in satisfactory condition.

4.6.3 Change case 2 – Automatic sorting of size and quality

The second step towards fully automated solution, and a natural next step after the automatic quality control, is automatic sorting by size and quality. There are two sizes of the crates, the IFCO 6420 and the half size 4314.

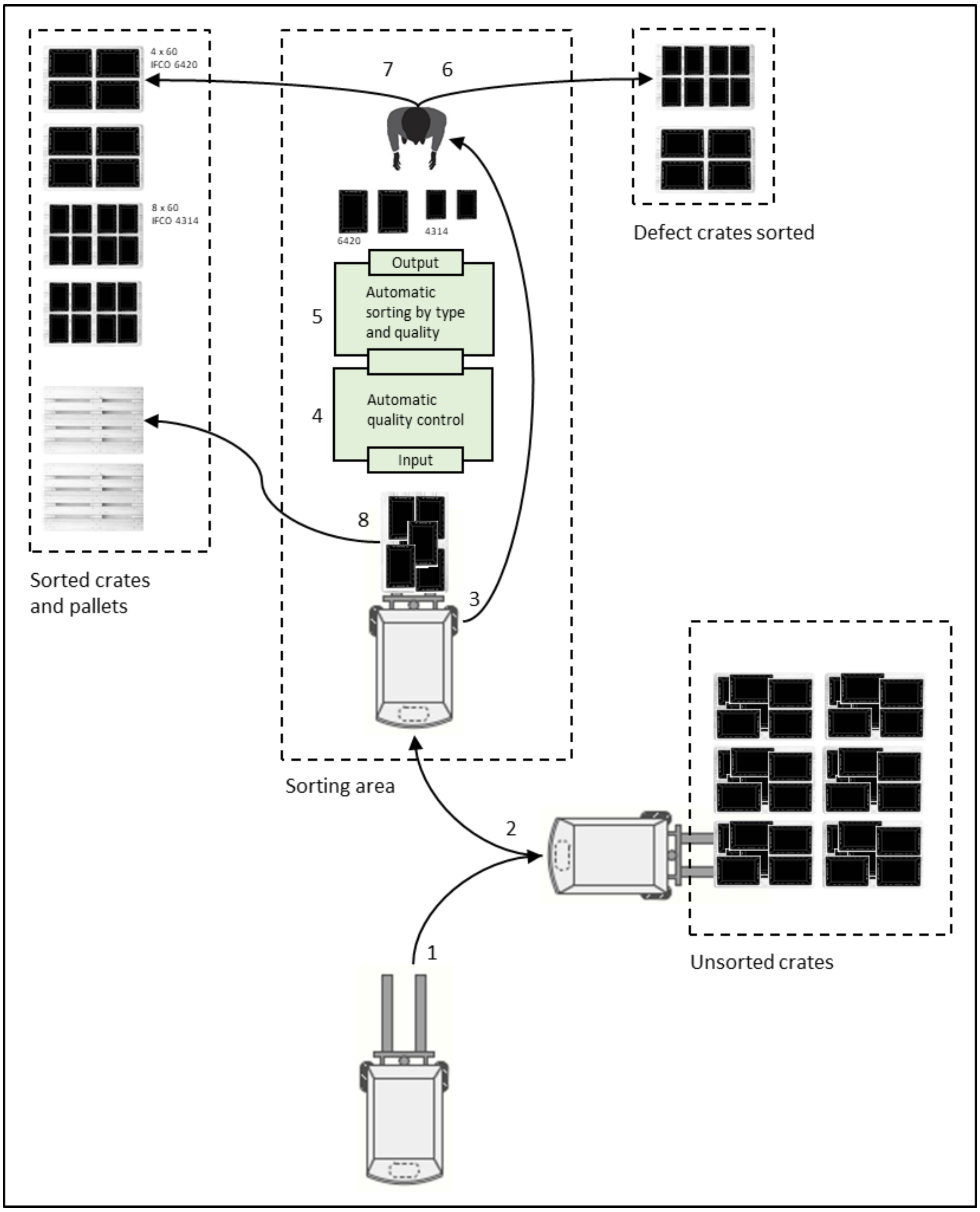

Figure 4-11 Block diagram of Change case 2

A new sub-process is added after the automatic quality control, marked with the number 5 in the figure above.

4.6.3.1 5-aspect taxonomy on change case 2

Since change case 2 is based on change case 1, which in turn is based on the manual case, and where the first two have undergone a 5-aspect taxonomy previously, only what is new in the process is considered in this chapter.

Structural

The differences between cases 1 and 2 are small when it comes to the structural part. It will be the same gripper used in the automatic quality control, which is used to sort crates. There are also the same 3D vision cameras that are used as sensors to determine size.

The gripper must be given greater freedom of movement to be able to place the different craters in different places. This is solved by placing the gripper on an overhead crane that has a horizontal movement. To be able to pick crates at different heights from the pallets, the gripper already can move vertically.

To distinguish the different sizes, the software that performs the quality control must be expanded to separate the crates by size. Otherwise, the same sensors are in use.

