Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Evaluation and concept development for end-of-line automation for untrimmed nickel cathodes

Evaluering og konseptutvikling for end-of-line automatisering for utrimede nikkelkatoder

Bachelor's thesis in Mechaincal Engineering
Supervisor: Olsen, Anna
May 2023

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PREFACE

This bachelors thesis is the culmination of five months of work during our sixth and final semester in mechanical engineering. We started out quite optimistic and with several ideas about how to tackle it, but as the semester went on it proved more difficult than initially planned. The group possessed two different but complementary sets of knowledge coming into it. One of us had taken a course which gave a broad overview of automation, the other has worked at the company with the process in question and had a fairly good understanding of its inner workings. It became quickly apparent that the knowledge garnered from the course would be inadequate, and by the end of the project we both had learned relevant theory far beyond what was taught during the course. We achieved this despite difficulties finding relevant literature. Most of the time what was found related only to automation in terms of programming, other times the contents proved to be far beyond our level of comprehension. Eventually relevant literature was found, some of which we relied quite heavily on in absence of other sources. In the end we believe we managed to use our knowledge learned previously during our time studying mechanical engineering, and knowledge learned during this project, to write a decent paper as a capstone to our time at NTNU.

We would like to thank Nikkelverk for the opportunity to write this thesis and visiting their facilities. Especially Harald Ellingsen for answering questions about the process and showing us around during our visit and Roger Johnsen for answering questions relating to engineering.

At NTNU we would like to thank our supervisor and programme director Anna Olsen for her hard work to the benefit of her students and her invaluable feedback on this thesis.

We also want to thank all current and former board members of the student union for Bachelor in Mechanical Engineering, MiT, and especially former *Hussjef* for the term 2021 to 2022 for creating a great environment and fun activities for the students.

ABSTRACT

The purpose of this bachelor thesis is to evaluate the requirements involved in implementing an automatic packaging system for untrimmed nickel cathodes. The thesis comes from Nikkelverk's desire to automate the current system they have for packing these cathodes. The packing is spread over two different stations and is done manually by the operators, the cathodes are transported between the stations using two forklifts. This system exposes the operators to unnecessary strain from the manual labour. In addition, there is an increased risk of accidents, which the company wants to avoid.

To answer the problem, the following performance objectives were created: analyse the current system, develop concepts that fit the available space and reduce traffic and strain on operators, and evaluate what automation would mean for the company.

The current system was analysed by a site visit. During the observation, the process times at the different stations were measured along with the time the cathodes are in transit. Further observations were carried out by the company's employees and used in the report. The measurements were further used to create a FlexSim simulation. From this simulation, the productivity of the system was measured together with the activity of the conveyors.

To develop concepts, the available space was investigated. It quickly became clear that traffic through this area is not only from packing, but also transport from elsewhere in the facility. Similar systems for packing were investigated, leading to the development of three concepts that utilise a robotic arm to move the cathode into production. The concepts differ from each other in the way they remove the bars by which the cathodes are suspended. The proposed concepts were also analysed by using FlexSim. The process times here were estimated on the basis of observations made of similar systems.

The simulations clearly showed that the current system is better in terms of productivity per hour, but is limited by high variability due to manual labour and carriers experience a lot of waiting time as the processes at the stations are not fast enough to handle the cathodes. The concepts, on the other hand, are slightly worse in terms of productivity, but production does not experience variability in process time and requires fewer operators present. This makes it possible to create more shifts to make up for lost production. In addition, they are safer since operators do not directly handle the cathodes and there is less traffic in the area.

The evaluation matrix clearly showed that the developed concepts were better in most cases. They required less manual labour, were more economical over a longer period of time, experienced less downtime, created less traffic, and are more secure than the current system. In contrast, they were worse in terms of productivity, and they were equal to the current one in terms of flexibility.

SAMMENDRAG

Denne bacheloroppgaven går ut på å evaluere de kravene som inngår i å implementere et automatisk pakkesystem for utrimmede nikkel katoder. Oppgaven kommer fra at Nikkelverk har et ønske om å automatisere det nåværende systemet de har for å pakke slike katoder. Pakkingen skjer spredt på to forskjellige stasjoner og er utført manuelt av operatørene, katodene er fraktet mellom stasjonene ved hjelp av to gaffeltrucker. Dette systemet utsetter operatørene for unødvendig belastning fra det manuelle arbeidet. I tillegg er det økt fare for at de blir utsatt for skade, noe selskapet vil unngå.

For å gi svar på problemstillingen ble de følgende resultat målene skapt: analysere det nåværende systemet, utvikle konsepter som passer det tilgjengelige arealet og som reduserer trafikk og belastning på operatørene, og evaluer hva automatisering vill bety for selskapet.

For å analysere det nåværende systemet ble gjennomført et bedriftsbesøk. Under observasjonen ble prosesstidene hos de ulike stasjonene målt sammen med tiden katodene er under transport. Ytterligere observasjoner ble utført av ansatte hos bedriften som ble videre brukt i rapporten. Målingene ble brukt videre for å danne en FlexSim simulering. Fra denne simuleringen ble produktiviteten av systemet målt sammen med aktiviteten av transportørene.

For å utvikle konsepter ble det tilgjengelige arealet undersøkt. Det ble fort klart at trafikk gjennom dette arealet ikke bare stammer fra pakkingen, men også transport fra andre steder i anlegget. Lignende systemer for pakking ble undersøkt, dette førte til utviklingen av tre konsepter som tar i bruk robotarmer for å føre katodene videre i produksjonen. Konseptene skiller seg fra hverandre i måten de fjerner stengene som katodene er hengt opp etter. Likt med det nåværende systemet ble også konseptene analysert ved bruk av FlexSim. Prosesstidene her ble estimert med bakgrunn i observasjoner gjort av lignende systemer.

Simuleringene viste tydelig at det nåværende systemet er bedre når det gjelder produktivitet per time, men er begrenset av stor variasjon som følge av manuelt arbeid og transportørene opplever mye ventetid siden prosessene hos stasjonene ikke er raske nok til å håndtere katodene. Konseptene derimot er noe dårligere når det gjelder produktivitet, men produksjonen opplever ikke variasjon i prosesstid og krever færre operatører til stede. Dette gjør det mulig å opprette flere skift for å ta igjen tapt produksjon. I tillegg er de tryggere siden operatørene ikke direkte håndterer katodene og det er mindre trafikk i området.

Evalueringsmatrisen viste klart at de utviklede konseptene var bedre i de fleste tilfeller. De krevde mindre manuelt arbeid, var økonomisk bedre over lengre tid, opplevde mindre nedetid, skapte mindre trafikk, og er sikrere enn det nåværende systemet. Derimot var de verre når det gjelder produktivitet, og de var like fleksible som det nåværende systemet.

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ABBREVIATIONS

CIM Computer-integrated manufacturing . . . 20

MSDs Musculoskeletal disorders . . . 18

WCP Work Cycle Program . . . 16

PLC Programmable logic controller . . . 16

LME London metal exchange . . . 30

CHAPTER

ONE

INTRODUCTION

1.1 Background

The Nikkelverk refinery located in Kristiansand is a subsidiary of the Glencore Company, and is the largest producer of nickel in Europe. Their nickel products come in multiple different grades of purity, and come in three different shapes: sheared squares in different sizes, small hemispheres, and whole untrimmed cathodes. It is the packaging process of the whole untrimmed cathodes that is the basis of this thesis. In addition to nickel they also produce copper and cobalt.

The packaging process of the untrimmed cathodes currently relies heavily on manual labour. Due to the limitations of this type of labour, periods of large orders are often accompanied by overtime. Traffic cause unnecessary risk of injury especially during overtime at night when workers are tired and inattentive. In recent years there has been one severe injury, which is one too many and happened during overtime. In addition certain steps of the process place undue strain on the operators. These factors contribute to increased cost of operation.

1.2 Problem Statement

The problem statement of this thesis is to evaluate the performance of the current system for packaging untrimmed nickel cathodes, and compare it to concepts for automated systems.

To explore this problem the current system is evaluated through the use of an evaluation matrix, and the concepts are then evaluated compared to the current system.

1.2.1 Result goals

To reach the main objective the following result goals are In order to reach the main objective of this thesis the following sub-goals were created:

- Analyse the current system.
- Develop concepts that fit within the available area and reduce traffic and strain on operators.
- Evaluate what automation would mean for the company.

1.3 Sustainability

Figure 1.3.1: The UN sustainability goals

From the UN sustainability goals (Figure 1.3.1) this thesis is broadly applicable to goal 3, 9, and 10. Sustainability goal 3 primarily focuses on health and mortality. Creating a safe workplace where workers go home as or more healthy than when they arrived will contribute to reach this goal. Automation leads to broader job opportunities for people with functional impairments. For example workers with back and joint pains are able to oversee automated lines. Where as they would not be able to stand and perform heavy labour all day. This is in accordance with sustainability goal 9 and 10 which focus on reducing inequalities and promote inclusive industrialization (*UN Sustainability Goals — Sustainable Development* 2023). The UN sustainability goal is something all members of society need to strive to make progress in, or else they will be impossible to reach.

Nikkelverk also has its own sustainability goals which are relevant for this thesis, these include health, safety, environment, society and human rights (Nikkelverk 2023b). In accordance with ISO 45001 certification an important goal of the company is to reduce health and safety risks to employees (Nikkelverk 2023a). As automation reduces the risk of injury and strain on employees installation of an automated system will help enforce the safety standard expected by the company.

1.4 Overview

In Chapter 2 the theoretical background of automation is presented, this includes an introduction in common trends in modern industry, how automation fits into these trends, what automation is and what it entails, and finally how and why automation is implemented. This chapter serves as the theoretical basis for the decisions made during development of the concepts.

Chapter 3 describes the method of how measurements were taken and strategies used in the project are explained. Followed by the results of the method in Chapter 4. Finally the results and method are discussed in Chapter 5 and the conclusion of this thesis is described in Chapter 6.

1.5 Limitations

The distance between Kristiansand and Trondheim, in combination with a parallel mandatory subject, made it only possible to do a single company visit this term. Because of this there were limited possibilities of testing, understanding, and locating more suitable locations. Any developments had to be limited to the available area at the current location. In addition it is not possible to test the developed concepts in the real world, and simulations based on estimations are the closest to testing that is achievable. Because of this some parts related to the process have been defined as out of scope.

- How the cathodes are inspected and marked before the packaging and changes that has to be made in this inspection and marking process.
- Whether there are any areas more suited for packaging closer to the production.

CHAPTER

TWO

THEORY

2.1 Lean Manufacturing and Automation

Manufacturing systems are a value-adding process, meaning value is added to the product as it goes through the different stages of manufacturing. Therefore, the efficiency of the process and the resultant quality of the product is of high importance to the health of the manufacturer.

Lean manufacturing is derived from the practices implemented by Toyota during the post-war period. One of the core principles of Lean Manufacturing is the elimination of waste. Several different types of waste fall under this principle (Pavnaskar et al. 2003).

- **Overproduction**
  Stocking too much product and it goes unused causing unnecessary costs relating to storage and production cost.
- **Waiting Waste / Waiting Time**
  Time which production is halted while waiting for the previous or following step to complete.
- **Transport**
  Moving product from one place to another, transportation adds no value to the product.
- **Motion**
  Unnecessary movement by operators, machines or of the product.
- **Inventory**
  Storage of unprocessed product can mask waste created elsewhere in the production of the product, and results in increased costs to contain the stored products.
- **Defects**
  Producing products which deviate from their intended specification, the occurrence of defects might also point to waste elsewhere.
- **Over-Processing**
  Over processing the product causing value added to the product to hit a point of diminishing returns.

The elimination or mitigation of waste is paramount for establishing a lean manufacturing process, and minimising costs while maximising profit.

2.2 What is Automation

The term “Automation” derives from the greek “automatos” which means “to think/act by itself” and plays an important role in modern society. From the thermostat in a bathroom to the various systems which run the international space station, they all utilise some degree of automation. The simplest definition of automation is a system which performs an action by itself without human interaction. This definition includes mechanical systems such as robotic arms who perform a set task, and digital systems such as a program which updates the number of visitors in a building based on feedback from a sensor.

The book *Automation, Production Systems, and Computer-Integrated Manufacturing* elaborates on the definition of automation by defining it as technology that allows for a process or procedure to be performed without human interaction by the use of a program with defined instructions combined with a control system that executes the program (Groover 2015). This definition specifies the inclusion of both a program of instructions and a control system to execute them, which points to the multi disciplinary nature of such technology. The definition is echoed in the book *Industrial Automation and Robotics* where the term is similarly defined, but it also includes another definition which defines automation as a process in industry where manual processes are converted to automated or mechanised processes (Gupta et al. 2016). Thus automation also includes the process where things are automated. The inclusion of a mechanised process as part of the definition of automation brings up an important note. While the term automation and mechanisation are often closely linked they are not the same.