Behavioural

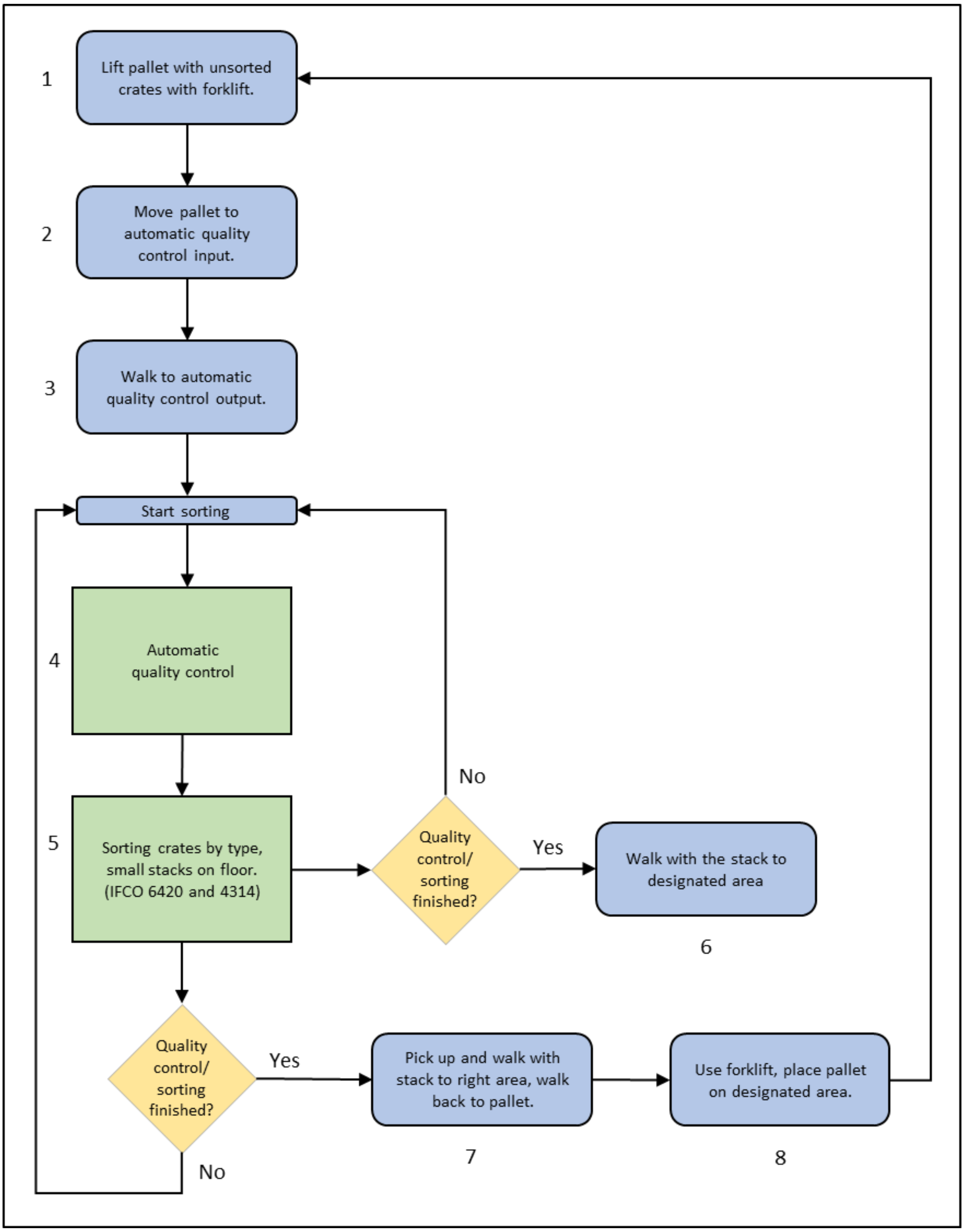

Figure 4-12 Flow chart of manual change case 2.

What distinguishes case 2 from no. 1 is that the crates are now stacked and presented to the operators according to size and quality. A predefined number of crates come stacked out of the machine ready to be carried to the specified place. The product from the automatic processes is now four different stacks, two stacks with approved crates one for each size, and two stacks with unapproved crates, one for each size.

Contextual

Table 4.6 shows observations and calculations for the new process. The process of sorting 51 crates has now been reduced from 449 seconds in case 1 to 258 seconds in case 2. This provides an opportunity to sort 712 crates per hour, compared to 409 in case 1.

Temporal

The below Gantt-chart shows the time schedule for each sub process as described in the Behavioural chapter.

	Task	Sum duration	Duration sec.	Unit
1	Drive to, choose, lift pallet with unsorted crates, forklift.	0	11	sec.
2	Move pallet to sorting position.	11	9	sec.
3	Walk in front of forklift and automatic quality control	20	5	sec.
4	**3D scan of crate from top side x 51 pcs.**	25	21	
5	**Gripper move in and grab crate x 51 pcs.**	46	25	
6	**Lifting crate x 51 pcs.**	71	25,5	
7	**3D scan of crate from below x 51 pcs.**	96,5	20,5	
8	**Automated sorting by size, stacks on floor (51 pcs.)**	117	26	sec.
9	Walk with stack to right area, walk back (4 times * 19,5 sec.)	143	78	sec.
10	Use forklift, place empty pallet on designated area.	221	37	sec.
1	Opex (NOK per hour)		989	NOK
2	Capex (NOK per hour)		157	NOK
3	Reliability (Stops per hour)		0,13	Stops per hour
4	Robustness (%)			
	Probability of failure 1		60	%
	Probability of failure 2		20	%
	Probability of failure 3		1	%
5	Efficiency, crates per. hour (51 crates / 288 sec.) * 3600 sec/hour		712	crates per hour
6	Cost per sorted crate (Sum Capex + sum Opex/ 391)		1,6	NOK per crate

Tabell 4-6 Duration of each sub-process, and KPI values for change case 2.

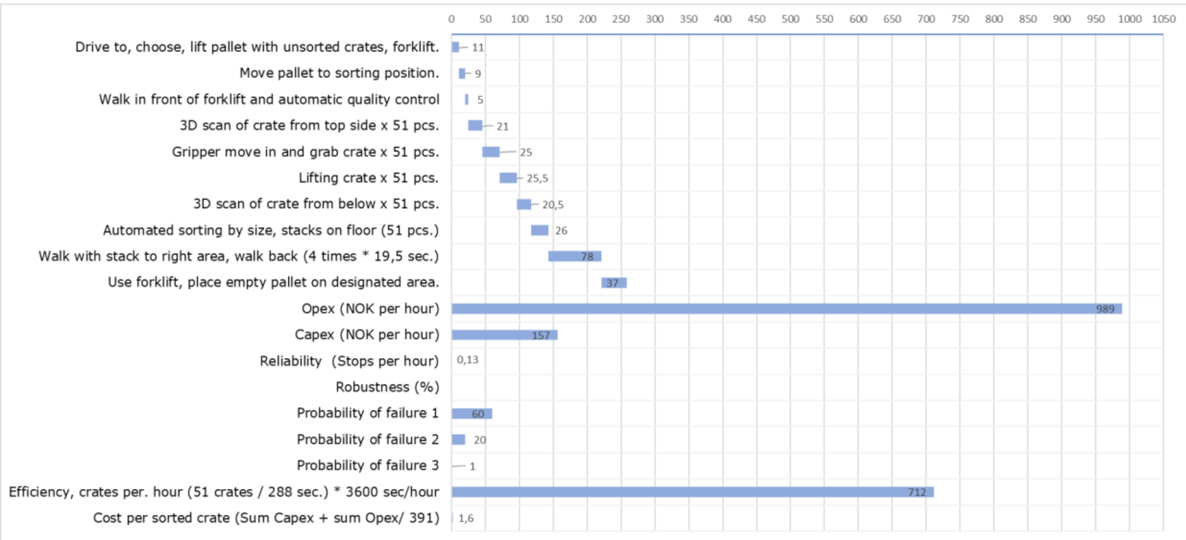

Figure 4-13 Duration of each sub-process, and KPI values for change case 2.

In relation to case 1, only line 8 in table 4.6 is new. The time to perform this subprocess is reduced from 217 seconds to 26 seconds.

Table 4.7 shows that both Opex and Capex have increased from 832 to 989 for Opex and from 92 to 157 for Capex, respectively. This is due to increased investments in structural components with a corresponding increase in service costs.

The probability of errors in the process is closely related to the human factor, and in this case fail 1 is reduced from 70% to 60% probability.

The efficiency of the process has increased by 74% from 409 to 712 crates per hour compared to case 1, and by 237% from 300 to 712 crates per hour compared to the manual.

There is now a greater reduction in the price per sorted crates from case 1 to 2, than we saw from the manual case to case 1. From the manual to case 1 there was a price reduction of 3.4%, from case 1 to 2 this price reduction is 29% from NOK 2.26 per crate to NOK 1.6 per crate.

System performance indicators (KPIs) - Manual process							
	Unit price	Operators	Days per year	Hours per day	Calculation	Sum	Unit
Opex							
Sallary	472 680,00	2	239	4	472680 / (239*4*2)	494	NOK per hour
Sick leave	247,00	2	20	4	(247*2*20*4)/239	165	NOK per hour
Maintenance forklift	8 000,00	2	239	8	(8000*2)/(239*8)	8	NOK per hour
Personal protective equipment	4 000,00	2	239	8	(4000*2)/(239*8)	4	NOK per hour
Work clothes	3 000,00	2	239	8	(3000*2)/(239*8)	3	NOK per hour
Yearly maintenance Automatic quality control	300 000,00		239	8	300 000/(239*8)	157	NOK per hour
Yearly maintenance sorting unit	300 000,00		239	8	300 000/(239*8)	157	NOK per hour
Sum						**989**	**NOK per hour**
Capex							
Purchase price forklift	250 000	2	239	8	(250 000*2)/(239*8*10 years)	26	NOK per hour
Automatic quality control	1 250 000		239	8	(1000 000*2)/(239*8*10 years)	65	NOK per hour
Automatic sorting unit	1 250 000		239	8	(1000 000*2)/(239*8*10 years)	65	NOK per hour
Sum						**157**	**NOK per hour**
Reliability							
Stops in production (One stop per day)						0,13	Stops per hour
Robustness (Probability of consequence)							
Probability of failure 1						60	%
Probability of failure 2						20	%
Probability of failure 3						1	%
Efficiency							
Crates sorted per hour				(51 crates / 288 sec.) * 3600 sec/hour		712	Crates per hour
Cost per sorted crate					Sum Capex + sum Opex/ 391	1,6	NOK

Tabell 4-7 KPI calculations for change case 2.

Perceptual

It is now over a doubling in the number of crates sorted per hour compared to the manual process. But there must still be two operators involved in the process to be able to meet the speed increase that we see both in and out of the process. This shows that a partial automation can solve some of the problems such as the seasonal variations but is not sufficient to meet the target of 1200 sorted crates per hour. So, in relation to case 1, it is the operators and the company they work for, who benefit most from the improvements.

4.6.4 Change case 3 Fully automated sorting process

This is the third and final step towards fully automation of the sorting process. Although the process is now called fully automated, it requires manual effort. Pallets with unsorted crates must be delivered to the infeed by forklift, in the same way the pallets with sorted crates must be picked up by forklift at the outfeed. This is in line with the expectations of Currence Robotics, and similar to the solution they have today for sorting pallets. It has been a prerequisite that they can reuse existing structural components as well as sensors.

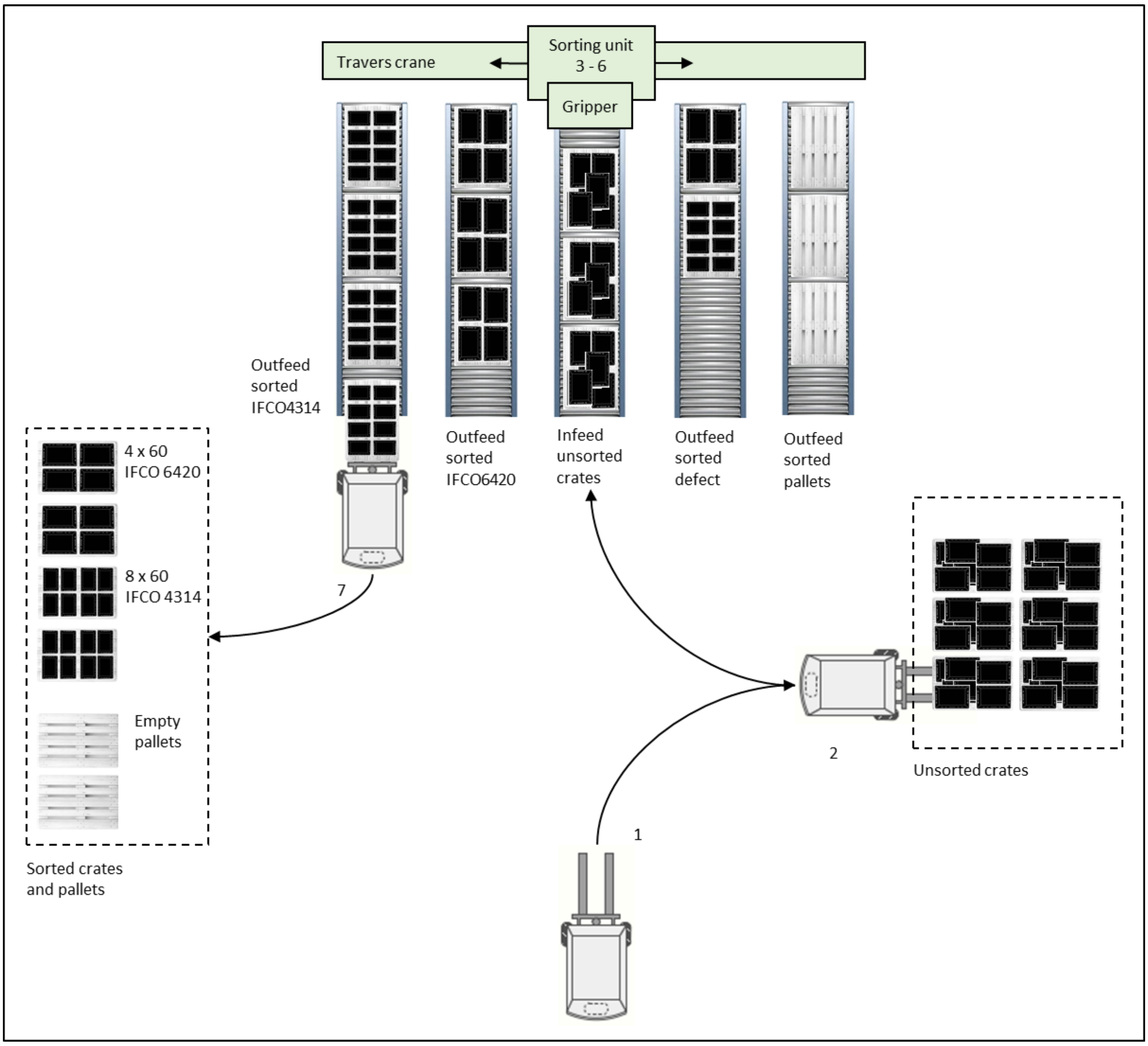

Figure 4-14 Block diagram of change case 3.

The figure above now shows the complete proposed solution. Shown here are 4 roller conveyors in front of the overhead crane that transport the sorting unit with sensors, and the gripper.