2.2.1 Automation and Mechanisation

The term automation and mechanisation are often used together, but imply different things. Mechanization is defined as the use use of powered machines to perform activities, as opposed to utilising hand powered tools, while a human operator is responsible for any decisions. Mechanisation is regarded as the step before automation in the transition from manual labour to autonomous operation. An example of mechanisation is the use of an electrical screwdriver to screw in screws rather than doing so by hand. Automation continues to use powered machinery, but also largely removes the human operator from the decision making process. There are different degrees of automation: semi-automated systems involve both manual and automatic activities, while fully automated systems consists solely of automated activities (Nof 2009 & Gupta et al. 2016).

2.2.2 Elements of an automated system

An automated system consists of three elements; a power source, programs of instructions, and control systems. All these element have to be present in some form for a system to be automated. This section goes into detail about what the different elements are. Figure 2.2.1 shows the relation between the different elements with power relating to each element, while the Program of Instructions relates to the Control System which in turn both relates to the Process and the process to it.

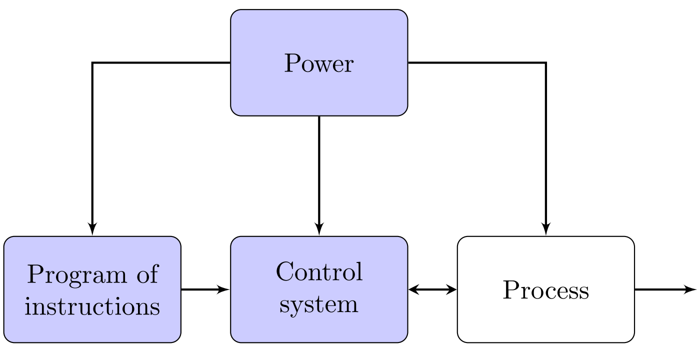


Figure 2.2.1: Figure showing the relation between the different elements in an automated system. Based on Figure 4.2 from Groover 2015.

Electric power is considered the primary source of power for most automated systems due to its availability and affordability. It can be transported over large distances, stored in batteries and easily converted to alternative energy forms as those listed below (Groover 2015).

- Mechanical
- Hydraulic
- Pneumatic
- Thermal
- Light
- Acoustic

Furthermore electricity powers the control system which reads the program of instruction, perform the required calculations, and send signals to the actuators. The signals themselves are usually low-voltage signals, and electric power is required to acquire and process data from the system (Groover 2015).

The program of instructions contains the steps the automated system has to perform to complete the processing of the product during its production. The steps which constitute a complete processing of the product is called a work cycle, and the program is called Work Cycle Program (WCP). There are different types of WCPs but they all work by affecting the input (process parameter) and output (process variable) of the process (Groover 2015). The different types of WCPs can be organised into five different categories: Set-point control, where the value of the process parameter remains constant; Logic control, where the value of the process parameter depends on the value of other process variables during operation; Sequence control, where the process parameters changes as a function of time either as discrete or continuous values; Interactive program, where an operator is required to interact with the control system; and Intelligent program, which grants the control system instructions through the application of artificial intelligence (Groover 2015).

The control system of the automated system executes the program of instructions. There are multiple different types of control system, as long as the system is capable of performing logical operations it can be used as a control system. This includes pneumatic control systems (Gupta et al. 2016), but in the manufacturing context it is usually electrically powered in the form of a digital computer who use a Programmable logic controller (PLC) or similar devices. Control systems can be categorised into two groups: closed-loop or open-loop systems. A closed-loop system, also called a feedback control system, operates by making the input process parameter dependant on the output process variable. (Groover 2015 & Gupta et al. 2016). This type of control system is used by the logic control WCP. An open-loop system in contrast has no feedback component but in turn is simpler and less expensive compared to closed-loop systems.

2.3 Packaging and End-of-line Automation

The packaging process is usually considered the final stage of the manufacturing process. The packaging is meant to protect the product it contains, and to facilitate ease of transport of the product (Griffin et al. 1985). This is important as customers prefer clean products and packaging free of contaminants, such as grease and dirt, as they are easier to handle.

End-of-line automation is the term given to automated systems at this stage of manufacturing. Increasing costs, labour shortages, and quality control issues are all underlying reasons for industries to pursue the implementation of such systems within their manufacturing process. This stage usually includes the following steps: scanning the product, weighting of the product, labeling and palletising (*What Is End-of-Line Automation? — BluePrint Automation* 2023).

2.3.1 Types of Automation

When transitioning to automated system an important decision is what type of automation is to be used. There are three types of automated systems: Hard Automation, Programmable Automation, and Soft Automation. Hard automation, also called fixed automation, uses equipment specialised for a specific product, it is generally most suited for mass-produced products with high production volumes and speed. Hard automation usually involve high investment cost, and limited flexibility.

Programmable automation utilises equipment performing operations according to a program, changes to the product can be accommodated with by changing the program. This type of automation usually has high investment cost and lower production rate than hard automation, but in turn has higher flexibility and can accommodate batch production.

Soft automation is an extension of programmable automation, it is also called flexible automation, and can accommodate a large variety of products with little downtime between reprogramming and tool changes. Such systems usually have much lower production rates than other types of automation and require a custom-engineered system with high investment cost, but in turn has high flexibility (Groover 2015 & Gupta et al. 2016).

The choice of which type of automation to pursue usually comes down to economics and is dependant on the production volume and expected variations in product. Until the expected production volume reaches a certain point manual labour will remain the most cost effective solution due to the initial costs related to implementing automated systems. Figure 2.3.1 shows the general relation of unit costs of manual labour, hard and soft automation as a product of product volume. By product volume equal to v1 soft automation becomes cheaper than manual labour, until the unit costs reaches v2 and hard automation becomes the cheaper alternative.

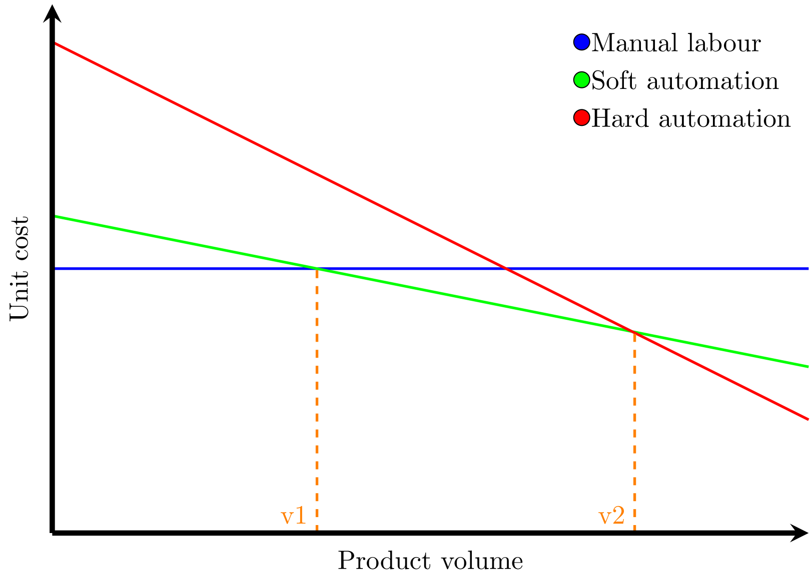


Figure 2.3.1: Graph showing the relation between product volume and unit cost, based on manual labour, soft automation, and hard automation.

2.4 Why and How to automate

2.4.1 Why automate

There are several reasons for companies to pursue automation, primarily it comes down to economics, productivity, and safety. The economics of an automated system usually comes down to determining the initial investment costs, and the long-term reduction in cost. As mentioned previously automation comes with high investment costs, and for several companies the question whether to automate stops there, but the long-term reductions can be significant. RNA Automation, a company specialising in integrating automated systems for manufacturers, conducted a case study regarding the costs associated with automation. They found that automation reduces training, employer, and pension costs. In addition, wage inflation is replaced by a maintenance program (*Cost of Manual Labour vs. Automation Infographic* 2023).

By utilising automated systems products are no longer subject to human error due to the increased repeatability and reliability of automation. Subsequently both the quality of the product and the efficacy of its production increases. In addition employee turnover becomes less of a problem as operators become less involved in production (*Cost of Manual Labour vs. Automation Infographic* 2023 & *How do Industrial Automation Expectations Differ from Reality* 2023). This also allows for the reallocation of workers to other more productive areas of the company.

As workers are removed from the production area they become less prone to injury as they are no longer directly operating the machinery. In addition the ergonomic situation can drastically improve. Several activities are prone to the development of Musculoskeletal disorders (MSDs), also known as ergonomic injuries (*What Is End-of-Line Automation? — BluePrint Automation* 2023). Heavy tasks and activities which involve repetitive motions and unusual working positions all contribute to the development of MSDs. To mitigate the effects of these activities the following measures are usually recommended. For heavy work such as lifting, carrying, and pushing it is recommended that loads above 25 kg should be lifted with mechanical aid, carrying over large distances should be avoided without the use of mechanical aid, and frequent stops and changes in direction should be avoided while pushing (*Heavy and repetitive work - Kunnskapsbasen - NTNU* 2023). As manual labour is replaced with automated machinery this becomes less of a concern.

Automation also avoids disruptions caused by workers having different preferences. Customisation of the workplace to fit an individual worker is not an unusual occurrence. Changes such as desk height and tool location are a few among a multitude of small changes that make the workplace more accommodating to the worker. While such changes might improve the productivity of said worker, it can pose a challenge if the worker leaves for a new workplace or the shift changes and another worker takes their place. In these cases the new worker might have to redo the customisation of the workplace taking valuable time and ultimately furthering the problem to the next worker in line. Overdoing customisation can also negatively motivate the workers to stay at the workstation they started at, and ultimately the workers continue doing the same repetitive task the implemented measures originally was meant to prevent.

2.4.2 How to automate, the USA Principle

The USA principle is a widely used strategy for handling automation. USA is an acronym of the stages in the strategy (Figure 2.4.1). Understand what the existing process is. Then simplify the process as much as possible. And then finally automate it. (Groover 2015)

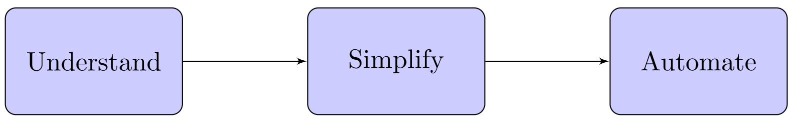


Figure 2.4.1: The USA principle

Understand

This first stage involves understanding all the details of every station in the production line. Flow charts can be used to get an overview of the extent of the current process. Mathematical models or coded simulations can also be used to help further understand the entire system. (Groover 2015) Gaining a complete understanding of the production line is essential to formulate algorithms for process control. Examples of different variables in a production line can be:

- The inputs
- The outputs
- What happens to the work unit
- What value are added to the work unit
- The actions of the previous station
- The actions of the next station
- The upstream operations
- The downstream operations

- Number of labourers
- Current machinery
- Costs of labourers
- Costs of Machinery
- Avoid injuries
- Process times of each station

Simplify

Simplifying the process can first be started once the process is fully understood. In this process it is important to question the necessity of the steps in the process. This can be done by using a checklist of questions like those in Figure 2.4.2. During the simplification stage it can be beneficial to consult the then strategies in Section 2.4.3.

It is much easier to automate simple processes. So answering questions like these will make finding an automated system much easier and the implementation of the system much cheaper (Groover 2015).

Is this necessary?

What is the purpose of this strap?

What is the purpose of this transport?

Can this be eliminated?

Is this the most appropriate
and optimal method?

Can this be combined?

Figure 2.4.2: Questions to ask during the Simplify stage.

Automate

After the Understand and Simplify stage have been conducted it is time to consider automation if it seems feasible. When considering automation the ten strategies defined in Section 2.4.3 are good principles to follow (Groover 2015).

2.4.3 Ten Strategies for Automation and Process Improvement

The ten strategies for automation were first formulated by Mikell P. Groover in 1980 and function as a roadmap to find improvements in a system. Whether the system is a candidate for automation or not the strategies can still be used when simplifying a system (Groover 2015).

1. **Specialisation of operations**
   The first strategy use highly specialised machines to achieve the highest efficiency possible. It should be noted that this would reduce the flexibility of the system.

2. **Combined operations**
   Producing a product often require many sequential operations. Instead of having one machine for every operation one can save space and costs by combining many operations into one machine. Machines usually require some time to set everything up before doing the intended operation. So when combining operations the setup time of the system often is reduced. There could also be a reduction in non operation time or manufacturing lead time. Non operation time is the period between operations and includes material handling like transport, waiting and storage time (Suiqbad 2013). Lead time is defined as the time between the order and delivery of a product (Martinsen 2023).