4.6.4.1 5-aspect taxonomy on change case 3

Structural

The complete solution consists of 5 main elements. The first is the infeed conveyor which is fed with pallets with unsorted crates. These pallets are detected by a laser-based sensor that also detects the height of the unsorted crates, so they do not exceed the maximum height. The second main unit is the main sensors which consist of several 3D vision cameras which are used to identify the size and quality of the crates. The third main unit is the gripper which lifts the crate for examination from the underside. This gripper is mounted on the fourth main unit, an overhead crane that moves the gripper with crate to the right outfeed conveyor.

Behavioural

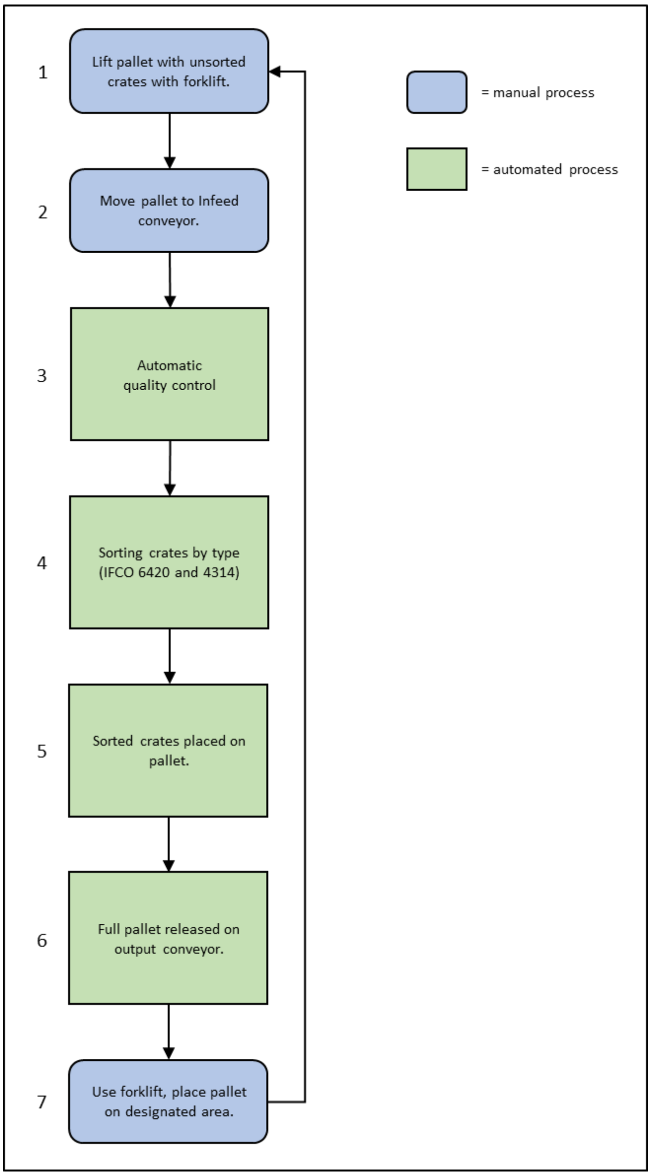

Figure 4-15 Flow chart of manual change case 3.

(1) The forklifts pick up pallets with unsorted crates, (2) which are lowered onto the infeed conveyor. Depending on the volume, the infeed conveyors can be adjusted in length to accommodate as many pallets as are necessary for the overall process. These conveyors are slightly lifted at one end, giving it a slight slope towards the machine, making the pallets travel to the machine due to gravity. A mechanical stopper holds back the next stack of pallets, so the robot gripper can work with the front stack. (3) When the pallet with crates arrives at the sorting unit, one by one the crate is identified, and quality checked from the top. Griper then picks up the selected crate, lifts it up, for quality control from the underside. 3D vision sensors are constantly being used to assess size and quality. (4)(5) Once size and quality are identified, the entire gripper moves along the overhead crane, placing the crate on a pallet on the correct outfeed roller conveyor. (6)(7) When the pallet on an outfeed conveyor is full, it is released, and it rolls forward so that it can be picked up by a forklift. The machine will work as long as there are unsorted crates on the infeed conveyor, and the sorted crates are picked up from the outfeed conveyor and this does not become full.

Contextual

Now the effect of the automation becomes very clear, the time it takes to complete the process has decreased for each case, with a 27% reduction between the manual case and case 1, and a 40% reduction between case 1 and 2, and between 2 and 3.

Task	Duration sec.				
	Manual process	Change case 1	Change case 2	Change case 3	Unit
Time to sort 51 crates	612	449	258	153	sec.
Decrease in time between cases.		-26,63	-43	-41	%
Decrease between manuel case and case 3				-75	%

Tabell 4-8 Reduction in time between different cases.

This has resulted in an increase in the number of sorted crates per hour, from 300 in the manual process to 1200 in the fully automatic. This is in line with the wishes and requirements of the main stakeholders. They anticipate a need for up to 1200 crates per hour, and an automatic solution must be dimensioned accordingly.

Task	Crates per. hour				
	Manual process	Change case 1	Change case 2	Change case 3	Unit
Efficiency (crates per. hour)	300	409	712	1200	crates per. hour
Increase in number of crates sorted between cases.		36	74	69	%
Increase between manuel case and case 3				400	%

Tabell 4-9 Increase in the number of sorted crates from case to case.

Temporal

The table below now shows all the sub-processes in the final proposal, and the time it takes. Processes 1, 2 and 3 are manual, and are performed with a forklift. Processes 3 through 7, marked with bold text, are automatic and are performed by the machine.

	Task	Sum duration	Duration sec.	Unit
1	Drive to, choose, lift pallet with unsorted crates, forklift.	0	11	sec.
2	Move pallet to sorting position.	11	9	sec.
3	**3D scan of crate from top side x 51 pcs.**	20	21	
4	**Gripper move in and grab crate x 51 pcs.**	41	25	
5	**Lifting crate x 51 pcs.**	66	25,5	
6	**3D scan of crate from below x 51 pcs.**	91,5	20,5	
7	**Automated sorting by size and quality, placed on pallet (51 pcs.)**	112	26	sec.
9	Use forklift, drive pallet with sorted crates to wrapping station.	138	15	sec.
1	Opex (NOK per hour)		1198	NOK
2	Capex (NOK per hour)		209	NOK
3	Reliability (Stops per hour)		0,13	Stops per hour
4	Robustness (%)			
	Probability of failure 1		10	%
	Probability of failure 2		20	%
	Probability of failure 3		1	%
5	Efficiency, crates per. hour (51 crates / 288 sec.) * 3600 sec/hour		1200	crates per hour
6	Cost per sorted crate (Sum Capex + sum Opex/ 391)		1,17	NOK per crate

Tabell 4-10 Duration of each sub-process, and KPI values for change case 3.