3. **Simultaneous operations**
   A natural evolution of *Combined operations* would be having one or more machines doing two or more operations simultaneously in the same work station. This saves the total processing time, but can only be achieved when the operations being combined are not dependent on each other, as shown in Figure 2.4.3.

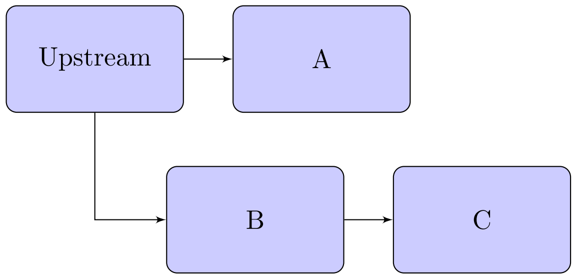


Figure 2.4.3: An example of what can be combined. A and B then C can be combined, but B and C cannot.

4. **Integration of operations**
   This strategy focuses on the linking the work stations to optimise flow of manufacturing. Achieving quick automated transportation by using automated work handling devices for transportation between work stations. At bottlenecks it may be pertinent to implement parallel work stations to mitigate the effects of the bottleneck (PlanetTogether 2023). Good solutions for integration are key to maximising the output.

5. **Increased flexibility**
   This strategy focuses on utilising the same equipment for different operations. Solutions that involve programmable or soft automation are commonly used here for their increased flexibility and little downtime between operations, which is the primary objective of this strategy.

6. **Improved material handling and storage**
   With *Integration of operations* it follows logically that automating transportation in a way that minimise non operation time such as storage, inspection or waiting time will lead to less work in process and reduced manufacturing lead time and labour costs.

7. **On-line inspection**
   Inspecting the products not only after it is produced, but while it is being produced by incorporating inspection into the manufacturing process will not only reduce the waste. It will also increase the quality of the product and cut down on unnecessary production time for defect products.

8. **Process control and optimisation**
   This focuses on the control system of a production line. There are a wide range of control schemes to choose from, the goal is to reduce the individual processing time by choosing the most optimised control system.

9. Plant operations control
   The differense between *Plant operations control* and *Process control and optimization* is that the previous strategy focused on the controls system of a process where *Plant operations control* involves the control system for the entire factory.

10. **Computer-integrated manufacturing (CIM)**
    CIM goes another step up the ladder and involves the entire enterprise and its network and databases.

2.5 What is an Evaluation Matrix

The evaluation matrix is a tool used to find the most promising option by scoring every option based on special criteria and representing the results in a matrix. The criteria are chosen by the group based on the important findings from the Understand stage in the USA principle. These criteria can either be weighted equally or relative to the importance the team places on each criterion. The weight of a criterion can be represented by a number from 0 to 1. Things to note when choosing criteria is that having too many will overly complicate and delay the evaluation. Defining the criteria properly are important to ensure a fair and reliable evaluation.

How to chose the scale which the options are scored after is up to the team. As long as every option apply the same scale. It is possible for the score to be represented by plus and minus or numerically. When comparing options to a current solution it is advisable to use the current solution as the median value of the chosen scale (Widman and Warner 2000).

Table 2.5.1: Structure of a weighted evaluation matrix.

Criteria	Weight	Option 1	Option 2	...	Option o
Criterion 1	w_1	S_{12}	S_{12}	...	S_{1o}
Criterion 2	w_2	S_{22}	S_{22}	...	S_{2o}
...	...	...	...	...	...
Criterion n	w_n	S_{n2}	S_{n2}	...	S_{no}

Table 2.5.1 shows how a weighted evaluation matrix are structured. Each criterion are assigned a weight and then given a score which is independent of the weight of the criterion. The best option is the one with the highest sum of the product of the options scores and the weight of the assigned criteria. Equation 2.1, where the weight is w and the score is S, shows how the score of one option is found.

$$\Sigma_{i=1}^{n} = w_n \cdot S_n \tag{2.1}$$

CHAPTER

THREE

METHOD

In this chapter the method used is described in the sequence the stages were done in. The aim is to represent the method as a recipe that can easily be followed and replicated.

To summarise the chapter the USA principle (2.4.2), coupled with the Ten Strategies (2.4.3) in stage S and A, are used as an approach to automation. The automated solutions are evaluated by utilizing an evaluation matrix.

3.1 Understand the process

To understand the process a visit to the company were done in the beginning of the project. With the aim to observe the operators working and measure different dimensions and times. One of the authors of this thesis have previously worked at the production line in question and therefor have knowledge of what the tasks of every workstation are, what inspection measures are conducted, and what deviations are acceptable.

During the the visit measurements of the available area and the current layout were sketched. Through interviews an understanding were developed of what the product is, what requirements are put on it, and what changes the cathodes can face in the future.

3.1.1 The current system

The current system of packaging is a mechanised process consisting of two mechanised stations, strapping and registration, and two forklifts used to transport the cathodes between the stations. The routes taken by traffic and the layout of the system is shown in Figure 3.1.1.

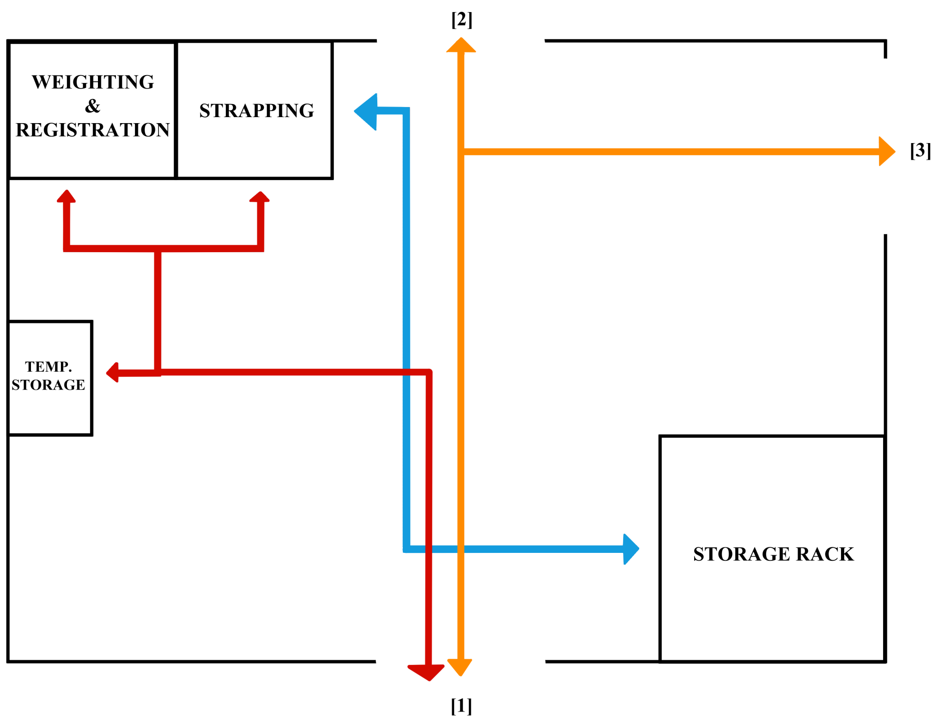


Figure 3.1.1: Diagram showing the traffic of the current system. Blue is the forklift tasked with retrieval, red is the forklift tasked with handling the bundle and yellow is additional traffic in the building. [1] leads outside, [2] leads to the shearing hall, [3] leads to the packaging hall (different products).

Storage Rack

The storage rack is the location where cathodes are stored before they go through the packaging process. The cathodes are hung by metal rods using the loops attached to the cathode. A larger forklift otherwise uninvolved in the packaging process is responsible for the transportation of the cathodes to the storage rack. While this happens no other transportation can occur within the process, as the available work area limits the mobility of other traffic. In order to retrieve cathodes from the storage rack and transport them to the next station a forklift equipped with a specialised fork is used.

Strapping

The strapping station consists of a pneumatic strapping machine and an in house design called a turntable. The turntable is a table with the capability of rotating the tabletop from a horizontal position to a vertical and then back again. The purpose of this is to reorient the cathodes horizontally. After 11 cathodes are transported here by the forklift two operators use the turntable and then inspects the cathodes for defects. If no defects are found the metal rods are removed manually from the loops and placed in a container to be reused. A powered handheld strapping machine is used to fasten a single strap lengthwise. Two wooden skids are placed underneath the bundle and fastened widthwise. Another forklift transports the completed bundle to the registration station. When the bundle leaves the station, the first forklift can place another set of cathodes in the station.

Registration

At the registration station the bundles are inspected and weighed, its gross, net, and tare weight are registered together with the bundle's lot number. This information is subsequently printed on labels and attached to the straps by an operator, in addition the same information is physically written on the bundle by the fifth and last operator.

When the registration is complete the bundle is transported to temporary storage, or if there already is a bundle present they both are transported outside. The same forklift which transported the bundle between strapping and registration are utilised for this.

3.1.2 Timing the workstations

To understand what kind of time the different steps in the process use every workstation was timed by an employee of the company. The method applied when timing the workstations were that a single bundle was timed from start to finish and a lap was registered for each described point in Table 3.1.1.

Table 3.1.1: Explanation of which intervals are timed.

Time of	Time starts	Time stops
Transport 1	When the forklift lifts up the cathodes from the rack	When the turntable starts moving
Strapping	When the turntable starts moving	When the forklift picks up the bundle
Transport 2	When the forklift picks up the bundle	When the bundle is placed on the weight
Registering	When the bundle is on the weight	When the forklift picks up the bundle
Transport 3	When the forklift picks up the bundle	When the bundle is placed in temporary storage
Transport 4	When the bundle is placed in temporary storage	When a fresh bundle is picked up from strapping

3.2 Simplifying the process

The simplification process of the current system was done through using the 10 strategies for automation and process improvement detailed in Section 2.4.3. In addition the different types of wastes described in lean (2.1) were also taken into account on how waste can be mitigated. Out of the strategies described, specialisation of operation, combined operation, simultaneous operation, and integration of operations were considered the most relevant for the simplification of the current system.

By utilizing the specialized operations strategy, machines can be optimized to perform a specific task efficiently, leading to increased productivity. However, the downside of this approach is that the machines may not be as flexible and adaptable to perform other tasks, which could limit their versatility.

Several operations of the current system which are performed in different stations which could be performed by a single machine in an automated system, this is where the combined operation strategy became relevant. As a natural consequence of using combined operations, simultaneous operations was also used to further consolidate what previously were separate operations. Particular interest was put into combining transportation with another operation and do them simultaneously and reduce non-operational time during the packaging process.

Integration of operation was a natural conclusion to reach with regards to automating the current system. The goal here was to make the transportation of the product as seamless as possible during the process, and to make it as efficient as possible.

A heavy emphasis was placed on reducing wastes as described in lean, focusing on: transportation, motion, and storage wastes. Because the current system utilize a lot of storage before, during and after the process. In addition there are a lot of transportation with big movements and operators moving around their workstations.

3.3 Automating the process

Development of the automated systems were done based on the results from the simplify stage. The focus was to develop automated solutions to the packaging line rather than the individual workstations. Because safety is of the highest importance a focus were placed on removing humans from operation areas.

There is no possibility to test how much time the developed concepts use, what machines will cost to purchase and operate in the future, or how much they would cost to install etc. To get around this issue estimations were taken by comparing the concepts to real world solutions and consulting ABB Group about costs. When the estimations were done they were used for simulations.

3.3.1 Simulation

In order to further understand and evaluate the process a simple simulation was created using the free version of FlexSim 2023. The simulation of the current system was based on the findings from Section 4.1.2. Whilst the developed concepts were simulated based on the estimations done in 4.3.4. The simulations are simplified models that do not take into account traffic conflicts, break time, or human error.

Simulation of the current system

The transport between registration and weighing, temporary storage, and outside use the same time. The reason was due to not being able to make the time vary depending on the completed process, they were still included to make the simulation better reflect the real life process. The setup of the current system within FlexSim is shown in Figure 3.3.1.