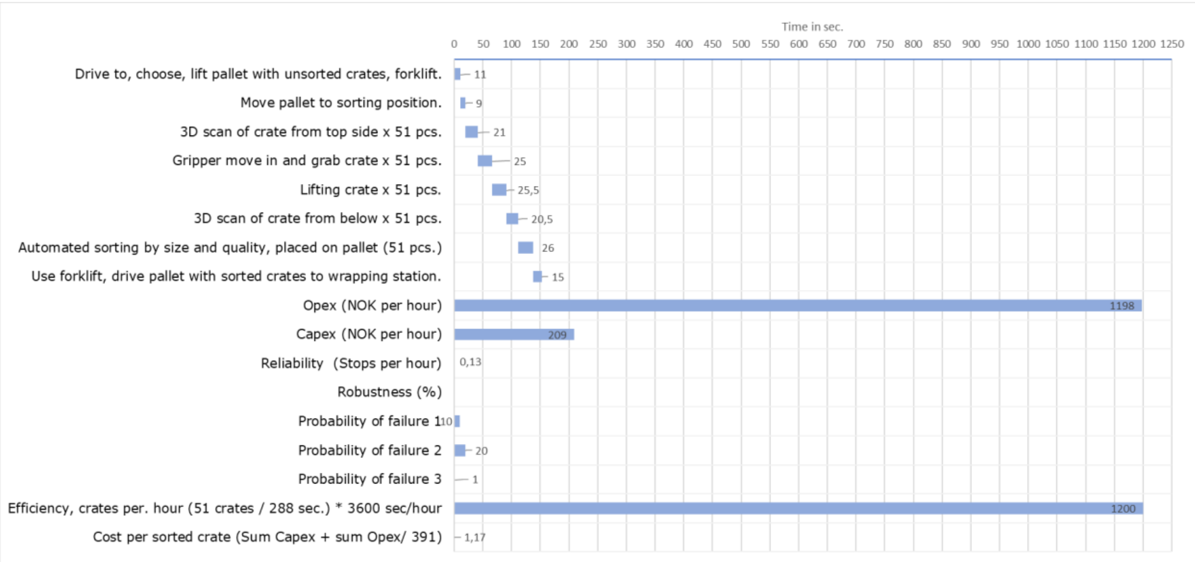

Figure 4-16 Duration of each sub-process, and KPI values for change case 3.

KPI calculations

Opex

Task	NOK				Unit
	Manual process	Change case 1	Change case 2	Change case 3	
Opex (NOK per hour)	675	832	989	1198	NOK
Increase between cases.		23	19	21	%
Increase between manuel case and case 3				77	%

Tabell 4-11 Opex for the manual, and the three change cases.

From change case 2, Opex has increased by 21%, from NOK 989 per hour to NOK 1198 per hour. In total, the operational costs have increased by 77%, from NOK 675 per hour in the manual case. This is a natural increase and is due to an ever-increasing maintenance cost. As previously mentioned, this estimate by Currence Robotics is to be about 1 million NOK per year.

The costs associated with the operators operating the machine may be reduced. But at the same time, it will be demanding for one person to operate the machine if it is to produce according to the estimate of 1200 crates per hour. So, two operators are a likely scenario despite the increase in capacity.

The forklift will be used as it is today, maybe more, so the maintenance costs on it remain unchanged.

Capex

Task	NOK				Unit
	Manual process	Change case 1	Change case 2	Change case 3	
Capex (NOK per hour)	26	92	157	209	NOK
Increase between cases.		354	71	33	%
Increase between manuel case and case 3				804	%

Tabell 4-12 Capex for the manual, and the three change cases.

The capital costs are simplified in this task and consist of purchases for the structural parts. Here, the forklift has been involved in all the cases, and the estimated cost for full automation, made by Currence Robotics, is divided between the three change cases.

The large percentage increase from the manual to the case 1 is due to the increase from the relatively inexpensive forklifts to the automation parts which cost 2.5 times as much.

The capital costs are large with the implementation of full automation, but the operating costs also increase a lot. Here, the increased capacity must be in line with the increased costs, and an ever-increasing volume of up to 1200 crates is needed to justify the capacity increase.

Reliability (Stops per hour)

Task	Stops per hour				Unit
	Manual process	Change case 1	Change case 2	Change case 3	
Reliability (Stops per hour)	0,13	0,13	0,13	0,13	Stops per hour

Tabell 4-13 Reliability for Change case 3

This KPI along with robustness have been the most difficult to calculate or predict. The answers you get from the interview vary with who you ask, and you also want to envision an automated solution that works perfectly. Therefore, this value has one stop per day, 0.13 stops per hour for all cases.

Robustness (%)

Task	Robustness (%)				Unit
	Manual process	Change case 1	Change case 2	Change case 3	
Robustness (%)					
Probability of failure 1	85	70	60	10	%
Probability of failure 2	20	20	20	20	%
Probability of failure 3	1	1	1	1	%

Tabell 4-14 Robustness for Change case 3

As mentioned, this is a difficult KPI to assess, as predicting the probability of such failures quickly can become a verry hypothetical exercise.

Failure 1

The probability of failure 1, which was given human failure, will naturally decrease as automation takes over more and more.

Failure 2

For failure 2, which often consisted of crashing the forklift into pallets, so crates ended up on the floor, has not been reduced by automation. The forklift is equally used in all cases.

Failure 3

Failure 3 was defined as a power outage or a fire, and the probability of these events does not increase due to automation.

It is possible that the two KPIs Reliability and Robustness were poorly defined, and thus did not provide the feedback that was desired.

Efficiency [crates per. hour]

Task	Efficiency (crates per. hour)				Unit
	Manual process	Change case 1	Change case 2	Change case 3	
Efficiency (crates per. hour)	300	409	712	1200	crates per. hour
Increase in number of crates sorted between cases.		36	74	69	%
Increase between manuel case and case 3				400	%
Cost per sorted crate (Sum Capex + sum Opex/ sorted)	2,34	2,26	1,61	1,17	NOK per crate
Decrease in time between cases.		-3,30	-29	-27	%
Decrease between manuel case and case 3				-50	%

The efficiency increases for each case, which gives more sorted crates per hour. Even though all costs also increase, the cost per sorted crate decreases in line with efficiency. If there is a need that is as great as the capacity, the automation, given these conditions, will be profitable.