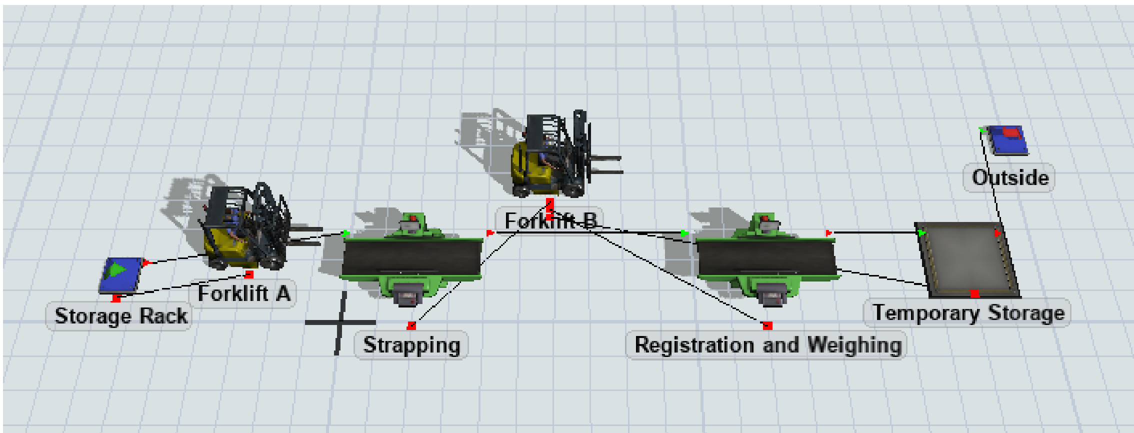


Figure 3.3.1: Screen capture of the setup within the FlexSim 2023 of the simulation of the current system.

To simulate the current system two transporters in the form of forklifts and two processors were used. Forklift A was responsible for transportation between storage and strapping. And forklift B was responsible for transportation between strapping, registration and weighing, and storage.

FlexSim is a powerful tool with the possibility of specifying load and unload time, acceleration, and max speed. None of these values were measured however. And consequently some trickery was required to make the simulation better reflect the real life process. Therefore to remove travel time added by FlexSim the transporters' max speed, acceleration, and deceleration were set to a value of a 1000 to make their contribution to the results negligible. And the resulting times from Table 4.1.2 were used as the unload time of the transporters and processors. Resulting in models that use the same times as the real world. Resulting in models that shows similar times as in the manual measurements.

Every process in the simulation used triangular distribution for its process time from the corresponding process in Table 4.1.3. Mode was substituted with the average of the corresponding process time. The reason for this substitution was due to the fact that the recorded times occur only once, but would trend towards the average if repeated endlessly.

The setup for the processors and transporters are shown in appendix A.2. To asses the activity level of the forklifts and throughput of the system. State trackers were placed on the transporters and a throughput tracker on the sink (Outside). The simulation ran until the values stabilised.

Simulation of the developed concepts

Two simulations were created based on the concepts, the first was based on the estimated performance of concepts 2 and 3, and the second was based on the estimated performance of Concept 1. The concepts all use robotic arms. They all used the same setup as seen in Figure 3.3.2. To estimate their performance, videos of a comparable system were analysed and used as an analogue. The movement time of the arm were set to half of the estimated time presented in 4.3.4. The reason the estimations were halved are that movement time in FlexSim 2023 is measured from point A to point B. Which means the arm needs a return trip. To simulate Concept 1 a slightly shorter movement time was used. A queue set to batching was used to simulate the stacking of the cathodes before entering the strapping machine. A multiprocessor with 2 processes was used to represent the strapping and registration of the bundles, each step was estimated to take 60s, this was divided by 11 to account for the size of each bundle. The specific setup of the processor and robotic arm are shown in appendix A.2

The concepts used the same setup as each other for the simulation with the exception of Concept 1 which used a different transport time for the robotic arm. Like the simulation of the current system, state trackers were used to track the activity of the robotic arm and throughput of the processor. The simulation was run until the values stabilised.

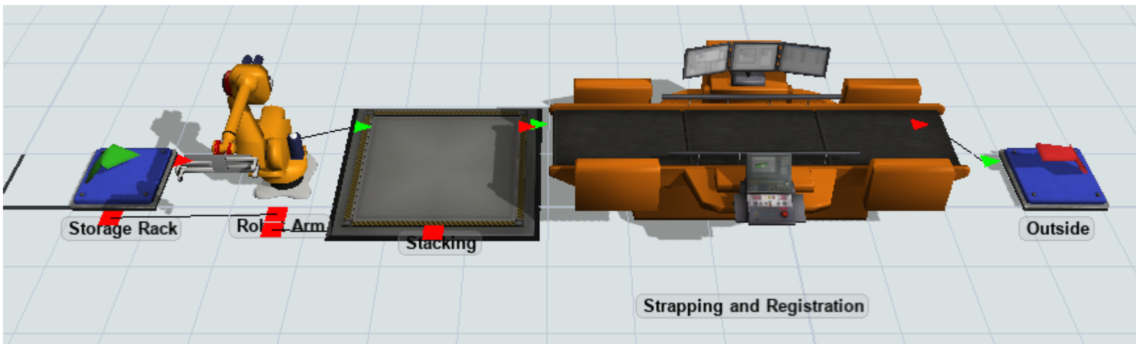


Figure 3.3.2: Setup for the simulation of the concepts.

3.4 Method of evaluation

The results from the previous stage are evaluated according to an evaluation matrix (2.5). The Evaluation Matrix takes into account the entire packaging process, from the input to output stage.

3.4.1 How the criteria are scored

The Evaluation Matrix scores the criteria on a scale from 1 to 5, the concepts are ranked according to the highest score. The current system is scored by the median value of 3, while the concepts are scored based on their performance in relation to the current system. The lower scores were given if the concept was found to perform worse in a criterion than the current system, and the higher scores were given to those where they performed better. Scores of 1 are given to the concept that performs the worst in the criterion, while 5 is given to the concepts which performs the best.

3.4.2 How are the criteria weighed

The weight of each criteria were chosen by the department manager and are represented Table 3.4.1.

Table 3.4.1: Weights of the criteria.

Criterion	Weight
Productivity	0.5
Manual labour	0.8
Economics	0.8
Downtime	0.5
Scalability	0.2
Flexibility	0.5
Traffic	0.8
Safety	1

3.4.3 The criteria

Eight criteria were chosen to evaluate the concepts: Productivity, manual labour, economics, downtime, scalability, flexibility, traffic and safety.

Productivity

This criterion gives an evaluation of the time to completion from input to output of the entire process compared to the current system. A reduction in work station process time means an overall reduction in lead time for the product, and thus an improvement of the overall system. This criterion also takes into account the variability in the time taken, high variability means that any potential improvement in lead time is offset by the lack of certainty for the expected time to completion. This makes any improvements such as made to order procedures difficult to implement. Thus high variability is seen as a negative.

Manual Labour

Manual labour gives an evaluation of how much human interaction is needed. This is judged by the number of operators required during operation, but also their role such as whether or not they are expected to perform tasks which experience heavy loads. Their associated cost is not considered here but included in the economics criterion instead.

Economics

Economics evaluates the economic aspect of each concept, this includes wages, fixed costs, variable costs, and initial costs associated with the implementation of the concept. This also includes the area that is occupied by the concepts.

Downtime

Downtime is defined here as the amount of time the machinery is inactive. This includes downtime due to maintenance of machinery, but also time spent by the operators switching roles and time spent by operators during break time.

Scalability

Scalability takes into account how easy it is to increase the capacity of the process to increase the volume of products delivered.

Flexibility

Flexibility takes into account the ability of the system to take into account changes in operation such as a change in product, handling failures such as wrong type of cathode or loosened straps, or change in demand for the product.

Traffic

Traffic is a measure of the amount of traffic that causes conflicts originating from the system, either directly or indirectly. A conflict here is broadly defined as an event where traffic adversely affects operation by i.e waiting or injury.

Safety

To score the safety of the system it is evaluated if there are a high risk of injury, such as high energy injury from machinery or injuries as cuts on sharp edges.

CHAPTER

FOUR

RESULTS

4.1 Understanding of the process

4.1.1 Observations

During the company visit a couple of key problems were identified. The main problem is the amount of time spent during the packaging process in transport. Through observations the product spends about half its time in transport, and not in the stations were actual value is added to the product. This problem is compounded by the fact that the entire process is reliant on two individually operated forklifts, one of which spends most of its time waiting for the strapping station to empty, and the other can only focus on one station at a time to the detriment of the others. The forklifts take up most of the work area allotted to the packaging process which is already limited, in addition the area also experiences traffic from other parts of the facility effectively cutting the area in two with the storage rack on one side and the stations on another. Furthermore the forklifts are potential safety hazards to the operators working in the area.

In addition to the transport, another problem is the efficiency of the packaging process itself. Its current setup makes upscaling production to meet future demand practically impossible unless changed completely, and relying on manual labour gives rise to highly variable lead times.

From observation it was located two bottlenecks in the system. At the strapping station and transportation outside.

4.1.2 Inspection

It was observed how the cathodes are inspected are initially done from the seat of the first forklift by looking for coloured markings on the loops of the cathodes. These markings are a result from inspection upstream. Yellow and green markings are not permissible for packaging. Neither are cathodes with areas of pores larger than half the cathode as acid residues could be inside the pores. When the cathodes arrive at the strapping station a quick visual check on the loops are done to check for copper formations. Table 4.1.1 show what the different markings on the loops mean. The white marking can be acceptable if the nodules are not too large there are no problem with packing them. The only problem would be if the nodule were large enough to make the stack unbalanced. However yellow and green can not be packed because they do not meet the standards of purity in the nickel. The red cathodes are grown thinner and lighter on purpose and are always stacked together. Some customers prefer these bundles so not mixing them with the normal cathodes are important. They are usually harvested on Thursday and Friday.

Table 4.1.1: Meaning of colour codes marked on loops upstream in the production line.

Colour code	Explanation
Green	Copper formations on the cathode
Yellow	Pieces of fabric stuck in the cathode
White	Nodules on the surface
Red	Thinner and lighter cathodes

4.1.3 The end product

The London metal exchange (LME) requires the bundle to be strapped in two dimensions and marked with the lot number and brutto and netto weight on the top cathode. And labeled with a warning sign (LME Board of Directors 2022). Conforming to these regulations are a requirement to trade on the LME.

The end product is a bundle of eleven 1285 mm x 720 mm cathodes resting on two wooden skids, as seen in Figure 4.1.1. Strapped in such a way that the lengthwise strap goes in between the skids and the bottom cathode.

Figure 4.1.1: How the bundle of cathodes looks after processing.

The product conforms to all regulatory LME markings and also adds a number the bundle has in the lot and the tare weight (weight of the packaging material). 11 is a number chosen as it adds up to around 1 metric tonne.

There are three variants of the bundle. Primary with normal cathodes, lighter cathodes marked with read, and A-Grade cathodes who are the same as primary cathodes but with a rougher surface. This rougher surface makes them harder to stack properly.

4.1.4 The cathode rods

The function of the rods are to hold the cathodes up and lead current used to grow the cathodes. They measure 960mm by ⌀26mm and are made of a steel core with a copper coating and a protective coating outside of that again. Because of the weight resting on them they are prone to buckling. Buckling usually happens in retrieval when they either fall of the fork down on the rack or the fork unintentionally push down on the rods and bends them.

4.1.5 Time measurements

Table 4.1.2: Times taken by employee in seconds. Cells marked with * are the average times.

Process in seconds	1	2	3	4	5	6
Transport 1	93.27	45.47	73.98	262.08	80.88	75.55*
Strapping	71.10	110.52	117.37	119.78	56.93	86.72
Transport 2	13.40	11.88	13.76	14.26	111.00	8.41
Registration	135.38	53.55	65.15	30.40	45.13	26.97
Transport 3	9.71	13.13	8.03	11.55	10.96	10.83
Total	322.86	234.55	278.29	438.07	304.90	208.48
Process in seconds	7	8	9	10	11	12
Transport 1	52.28	75.55*	19.96	14.13	23.91	89.52
Strapping	75.78	60.17	77.67	70.08	68.55	114.74
Transport 2	14.51	14.43	9.71	13.23	13.83	13.98
Registration	35.73	41.76	36.40	45.63	52.82	69.85
Transport 3	10.30	9.88	10.23	7.26	13.93	15.04
Total	188.60	201.79	153.97	150.33	173.04	303.13

The median, average and standard deviation were found using the excel commands `MEDIAN()`, `AVERAGE()` and `STDAV.S()`. The total is not the total sum, but of the total processing time from Table 4.1.2.

Table 4.1.3: Statistical values of the process time in seconds.

Process in seconds	Median	Average	S.Dev	Min	Max
Transport 1	63.13	75.55	71.73	14.13	262.08
Strapping	76.73	85.78	23.39	56.93	119.78
Transport 2	13.80	21.03	28.40	8.41	111.00
Registration	45.38	53.15	28.90	26.97	135.38
Transport 3	10.57	10.90	2.27	7.26	15.04
Sum	-	-	-	113,7	643,28
Total, sec	221.51	246.50	85.44	150.33	438.07

In addition the time it took for the forklift to move the buildup in temporary storage outside were noted and represented in Table 4.1.4. These times would be defined as the *Transport 4* interval in Table 3.1.1. It is important to note that this time would affect the time strapping takes and is therefor not represented in the total process time.

Table 4.1.4: Transport time outside in seconds.

1	2	3	4	5	6	7
45.00	50.00	170.00	40.00	64.59	127.00	25.00
8	9	10	11	Median	Average	S.Dev
35.00	40.00	62.00	182.00	50.00	76.42	56.13

4.1.6 Changes in the future

There are plans for a change in manufacturing in 10 to 20 years. This change may increase the output and change the look of the cathode. Instead of beeing supported by two loops the cathode will be directly grown on a permanent cathode and stripped of directly as a final product resulting in cathodes without loops. The dimensions of the cathodes might also change. However, potential future changes are out of scope since 10-20 years are far into the future.

4.2 Simplified model

The current system is pretty simplified as it is. However the inspection of the cathodes could happen in storage simultaneously as the production line is in operation, saving time from the packaging. In retrieval the weighting and removal of rods have been consolidated. In addition the cathodes will be deposited lying down, saving time on tilting the cathodes horizontally. To integrate the operations all transportation are done by automated conveyors reducing unnecessary movement and decreasing the time between each operation. Figure 4.2.1a and 4.2.1b show the current and simplified models side by side for comparison.

Table 4.2.1: Steps of the current system, and the steps of the simplification.

(a) The current system.

Storage Rack	Storage
Transport	Retrieval Inspection Depositing vertically
Strapping	Tilting horizontally Remove rods Lengthwise strap x1 Two skids Widthwise strap x3
Transport	Forklift
Registration	Inspection Weighing Registration Marking
Transport	Temporary storage Outside when buildup

(b) Result from the simplification.

Storage	Storage Inspection
Retrieval	Retrieval Remove rods Weighing Depositing horizontally
Transport	Conveyor
Strapping	Lengthwise strap x1 Two skids Widthwise strap x3
Transport	Conveyor
Registration	Inspection Registration Marking
Transport	Outside storage

4.3 Developed concepts

The developed concepts builds on the simplified results presented in Table 4.2.1b. During the development process an emphasis was put on future proofing the concepts. The result of development was three concepts. These are in general very similar, with the difference being the method of extracting the rods. They all only require 2 operators. One operator on a forklift outside, retrieving the finished bundles and sorting them, and a second operator who oversees the automated process inside. To keep the second operator safe the area are fenced off.

4.3.1 Concept 1

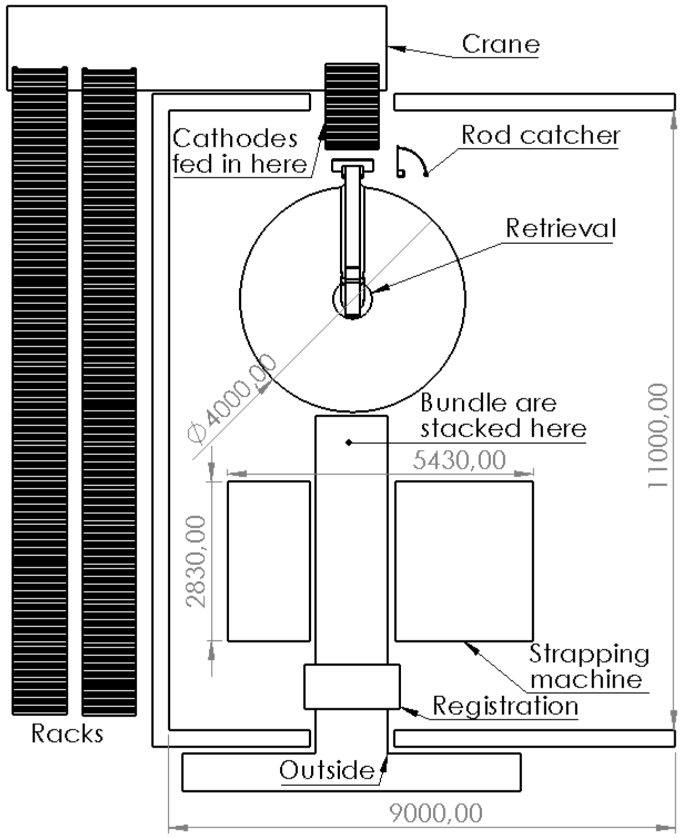


Figure 4.3.1: The proposed layout of Concept 1 showing the placement of the robotic arm (marked retrieval), the strapping machine, registration, and rod catcher.

Storage and input

The cathodes are stored on racks the already existing racks to the left of Figure 4.3.1. From there a crane, or other means of transportation, moves a selection of cathodes to fill up the smaller rack which are fed through the wall. From this rack the first cathode in line is inspected while waiting to be retrieved. The inspection functions as vision inspection that checks the loops for coloured markings. If a green or yellow marked cathode appears then the cathode is moved on top a pallet after the rod is removed. For this to work a new marking need to be implemented for cathodes with large areas of pores. However this is out of scope for this thesis.

Retrieval

A robotic arm with an integrated load cell picks up one cathode and tilts it vertically in such a way that the rod slides out of the loops into a funnel that controls the fall without damaging the rod. Figure 4.3.3 shows how the rod will fall down on the red rubber block dampening the fall. Then it is pushed onto the slide and glides down it and through the slit at the bottom where a separate machine, independent of retrieval, gathers the rods up and stores them in a container (Figure 4.3.2).

Figure 4.3.2: Currently the rods are stored and transported in these containers.

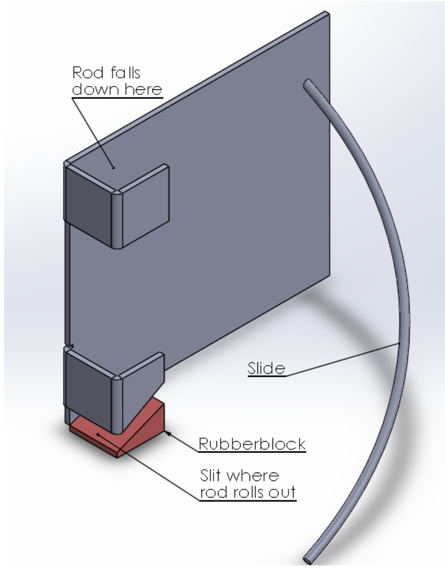


Figure 4.3.3: Rod catcher. Rod falls down on the red block and are pushed onto the slide and glides down and rolls out the slit.

If the rod has not cleared the loops the cathode is placed on a pallet. Whether the rod has left can be controlled by a proximity sensor or by controlling weight changes in the load. If the rod is clear and the cathode passed the inspection the cathode is weighed and placed on the conveyor belt marked on Figure 4.3.1. This operation is repeated until the stack of cathodes totals 11 cathodes. Figure 4.3.4 shows the process flow of the retrieval process and the inputs from a sensor performing quality control as part of a control system.

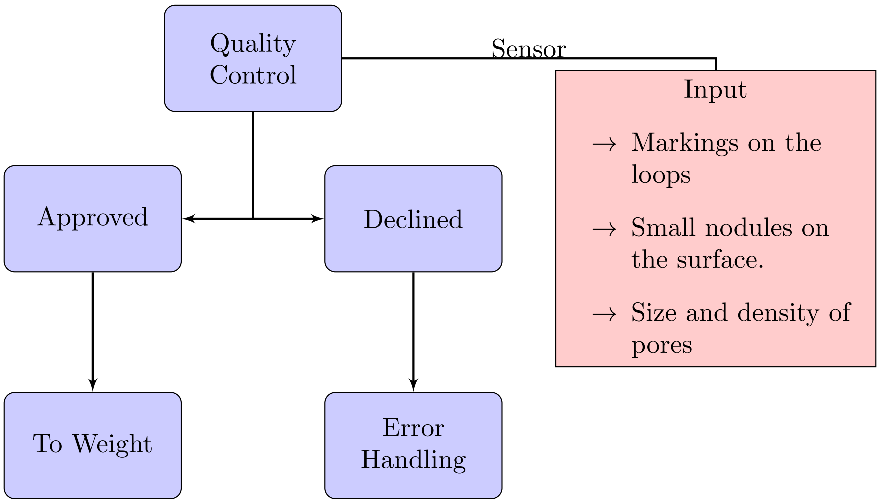


Figure 4.3.4: Process flow and inputs of retrieval. The figure shows the steps of the process (blue), and the information that is gathered (red), and what processes it (sensor).

Strapping

For strapping the bundle a machine capable of rotating the product and adjoining two skids underneath are used. The bundle is transported into the strapping machine lengthwise to reduce unnecessary rotation when it is strapped lengthwise. Doing it this way is also much safer as rotating 11 unsecured cathodes, each weighing around 100 kg, is incredibly unsafe. After it is strapped lengthwise the bundle is rotated 90°and strapped front to back three times with the wooden skids at the ends.

Figure 4.3.5 shows the process flow of the retrieval process and the inputs from a sensor and computer a control system for the processes.

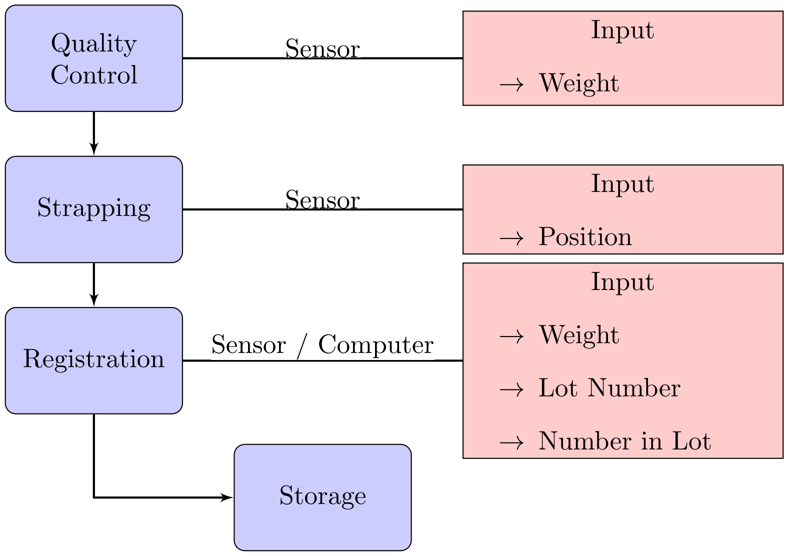


Figure 4.3.5: Process flow and inputs of strapping and registration. The figure shows the steps of the process (blue), and the information that is gathered (red), and what processes it (sensor/computer).

Registration

Four proximity sensors are used to determine how level the bundles are. If the bundles are sufficiently level they are registered as primary grade, if they are not they are registered as A grade. A computer gathers this information, the total weight gathered from the load cell of the 11 cathodes in the bundle, lot number, and number in lot onto a label. This label and additional required markings are put onto the bundle. After registration the bundles are transported outside through a hatch.

Transport

After the bundles are registered they are fed outside into a conveyor system like the one utilized in the old copper production (Figure 4.3.6). From this conveyor a forklift can pick up the bundles and sort them into storage completely undisturbed by the inside process.

Figure 4.3.6: Conveyor outside the old copper production.

4.3.2 Concept 2

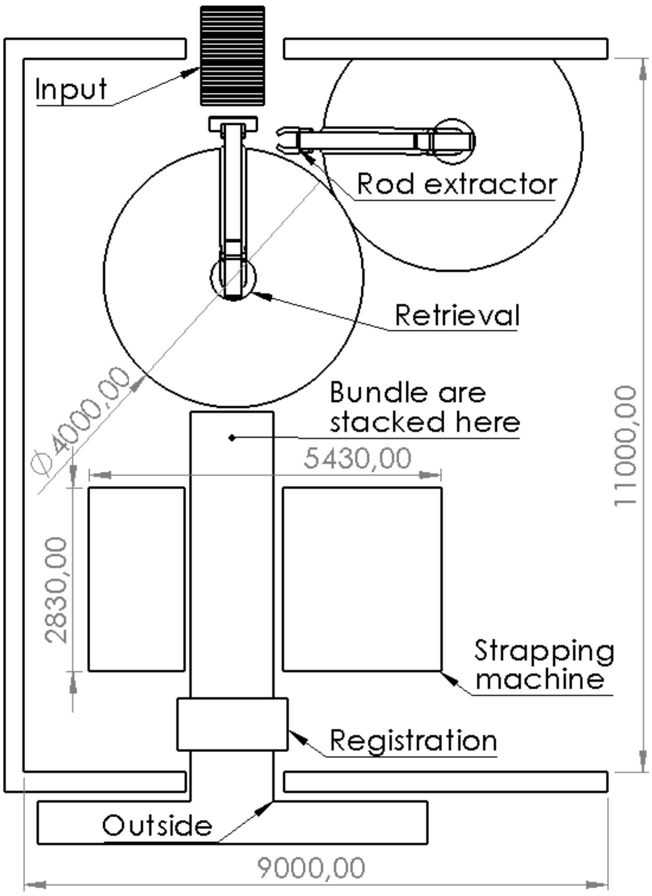
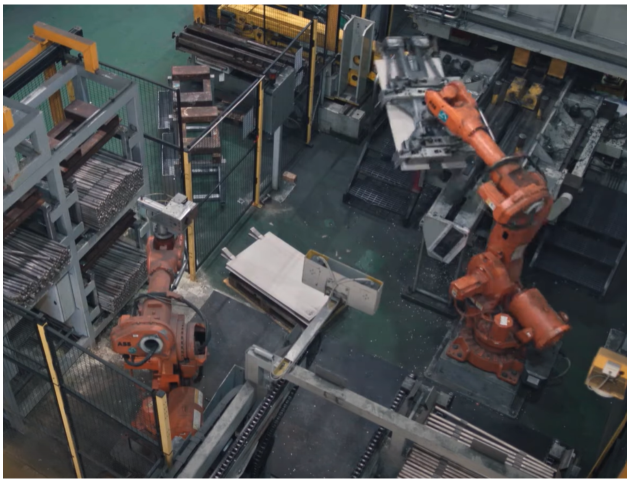


Figure 4.3.7: The proposed layout of Concept 2 showing the placement of both robotic arms, the strapping machine, and registration.