System performance indicators (KPIs)							
	Unit price	Operators	Days per year	Hours per day	Calculation	Sum	Unit
Opex							
Sallary	472 680,00	2	239	4	472680 / (239*4*2)	494	NOK per hour
Sick leave	247,00	2	20	4	(247*2*20*4)/239	165	NOK per hour
Maintenance forklift	8 000,00	2	239	8	(8000*2)/(239*8)	8	NOK per hour
Personal protective equipment	4 000,00	2	239	8	(4000*2)/(239*8)	4	NOK per hour
Work clothes	3 000,00	2	239	8	(3000*2)/(239*8)	3	NOK per hour
Yearly maintenance Automatic quality control	300 000,00		239	8	300 000/(239*8)	157	NOK per hour
Yearly maintenance sorting unit	300 000,00		239	8	300 000/(239*8)	157	NOK per hour
Yearly maintenance outfeed	400 000,00		239	8	300 000/(239*8)	209	NOK per hour
Sum						**1198**	**NOK per hour**
Capex							
Purchase price forklift	250 000	2	239	8	(250 000*2)/(239*8*10 years)	26	NOK per hour
Automatic quality control	1 250 000		239	8	(1000 000*2)/(239*8*10 years)	65	NOK per hour
Automatic sorting unit	1 250 000		239	8	(1000 000*2)/(239*8*10 years)	65	NOK per hour
Automatic sorting unit	1 000 000		239	8	(1000 000*2)/(239*8*10 years)	52	NOK per hour
Sum						**209**	**NOK per hour**
Reliability							
Stops in production (One stop per day)						0,13	Stops per hour
Robustness (Probability of consequence)							
Probability of failure 1						10	%
Probability of failure 2						20	%
Probability of failure 3						1	%
Efficiency							
Crates sorted per hour				(51 crates / 288 sec.) * 3600 sec/hour		1200	Crates per hour
Cost per sorted crate					Sum Capex + sum Opex/ 391	1,2	NOK

Tabell 4-15 KPI calculations for change case 3.

The table above shows how the calculations for the various KPIs are done.

Perceptual

There are four main stakeholders that are considered in this case. The company that owns and leases the crates, the company that sorts the crates, the operators who do the work, and Currence Robotics who will develop the automated solution for the sorting.

In this context, the company that owns and rents out the crates is most concerned with sorting out the defective crates. Sending out defective crates gives their customers a bad experience and they earn less. If the automatic processes manage to separate all the defects, something they should, this will only be positive for them.

The company sorting the crates depends on being able to handle an increasing number of crates. To be able to handle up to 1200 crates per hour, they need 4 times the number of operators compared to today. Eight operators, each with their own forklift, will not only increase costs but also require a lot more space. Creating a traffic flow with eight forklifts that works is a big task that requires a lot of space and may not be practically possible without huge costs in premises, which can exceed the cost of the automatic solution many times over.

For the operators, the automatic solution will lead to fewer physical and heavy tasks. If there are enough crates to sort and they do not feel that their jobs are threatened, on the contrary, they may experience less stress in everyday life.

Currence robotics has spent considerable time and resources developing the "Sort" robot that sorts pallets. Being able to reuse parts, technology and knowledge in new products will be able to reduce all costs associated with a new product. A machine that sorts crates is also a natural part of having a machine that sorts pallets, as these are closely linked. Both because the crates are transported on pallets, but also because those who have many crates also have many pallets. Grocery stores get their goods on a mix of pallets and crates.

4.7 Evaluation

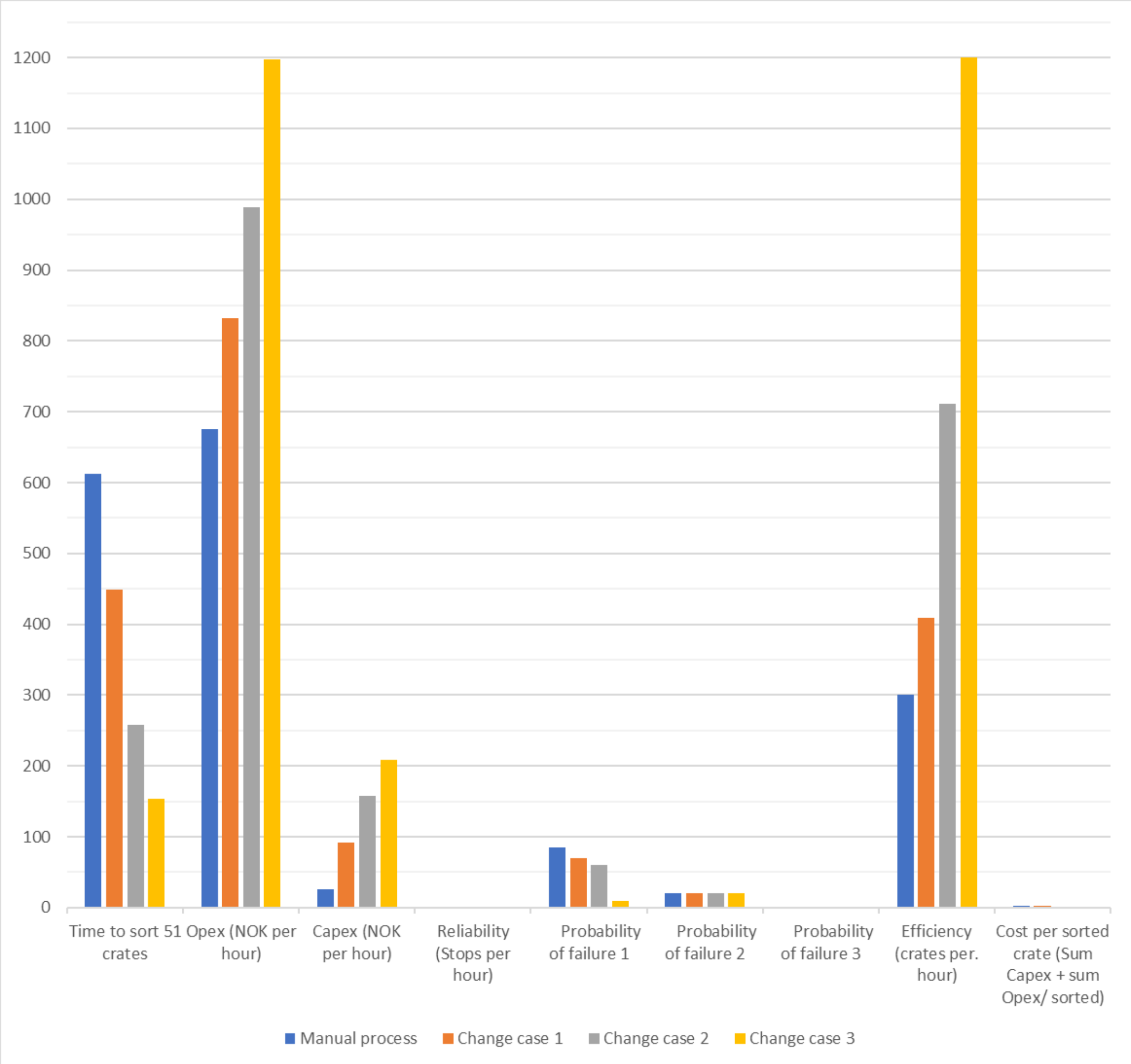

Figure 4-17 5-aspect and KPI comparison between manual- and the change cases.

The starting point for this thesis has been a manual sorting process, where several different reusable plastic crates are sorted. It has been a desire of the client to look at the process of two different crates IFCO 6420 and 4314. To be able to compare with the manual case, three change cases have been created where gradual automation has been implemented. Change case three is completely automated according to the client's standards. As a method, Systems Engineering has been used in all cases, where 5-aspect taxonomy forms the basis for the surveys and results.