Instead of using gravity to remove the rods this design use the same method of extraction as the new shears (shear 51) pictured in Figure 4.3.8. A second robotic arm pulls out the rod, checks if it is straight, and stores it in a container visible at the left of Figure 4.3.8a. This is adapted in Figure 4.3.7 where the rod extractor retrieves the rod and place it in a container not marked on the illustration.



(a) An overview of shear 51.

(b) Closeup of retrieval at shear 51.

Figure 4.3.8: Cathode retrieval at shear 51.

4.3.3 Concept 3

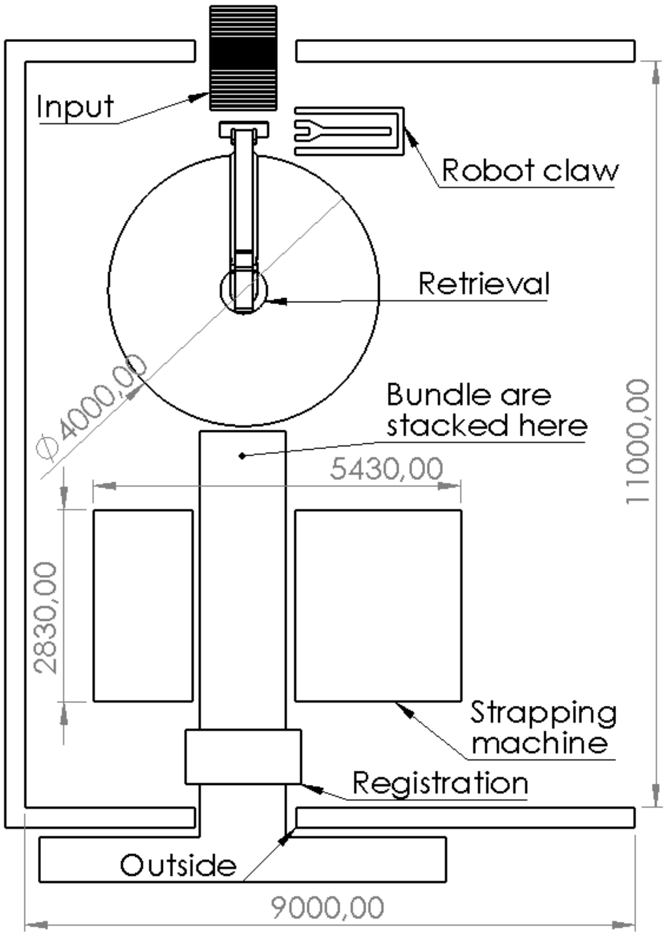
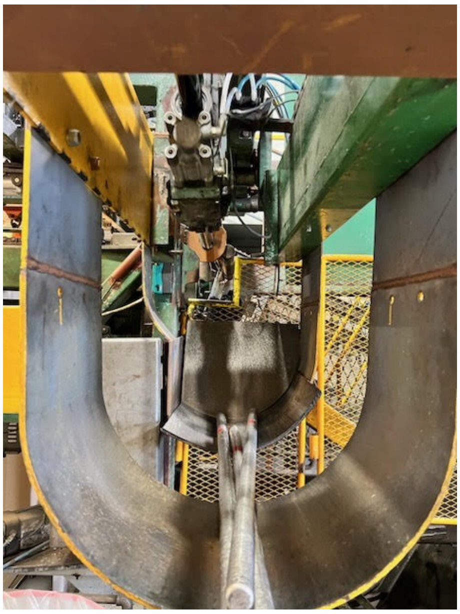
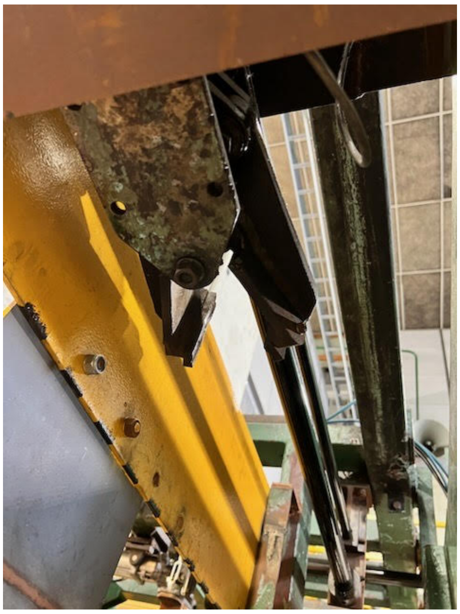


Figure 4.3.9: The proposed layout of Concept 3 showing the placement of the robotic arm, robotic claw pictured in 4.3.10, the strapping machine, and registration.

In Concept 3 (Figure 4.3.9) the rod is removed the same way as the cathodes going into the older shears as shown in Figure 4.3.10. The rod is pulled out of the loops by a robotic claw specialized for this task and dropped into a basket where an operator retrieves it. It is estimated that this design will use the same amount of time to stack enough cathodes for an entire bundle as Concept 2.



(a) Overview of extractor with basket.



(b) Closeup of robot claw.

Figure 4.3.10: Rod removal at the older shears.

4.3.4 Estimated time usage

From watching videos of shear 51 operating; retrieving one cathode takes approximately 30 s therefore, retrieving 11 cathodes for an entire bundle would take 330 s. These estimations are considered applicable to the concepts and are therefore used in the simulations of concepts 2 and 3. As Concept 1 is estimated to require less time to remove the metal rods, it is estimated to use 25 s to retrieve cathodes. Since machine operations are usually more consistent than manual operations the process time of the robotic arms are reckoned to be constant for the purpose of the simulation.

4.3.5 Estimated cost of automation

The estimated costs of the current and developed concepts are represented in Table 4.3.1. These estimated values are based on estimations given to us by representatives of the company and suppliers. And are based on a production of 46 000 tons in a year. From Figure 4.3.11 it is evident that at the end of the second year concepts 1 and 3 are cheaper to operate than the current system. And Concept 2 are cheaper in the beginning of year three.

Table 4.3.1: Costs of the current and developed solutions in million NOK.

Cost in million NOK	Current	Concept 1	Concept 2	Concept 3
Implementation	0	7.500	10.000	8.000
Labour	7.380	2.952	2.952	2.952
Operation	0.210	0.405	0.435	0.405
Trucks	0.650	0.325	0.325	0.325
Packaging	7.130	7.130	7.130	7.130
Sum, yearly	15.370	10.812	10.842	10.812
Sum, 10 years	153.700	115.620	118.420	116.120

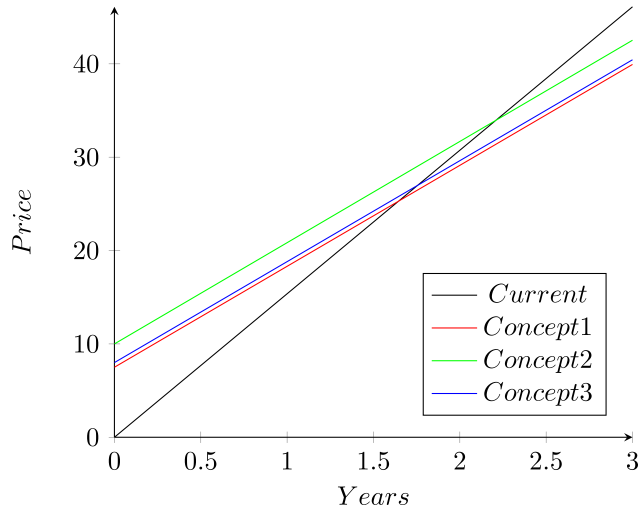


Figure 4.3.11: Total cost over three years.

The values are a result of consulting with the company and suppliers about purchase, assembly and operation. Maintenance and operational costs of the other modules are to be seen as negligible compared to the costs of the strapping machine and robot arms.

Concept 1 require the least amount of modules with only a strapping machine and one robotic arm. Concept 2 requires an additional robot arm and Concept 3 requires the robotic claw. More explanations of what the estimations are based on are presented in Table 4.3.2.

Table 4.3.2: Cost estimation of modules with explanations.

NOK	Initial	Yearly	Comment
Robot arm	2 500 000	30 000	The initial cost is purchase and assembly and come from consulting ABB robotics. They estimate their products use 5k in maintenance. Energy costs are estimated to be 25k.
Robot claw	500 000	Negligible	They already exist. Construction is the only thing that is left.
Strapping machine	3 000 000	50 000	Estimation based on the strapping machine at the new copper line.
Forklifts	0	325 000	Forklifts are already there.
Other	2 000 000	Negligible	A rough estimate that includes construction work, conveyors, racks, etc.

4.3.6 Results from the simulations

The following section presents the results from the simulations. Note that one bundle roughly equals 1 000 kg, and the systems' productivity is equal to their throughput.

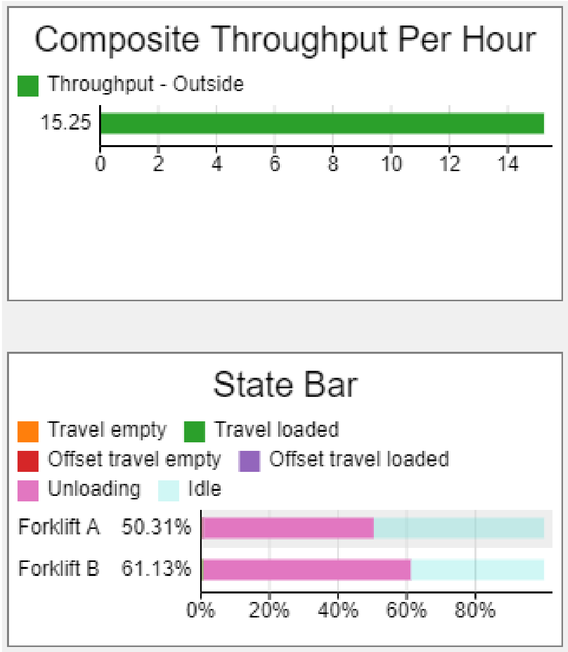


Figure 4.3.12: Results from the simulation of the current system.

During the simulation the throughput of the system consistently trended towards a value of 15.25 bundles/h as shown in Figure 4.3.12. Note that 1 bundle roughly equals 1 000 kg. The throughput of the system is equal to its productivity.

From the statistics in Table 4.1.3 the system has on average a throughput of 14.6 bundles/h as shown in Calculation 4.1.

$$\textit{Statistics Avg. Throughput}: \frac{3600 \text{ s/h}}{246.5 \text{ s/bundle}} = \underline{\underline{14.6}} \text{ bundles/h} \tag{4.1}$$

During the simulation the activity of Forklift A trended towards 50.31 % and Forklift B towards 61.13 % as seen in Figure 4.3.12. From the statistics given in Table 4.1.3 the average activity of Forklift A is 53.17 % and Forklift B averages 56.89 % as seen in Calculations 4.2 and 4.3.

$$\textit{Avg. Activity Forklift A}: \frac{85.78}{75.55 + 85.78} \text{s} \cdot 100\% = \underline{\underline{53.17}}\% \tag{4.2}$$

$$\textit{Avg. Activity Forklift B}: \frac{21.03 + 10.9 + \frac{76.42}{2}}{21.03 + 53.15 + 10.9 + \frac{76.42}{2}} \text{s} \cdot 100\% = \underline{\underline{56.89}}\% \tag{4.3}$$

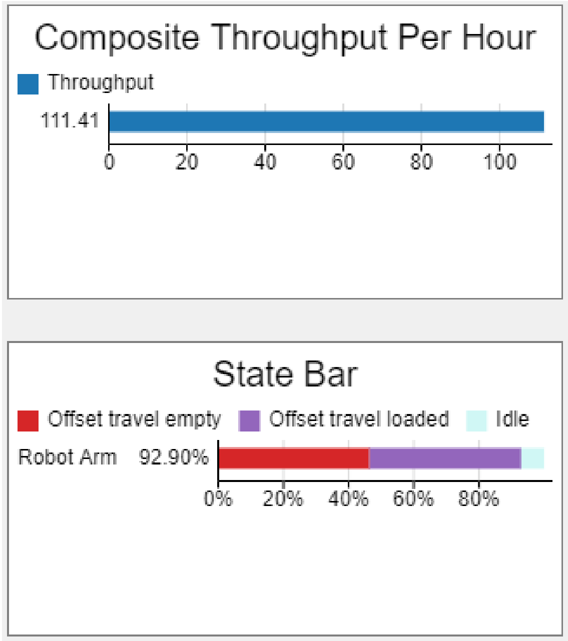


Figure 4.3.13: Results from the simulation of the concepts 2 and 3.

The throughput of concepts 2 and 3 is derived from the results shown in Figure 4.3.13 and given by Calculation 4.4. The activity of the robotic arm trended towards 92.2%.

$$Concept\ 2\ \&\ 3\ Throughput : \frac{111.41}{11} \text{bundles/h} = \underline{\underline{10.23}} \text{ bundles/h} \tag{4.4}$$

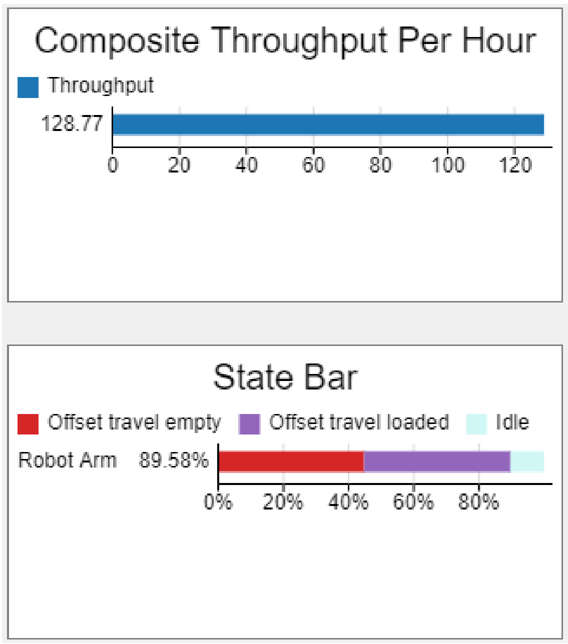


Figure 4.3.14: Results from the simulation of the Concept 1.

The throughput of Concept 1 is derived from the results shown in Figure 4.3.14 and given by Calculation 4.5. The activity of the robotic arm trended towards 89.58%.

$$Concept\ 1\ Throughput : \frac{128.77}{11} \text{bundles/h} = \underline{\underline{11.71}} \text{ bundles/h} \tag{4.5}$$

Additional tests were conducted with increased process times on the multiprocessors. Their effect on the throughput of the system remained non-existent until it reached a total time of around 330s, then the throughput would begin to decrease. Decreased process times had little to no effect on the throughput.

4.4 Results of the evaluation matrix

Table 4.4.1 shows the results from the evaluation. All the concepts scored higher than the current system. With Concept 1 being the best option.

Table 4.4.1: Evaluation matrix

Criteria	Weight	Current	Concept 1	Concept 2	Concept 3
Productivity	0.5	3	2	1	1
Manual Labour	0.8	3	4	5	4
Economics	0.8	3	5	4	4
Downtime	0.5	3	5	4	4
Scalability	0.2	3	5	4	4
Flexibility	0.5	3	3	3	3
Traffic	0.8	3	4	4	4
Safety	1	3	4	4	4
Final score	-	15.3	20.4	19.2	18.4

CHAPTER

FIVE

DISCUSSION

The results of this thesis draw upon the understanding of the current process, the development of concepts for automated systems, and the evaluation of these concepts. To understand the process was a fundamental part of writing this thesis. In order to build this understanding physical observation of the current system was undertaken early on in this project as part of a company visit. This had both its advantages and disadvantages.

The company visit resulted in decent knowledge about the current system, the work of the operators, and the resulting product. This became very important as the information was not easily obtained otherwise. During the visit the process time of each work station was measured. It became quickly apparent that these measurements were quite lacking, both in terms of number of measurements and which process was measured. Due to limited time a new set of measurements were taken by an employee of the company on the basis of the earlier measurements. This new set resulted in those shown in Table 4.1.2

Advantages doing these measurements early was that it gave adequate amount of time to analyse the findings and set them in context to what was seen during the company visit. In addition it gave freed up time to work elsewhere on the project. A disadvantage of doing the measurements early was that once they were made they largely went unused while other portions of the project were researched and completed. Then when they were finally used the information gathered was not quite exactly what was needed, more of this is detailed in Section 5.3. New measurements were not possible due to distance and timeframe.

Due how the times were measured the step where two cathode bundles were transported outside became ambiguous as to its prominence. From the perspective of the transported bundles it is a sizeable contribution, but to the overall production the induced downtime is largely incorporated into the other process times. Therefore is not included in the total time as shown in 4.1.3, however it is included when calculating the activity of the transporters in Calculation 4.3. The reason is due to the step directly affects the transporter.

The measurements themselves varied quite heavily, from an average total of 150.33s to 438.07s. There can be several reasons for these discrepancies. Foremost it is simply due to the relative efficiency of the different shifts, the more experienced shifts are bound to be more efficient than the less experiences. Another reason could be unforeseen events like traffic which affected the process. Certain steps lacked a measured time, therefore the average value of the step was used instead, though the substituted values themselves were not used to calculate the average time of said step. The use of the average values in such a manner might have affected the end result by inflating the end result. Additionally there are several steps where the measurements vary significantly with comparatively large difference between values as seen in the standard deviations.

Ideally additional measurements would have been taken to decrease the large deviation seen in the results. This would have given more accurate readings and given a clearer picture of the production. Additional measurements might also have given insights into trends in productivity which could be used to identify deficiencies otherwise ignored.

5.1 The concepts

Due to the limitations of this thesis and the nature of the tasks. Only three very similar concepts were developed. Because of the restrictions on strapping in two dimensions there are limited options on how to automate this. As a result the concepts differ only in how the rods are extracted.

There is an open question on where to place the load cell, on the robotic arm itself, where the cathodes are stacked, or after the strapping at the registration station. The benefit of installing the load cell in the arm or where the bundle is stacked are that the cathodes can be individually weighed. This gives more specific knowledge about the individual cathodes making up the bundle, and thus allows for customers to know any discrepancies in weight. Which can be desirable for customers, and gives the company itself more information about the products they produce.

The cons of having the load cell on the arm is the additional time required to make accurate readings, here small additions can quickly compound to make a large impact on the overall efficiency of the system. Installation of the load cell might also require modifications of the arm resulting in additional costs.

The pros are that it makes it possible to sense whether the rod has cleared the loops by measuring changes in the weight. Additionally large weight discrepancies can quickly be identified and handled before they are stacked in the bundle.

An alternative method of retrieval would be to handle all 11 cathodes at once, and subsequently remove the rods simultaneously. This method could be faster than the use of robotic arms, but this comes at the cost of decreased flexibility in how the cathodes are handled. There are difficulties with retrieving 11 at a time. When 11 cathodes are pressed together the rods line up in a very unpredictable arc that makes using any claw to grab the rods impractical, and because of the forces of the loops pressing on each other and the rods a lot of friction is formed. This friction makes it a lot harder to pull any rod out compared to when there are only one set of loops. It has not been possible to test whether gravity will be strong enough to overcome this friction. As it is when there are only one.

Pros of retrieving one at a time

- Register weight discrepancies. A lot of information for the customers.
- Can bend the ears resulting in less space for storage. About 11% reduction in storage area proven in Calculation 5.1.
- Possible to lay cathodes in alternating direction leaving a flatter top surface.

Cons of retrieving one at a time

- Significantly slower.
- Introduces more points of failure. Because of more movement and more operation.

From drawing *3-5394* received from Nikkelverk the cathodes measure 720 by 1280 mm with loops protruding 184 mm. Currently the loops are not bent, but if they were they would peek out roughly 2 cm.

$$\begin{aligned} \textit{Not bent}: 720\ \text{mm} \cdot (1280\ \text{mm} + 184\ \text{mm}) &= 1.05408e6 \cdot 10^6\ \text{mm}^2 \\ \textit{Bent}: 720\ \text{mm} \cdot (1280\ \text{mm} + 20\ \text{mm}) &= 0.936 \cdot 10^6\ \text{mm}^2 \\ \textit{Reduction}: \frac{(1.05408 - 0.936) \cdot 10^6\ \text{mm}^2}{1.05408 \cdot 10^6\ \text{mm}^2} \cdot 100\% &= \underline{\underline{11.2\%}} \end{aligned} \tag{5.1}$$

5.1.1 Challenges not addressed

There are several challenges which were not addressed due to time constraints, simplification, or falling beyond the scope of this thesis. An important step in the production of the bundles which has been ignored is the fact that the first bundle in a lot is weighed on two separate scales in order to check if they are calibrated.

This could be solved by weighing the bundle in two places during the packaging process, for example having one module on the robotic arm and another leading into the strapping station. This would have the benefits mentioned previously in Section 5.1, but also makes it possible to monitor the calibration in real time.

Another solution would be to have a reference weight, like a cathode, that's always available to be picked. If the load cell registers a difference in the weight to what it should be if the load cell is not calibrated. The benefit of using a reference weight is that the scale will always be compared to a fixed marker. Where as comparing the output of two scales which both could be off introduces a degree of uncertainty. However this would not allow for calibration in real time and would use more time as the arm would need to pick up the reference weight to calibrate and return the reference weight.

Another challenge not addressed is how to handle re-strapping bundles if a strap snaps during handling. The easiest solution to this would be to keep the current strapping station as a backup for manual strapping, but move it to where the current storage racks are located, as this space is not used in the developed concepts. This is illustrated later in Figure 5.6.1. Right now the turntable can move. Which creates potential for crushing injuries. Therefor the table will need to be modified so it is stuck in the horizontal position.

5.2 Review of the measured time

There is unfortunately too little data. Ideally several hours would've been used, but there was little time to observe and create a consistent methodology for measuring process times. The few times taken by the group were found to be not representative of the desired intervals. Instead of using these an employee took some times guided by the intervals defined in Table 3.1.1. From this 12 bundles where timed with the exception of retrieval which lacked two data points. Therefore these were substituted with the average time.

Even though there are few measurements there is a lot of deviation in the small sample. If there was a bigger pool of data it would be expected that the data showed high amounts of variation in the process times. This variation is due to the unpredictability of manual labour that automated systems does not have.

5.3 Discussion of the simulations

The original intent was to simulate both the current system and the concepts by programming it in python. This became more difficult than anticipated, and after numerous iterations the simulations never worked as intended and was ultimately abandoned. Instead alternatives were explored and FlexSim 2023 was ultimately chosen due to its accessibility. Despite this it came rather late in the writing of this thesis and therefore was never properly planned for when measuring the process times. Thus instead of fitting the information to the simulation, the simulation was fitted for the information.

Through the results from the simulation the production efficiency of the current system and the concepts could be evaluated, along with the utilisation of the equipment during operation. It is important to note that the results from all the simulations are on the optimistic side. FlexSim 2023 is a powerful program capable of simulating quite detailed and complex operations. In order to make full use of the program and its capabilities it is important to have a good amount of knowledge and experience working with it. While online resources did help somewhat in making up for this lack during the writing process, the simulations were still quite rudimentary compared to what is possible. The simulations were also slightly hampered by the method used to measure the process times of the current system. Since the operations of the simulation had to conform to the statistics in Table 4.1.3 they could not take advantage of its ability to simulate facilities to scale.

Despite the limitations of the simulations the results revealed by them are reasonable. The simulation of the current system gave a throughput of 15.25 bundles/h, in a conversation with an employee of Nikkelverk it was confirmed that the numbers reflect the expected real life production. It can therefore be inferred that the results of 14.6 bundles/h derived from the statistics in Table 4.1.3 are also within reason. Meaning while the simulation is simplified they do represent its real life counterpart reasonably well.