In accordance with the main stakeholders, five KPIs have been prepared and used in all cases. The five KPIs are:

- Opex [NOK]
- Capex [NOK]
- Reliability [Stops over time]
- Robustness [%, Probability of consequence]
- Efficiency [crates per. hour]

The results from these KPIs have been gradually presented in Chapter 4.6 and will be summarized in this chapter.

	Task	Duration sec.					Change from	
		Manual process	Change case 1	Change case 2	Change case 3	Unit	manual case	Unit
	Time to sort 51 crates	612	449	258	153	sec.	-75	%
1	Opex (NOK per hour)	675	832	989	1198	NOK	77,5	%
2	Capex (NOK per hour)	26	92	157	209	NOK	803,8	%
3	Reliability (Stops per hour)	0,13	0,13	0,13	0,13	Stops per hour	0	%
4	Robustness (%)							
	Probability of failure 1	85	70	60	10	%	-88	%
	Probability of failure 2	20	20	20	20	%	0	%
	Probability of failure 3	1	1	1	1	%	0	%
5	Efficiency (crates per. hour)	300	409	712	1200	crates per. hour	400	%
6	Cost per sorted crate (Sum Capex + sum Opex/ sorted)	2,34	2,26	1,61	1,17	NOK per crate	-49,822	%

Tabell 4-16 KPI comparison between all cases.

The company that sorts the crates currently sorts to 300 crates per hour with two operators. This is already not enough, especially since there are some large seasonal variations. To meet future requirements from main stakeholders, it is a requirement that an automated solution must be able to sort 1200 crates per hour.

The unsorted crates arrive on pallets, and these pallets contain several different crates. During the observations, it was found that each pallet contained an average of 51 crates of 6420 and 4314. It is therefore based on the time it takes to sort these 51 crates, which are then multiplied to find the number of sorted crates per hour.

The various KPIs are shown graphically for each case in Figure 4.17 and the values are shown in Table 4.16.

For some KPIs, there is a clear connection between the implementation of automation and the changes in value that the KPI shows. This is evident in the time it takes to sort 51 crates, which takes 612 seconds in the manual process, and which is gradually reduced to 153 seconds in change case 3, a reduction of 75%.

With reduced time consumption comes the ability to sort more crates per hour. From 300 in the manual case via 409 pieces and 712 pieces in change cases 1 and 2, to 1200 in change case 3. This is an increase of 400% from the manual case.

System performance indicators (KPIs)							
	Unit price	Operators	Days per year	Hours per day	Calculation	Sum	Unit
Opex							
Sallary	472 680,00	2	239	4	472680 / (239*4*2)	494	NOK per hour
Sick leave	247,00	2	20	4	(247*2*20*4)/239	165	NOK per hour
Maintenance forklift	8 000,00	2	239	8	(8000*2)/(239*8)	8	NOK per hour
Personal protective equipment	4 000,00	2	239	8	(4000*2)/(239*8)	4	NOK per hour
Work clothes	3 000,00	2	239	8	(3000*2)/(239*8)	3	NOK per hour
Yearly maintenance Automatic quality control	300 000,00		239	8	300 000/(239*8)	157	NOK per hour
Yearly maintenance sorting unit	300 000,00		239	8	300 000/(239*8)	157	NOK per hour
Yearly maintenance outfeed	400 000,00		239	8	300 000/(239*8)	209	NOK per hour
Sum						**1198**	**NOK per hour**
Capex							
Purchase price forklift	250 000	2	239	8	(250 000*2)/(239*8*10 years)	26	NOK per hour
Automatic quality control	1 250 000		239	8	(1000 000*2)/(239*8*10 years)	65	NOK per hour
Automatic sorting unit	1 250 000		239	8	(1000 000*2)/(239*8*10 years)	65	NOK per hour
Automatic sorting unit	1 000 000		239	8	(1000 000*2)/(239*8*10 years)	52	NOK per hour
Sum						**209**	**NOK per hour**

Tabell 4-17 Opex and Capex calculations for change case 3.

Despite this increase in capacity, both operators from previous cases are retained in the calculations, also on change case 3 which is automated. This is because it will be impossible for one person to both feed the machine and empty it of sorted crates fast enough when it sorts 1200 crates per hour.

Such an increase does not come without a cost and a distinction is made between operating costs (Opex) and capital costs (Capex). Simplifications have also been made within these two KPIs, which are shown in Table 4.17.

In the process described, there are two operators working, and in the Opex costs, salaries, sick leave, personal protective equipment, and work clothes for the operators are included. In addition, there are the two forklifts, one for each operator. Table 4.16 shows an increase in Opex costs of 77% due to an annual maintenance cost of the automated solution. This is estimated by Currence Robotics to be NOK 1 million and applies to a fully automated solution. This cost is divided between the three change cases.

For capex costs, the purchase price for the structural components is included. Currence Robotic has estimated a price of NOK 3.5 million for a fully automated solution. This price is divided into the three change cases to have a basis for comparison. Table 4.16 shows an 803% increase in capital costs. This is because in the manual case only two forklifts made up the capital costs, and in change case 3 the estimated price of an automated solution of 3.5 million is included in addition. Capex costs are spread over 10 years, as this is a conservative estimate of the lifespan to the machine. A more correct economically presentation would probably be in a 5-year span, the time it takes before the parts are depreciated to 0.

Despite this increase in costs, the price of each sorted crate decreases. This price comes from the sum of Capex and Opex, divided by the number of sorted crates in each case.

Task	Efficiency (crates per. hour)				
	Manual process	Change case 1	Change case 2	Change case 3	Unit
Efficiency (crates per. hour)	300	409	712	1200	crates per. hour
Increase in number of crates sorted between cases.		36	74	69	%
Increase between manuel case and case 3				400	%
Cost per sorted crate (Sum Capex + sum Opex/ sorted)	2,34	2,26	1,61	1,17	NOK per crate
Decrease in cost between cases.		-3,30	-29	-27	%
Decrease between manuel case and case 3				-50	%

Tabell 4-18 Efficiency (crates per hour) and cost per sorted crate

As shown in Table 4.18, if the supply of crates is in line with the increasing capacity, the costs per sorted crates will decrease for each change case.

The table below shows an increasing number of crates for sorting per hour. The sum of the costs (Opex and Capex) is retained for each case. The number of crates available is then divided by the cost of each case to find the cost per sorted crate. The squares marked green are where the price is approximately equal to or lower than in the manual case.

Task	NOK per sorted crate			
	Manual process (300)	Change case 1 (409)	Change case 2 (712)	Change case 3 (1200)
Cost per sorted crate at **300** crates available per hour	2,34	3,08	3,82	4,69
Cost per sorted crate at 4**00** crates available per hour		2,31	2,87	3,52
Cost per sorted crate at **500** crates available per hour		1,85	2,29	2,81
Cost per sorted crate at **600** crates available per hour			1,91	2,35
Cost per sorted crate at 7**00** crates available per hour			1,64	2,01
Cost per sorted crate at 8**00** crates available per hour			1,43	1,76
Cost per sorted crate at 9**00** crates available per hour				1,56
Cost per sorted crate at 10**00** crates available per hour				1,41
Cost per sorted crate at 11**00** crates available per hour				1,28
Cost per sorted crate at 12**00** crates available per hour				1,17

Tabell 4-19 Cost of sorting crates at different available volumes per hour.

For all change cases, the cost per sorted crate will be lower than in the manual case before they reach their maximum capacity.

With an access of 600 crates per hour, change case 3 with the largest expenses will also be cheaper per sorted crate than the manual case.

As mentioned in Chapter 4.6, the KPIs Reliability (stops per hour) and Robustness (probability of failure) have been difficult to determine, both in calculations and in interviews, and that these KPIs have not provided the feedback that was expected. It is now clear in retrospect that these should have been defined differently. This is especially true for Reliability, where in interviews about the manual process, there have been divided opinions and perceptions about what a stop is, and what is just a normal work pace with small talk and natural breaks.

Task	Stops per hour				
	Manual process	Change case 1	Change case 2	Change case 3	Unit
Reliability (Stops per hour)	0,13	0,13	0,13	0,13	Stops per hour

Task	Robustness (%)				
	Manual process	Change case 1	Change case 2	Change case 3	Unit
Robustness (%)					
Probability of failure 1	85	70	60	10	%
Probability of failure 2	20	20	20	20	%
Probability of failure 3	1	1	1	1	%

Tabell 4-20 Reliability and Robustness for manual- and the change cases.

In chapter 4.3 Reliability is only described as stops per unit of time. With a slightly unclear definition, and divided opinions about what is a stop in the manual process, but at the same time with the certainty that some stops are, it is difficult to say if one stop per day, 0.13 per hour is a valid assessment.

In Robustness, probability of failure 1 is defined as a simple failure that can be quickly corrected like a box or crate falling on the floor, and an operator uses one or two second picking it up. These are small errors that are directly related to how large a part of the process the operators are part of. With an increasing degree of automation, the probability of such errors will be reduced. Therefore, the probability of failure 1 is reduced between the cases.

The definition of failure 2 has been a bit inconsistent throughout the thesis. It has both been defined as components that fail and need to be replaced, and slightly larger work accidents such as crashing the forklift into a pallet that results in many crates falling on the floor.

In definition one, with defective components, the probability should increase for each case due to increasing number of components used in the automation solution.

In definition two, slightly larger work accidents primarily caused by forklifts, the probability will be unchanged between the cases because forklifts are used to about the same extent.

The intention was that definition one should be used, but it has not been followed up through the thesis.

In Table 4.20, the probability of failure 3 is the same for all cases. This is defined as a major accident that stops the process for a long time. This could be a power outage in the area or a minor fire.

An automated solution requires electricity, but it is not a question of enormous power consumption. There are relatively light parts to be lifted and moved, with associated small electric motors in the various moving parts. A sufficiently dimensioned power supply in the room will not affect the power supply in the area.

Can therefore not see that the probability of failure 3 will increase significantly.

5 Discussion

The goal of this thesis was to use Systems Engineering in a specified process, which was to be automated by Currence Robotics. Furthermore, in three steps an increasing degree of automation was to be implemented in the process, and each step was then to be analysed with Systems Engineering.

Systems Engineering as a tool has provided a deep and thorough understanding of the processes and associated sub-processes, and the contextual part with the associated Gantt diagrams provides a good basis for comparison.

Task	NOK per sorted crate			
	Manual process (300)	Change case 1 (409)	Change case 2 (712)	Change case 3 (1200)
Cost per sorted crate at **300** crates available per hour	2,34	3,08	3,82	4,69
Cost per sorted crate at **400** crates available per hour		2,31	2,87	3,52
Cost per sorted crate at **500** crates available per hour		1,85	2,29	2,81
Cost per sorted crate at **600** crates available per hour			1,91	2,35
Cost per sorted crate at **700** crates available per hour			1,64	2,01
Cost per sorted crate at **800** crates available per hour			1,43	1,76
Cost per sorted crate at **900** crates available per hour				1,56
Cost per sorted crate at 1**000** crates available per hour				1,41
Cost per sorted crate at 11**00** crates available per hour				1,28
Cost per sorted crate at 12**00** crates available per hour				1,17

Tabell 5-1 Cost of sorting crates at 4 different available volumes per hour.

The table above shows the cost per sorted crate for a varying number of available crates for each change case. Change case three, on the far right, has the largest costs associated with the process as it is most automated. It is interesting to see that this case, compared to the manual with 300 crates per hour, is profitable already at 600 crates per hour. Case 3 has a capacity of 1200 crates per hour, and it shows how flexible a fully automated process can be, and that it can be installed long before the need approaches maximum capacity.

There are many simplifications made in this thesis also in connection with the KPIs. If it turns out that the real cost picture is significantly higher in change case three, it is still likely that the process is profitable, given the cost per sorted crate at 1200 crates per hour is half of what it is at 600 crates per hour.

The KPI Reliability (stops per hour) did not provide the feedback that was intended, as it proved difficult to calculate or in other ways make the values probable. Robustness [%, Probability of consequence] also proved to be a theoretically difficult exercise, it was somewhat better defined than Reliability, but still not good enough. This shows the importance of well-thought-out KPIs, and possibly a test case to see what results they give and how easy it is to arrive at probable values. A simplified test case was also proposed by the supervisor, but not completed.

6 Conclusion

The chosen method provided a good understanding of the process, which is critical to be able to evaluate how the implementation of automation will affect the process.

Given the validity of the results in this thesis, it is a good idea from Currence Robotics to automate this process. If they can reuse parts and equipment from their existing pallet sorting machine, the probability will increase that this will be an economically profitable project.

The good results for the automated solution include those operators who are already performing this process manually. Together with the increased capacity, these are good arguments for Currence Robotics, that one can keep today's employees, increase capacity, and make it all more profitable.

There is still a lot to be done to validate the results from this thesis, but with such good results this can be motivating for further work.

7 Further work

When the results for the automated solution, change case 3, show such good results in terms of capacity and cost per sorted crate, it will be a natural step forward to validate these results. Capacity and cost are always relevant KPIs, but considerations should be made as to which other KPIs should be included and how they should be defined. A more detailed cost picture will also help to strengthen the validity of the results.

A simulation of the automated process will further strengthen the value of the results, and if not, it can reveal possible errors or deficient assumptions.

Building a test case of the process, a prototype, will also be a further option. By using existing parts from the pallet sorting robot "Sort", it is possible to see what can be reused. It will also be interesting to see if the software from "Sort" can be reused, and to what extent it needs to be rewritten.

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