A similar conclusion can be inferred from the activity levels of the transporters about the veracity of the simulation results. Forklift A trended towards an activity level of 50.31%, while Forklift B trended towards an activity level of 61.13%. From the statistics in Table 4.1.3 the activity level of Forklift A is 53.17% and Forklift B had an activity level of 56.89%. These results are within 10% of their simulated counterpart, and there the simulation can be taken as a reasonably accurate reflection of the real life process.

Table 5.3.1: Activity and productivity.

	Simulation	Statistics
Forklift A Activity	50.31%	53.17%
Forklift B Activity	61.13%	56.89%
Current System Productivity	15.25 bundles/h	14.6 bundles/h
Robot Arm	78.58%	-
Concept 1 Productivity	11.71 bundles/h	-
Concept 1 Activity	89.58 %	-
Concept 2 & 3 Productivity	10.23 bundles/h	-
Concept 2 & 3 Activity	92.90 %	-

In addition to contributing to determining the veracity of the simulation, the activity of the transporters also reveal the presence of waste as described in Section 2.1. As seen in Table 5.3.1, Forklift A spends about 50% of the time idle, while Forklift B spends about 40% of the time idle. This points to a significant presence of waiting waste during production. This indicates that the value-adding processes of strapping and registration are too slow to keep up with the transporters, meaning overall that the transporters are underutilised during production.

One solution which could increase the utilisation of the transporters is to increase the number of work stations so that there is a more continuous production and less waiting time. In theory this could work, limiting the amount of time the forklifts wait for the product to finish processing. But this would result in increased cost for the additional equipment and workers, and with limited floor space it could make traffic worse and entirely mitigate any increase in efficiency.

Compared to the activity of the current system the concepts resulted in considerably higher values, 89.58% for Concept 1 and 92.9% for concepts 2 and 3. This comes at the cost of a significant reduction in productivity, 11.71 bundles for Concept 1 and 10.23 bundles for concepts 2 and 3. Compared to the productivity of the current system this is a significant reduction, this reduction is to be expected as the cathodes are stacked one by one instead of taken all at once. A consequence of this reduction is the need to increase the number of shifts in order to meet production quota.

Any changes to the process time of the multiprocessor yielded interesting results. As mentioned in Section 4.3.6 there was a negligible impact on the productivity of the system until it matched the retrieval time of the robotic arm. This clearly marked the robotic arm as the bottle neck of the system, but also made it clear that the efficiency of the strapping and registration made little difference to the overall production. So while the process times used in the simulation were estimated based on the performance of a similar system, for the purpose of the simulation they could have been chosen arbitrarily. This leaves room for greater flexibility in terms of equipment investment, as long as the process does not match the time it takes to stack the cathodes. On the downside this also points to the presence of waste, since the multiprocessor awaits the next batch of cathodes to be processed. Although since the bottleneck is limited to one area, rather than spread out over the entire system, it is easier to handle. Therefore the faster the retrieval process can be performed, the less waste is generated by the system.

5.4 Reliability of the estimations

Due to the limitations of this thesis there has not been an opportunity to test the results. Therefor it was necessary to compare the concepts to solutions from the real world and making estimations based on this data and knowledge of which of the ten strategies reduce which types of time. For example non operational time.

5.4.1 Discussion of the estimated time usage

Because Concept 2 was inspired by shear 51 and functions almost identically it is reasonable that used time would be similar. It is also reasonable to expect Concept 3 which use a different machine to grab and drag the rods to use about the same time. This is because they do the same high precision action that needs adequate time to position everything correctly for reliable results. However it should be noted that the retrieval at shear 51 are about 10 years old, and located before a machine that needs time to shear the cathodes. This means that it has no need to work any faster and might not work at its theoretical limit. With this in mind and improvements in the robotic field the last 10 years it is likely that a new implementation could use less time, but lacking alternative data the given time was used as a conservative estimation.

However gravity is constantly working on everything and require no time to position itself. Therefor Concept 1 needs less coordination than 2 and 3. All that is needed is to position one arm so that when it tilts the cathode, the rod slides into a funnel. A conservative estimate is that this would take up to 5 seconds faster to retrieve one cathode. But it is possible it is even faster and that would increase the overall capacity above the estimations made here.

5.4.2 Examination of the cost of automation

It is difficult to estimate what something will cost to purchase and install. And even more difficult to know what the energy prices will be in the future. Especially with high prices and an ever growing demand for energy in the world. The method applied to find believable estimations was to consult with the engineering department and ABB to get estimations for what their machines cost to purchase and operate.

The strapping machine used at the new copper line is the best and most expensive Signode provides. According to Nikkelverk it costs around 3 million and is estimated to use 50 000 NOK worth of energy every year. Taken into account that it is one of the best strapping machines on the market it is a possibility that a machine to 3 million NOK is over-engineered and will not be utilized to its theoretical capacity. Additionally the retrieval of cathodes to be bundled with the current system is relatively slow, and slower still based on the results from the simulation of the developed concepts. Though it might be needed in the event of an increase in demand for the product, otherwise production will not be filled to capacity. Also it does not have the capability of strapping bundles in two dimensions, an important requirement for the LME.

With this taken into consideration a cost of 3 million NOK is seen as a conservative estimate for the purchase and installation of a machine with lower capacity but with the ability to strap in two dimensions.

ABB, who produce the robotic arms utilized at shear 51, estimated that newer models of these machines would cost 2.5 million NOK to acquire and install. The salesperson also estimated that service, parts, travel expenses, etc. would cost 5 000 NOK yearly. However this might be somewhat underestimated with the current inflation rate. A representative from the engineering department estimated that these machines cost 25 000 NOK yearly in energy consumption for the company, each.

The desired result from the cost estimations was to find out which option in the evaluation matrix was cheapest to install and operate on a 10 year basis. The productivity of the concept was not taken into account in this estimation. Due to a lack of knowledge regarding the sale of the product, revenue from this was not taken into account either.

The results in Figure 4.3.11 corresponds with what was expected from the theory. High initial costs, but will eventually be cheaper compared to keeping manual labour over the same period. The graphs show that all the automated suggestions are cheaper after around 2 years. This is probably optimistic, but since the criterion is evaluated after a period of 10 years, there are then 8 years of buffer time. Manual labour rises by 5 million NOK more a year than the automated solutions and would therefore likely be more expensive than automating over a ten-year period regardless of whether the estimates are accurate or not. The construction time of a new system was not taken into consideration, it is a reasonable assumption that such a task will take up a considerable amount of the year. Then the time to recuperate the costs will increase by the installation, given that during this time no revenue is generated. If they don't pack somewhere else.

Because of the current traffic the automated solutions will either take as much or less space than the current manual labour. Available real estate is a problem for the company and no change or a reduction in the used space are desirable.

Calculations 5.2 show the maximum yearly cost or maximum initial cost that are allowed for Concept 2 if it were as expensive as manual labour after 10 years. The results show that if the initial cost is 7.5 million NOK then the yearly cost would be 14.37 million. However the actual yearly costs are probably not that much different from the estimations. So the maximum initial costs if the estimations are trustworthy would be 45.28 million NOK. This means that the budget could be blown by 35 million and still be cheaper on a 10 year basis. Because Concept 2 is estimated to be the most expensive proposal the other concepts would also be within these values. The evaluation of the criterion is then to be considered credible.

$$
\begin{aligned}
Current: & f(x) = 15.37x \\
Concept\ 2: & g(x) = 10.842x + 10 \\
\\
Max\ yearly\ cost: & f(10) = a \cdot 10 + 10 \rightarrow a = \underline{\underline{14.37}} \\
Max\ initial\ cost: & f(10) = 10.842 \cdot 10 + b \rightarrow b = \underline{\underline{45.28}}
\end{aligned}
\tag{5.2}
$$

5.5 Review of the evaluation matrix

The purpose of the evaluation matrix was to give a concise overview of the performance of the various concepts compared to the current system. Each criteria was given a different weight based on that criterion's importance, the value of each weight was chosen in dialogue with the company.

There were several considerations when choosing which criteria to include in the evaluation matrix, and how to evaluate them. What was important was that they represented the company's needs and values, but also reflected the principles for automation and production.

Productivity
The scores given by this criterion were based on the throughput of the developed concepts relative to the current system. The productivity of the developed concepts were based on the findings from the simulations, and the productivity of the current system was based on the findings from a simulation and the statistics. The results of these findings can be found in Table 5.3.1.

Every concept proved to perform considerably worse than the current system, therefore they all scored lower. As Concept 1 proved to perform slightly better then the other concepts it was given a score of 2 while the rest were given a 1.

Manual Labour
The main source of manual labour in the concept relates to the accumulation of rods and their removal. Otherwise the process is fully automatic and requires little to no manual labour. Concept 3 requires an operator to empty the basket the rods fall into. Likewise there are no set method of organizing the rods into the containers they are transported around in in Concept 1. Concept 2 were seen as the best option as it is a modified version of shear 51 which is fully automatic and require no lifting by the operators.

Economics
The scores given here are based on the findings shown in Table 4.3.1. Here it is made clear that the current system is by far the most expensive of the option over a 10 year period, thus all the concepts score higher than it. Comparatively there is little difference in cost between the concepts, but as Concept 1 is the cheapest it scores 5 while the others score a 4.

Downtime
All the concepts are better than the current system because the machine can go continuously. Concept 1 were judged as the best due to the fact that it requires the least amount of complex machinery which would also reduce the maintenance compared to concepts 2 and 3.

Scalability
Here the main questions was whether the bottlenecks of the system could be mitigated by increasing its capacity. To increase the capacity of the current system was considered to be practically impossible, as the amount of traffic would impede effective transport within and outside the system, worsen safety, and increase the number of operators. In addition the space required for such an increase is not present at the current facility. The concepts were found to be more space efficient, and the only bottleneck is with the retrieval process. Increasing the capacity of the retrieval process was found to be easier compared relieving the bottlenecks of the current system. As Concept 1 is the most space efficient it was given the highest score. Another way of evaluating scalability is by exploring the possibility of scaling up shifts. The developed concepts only require 2 operators, where as the current system requires 5. Because of the manual labour and number of operators it is currently not feasible to scale up the number of shifts. However the developed concepts need less physical activity and are therefor more accommodating to scaling up the number of shifts. Additionally 3 shifts with 2 operators are in total 4 operators less than 2 shifts with 5.

As shown by the weight of this criterion the differences between the different systems are less important than other factors such as safety. Even disregarding this criterion it did not play a deciding factor in the final score.

Flexibility
It was difficult to determine whether the concepts scored better or worse than the current system. The current system is more capable of handling errors such as loose straps or similar, but also requires little retooling in case of small changes to the products. On the other hand the equipment used in the concepts can be used to perform more complex actions such as alternating the orientation on the stacked cathodes. In addition the equipment used can also be repurposed for facilities elsewhere. In the end there was no clear winner, they all had their merits and were to similar to differentiate. Therefore they were given equal scores, both concepts and the current system.

Traffic and Safety
They are all judged as an improvement to the current system. Since no operators are allowed inside the automated machinery and there are no forklifts inside the building, the implementation would be better than how it is currently. However none of the developed concepts significantly differentiates itself for one another, therefore they were all given the same score.

As seen by the final score given in the evaluation matrix the concepts proved to be quite similar to each other, while leaving the current system behind. It was not surprising that the concepts scored higher than the current system as they were the primary focus of the thesis, but it might also point to bias in the evaluations. Concept 1 emerged quickly as the favoured option, this was reinforced by its productivity and economic considerations. In addition the difference between the final score of the current system and the developed results might appear much larger than it actually is, and there by give an exaggerated impression of its strengths and weaknesses. Despite the findings given here there is a reason why it has been kept as is for a while.

There are a couple of drawbacks to the use of evaluation matrices. Firstly, it is a simplification of a complex procedure. Whilst it gives an overview of the comparative strengths and weaknesses of different concepts, it does not grant much insight into details. Secondly it is dependent on the decisions we ourselves take making it more subjective than some might want. While the goal is to make it as objective as possible, certain points have to be decided on a subjective basis due to the nature of this thesis. The group lacks the ability to undergo first hand testing of any concepts which are developed, thus their effectiveness can only be evaluated on a theoretical basis. This means that they could potentially be quite different on paper compared to an actual implementation.

5.6 What would automation mean for the company

Automation would have several effects on the packaging. Most importantly it would increase safety by removing humans from moving machinery and reducing traffic in the area. Furthermore there will be space for additional safety measures. Figure 5.6.1 show how traffic can flow through the work area. The red lines are where forklifts will pass, the yellow line show where the pedestrians will walk. When the racks are gone there will be space for installing a door in the wall marked [1]. Behind this wall there are currently a small workshop where pedestrians can pass through.

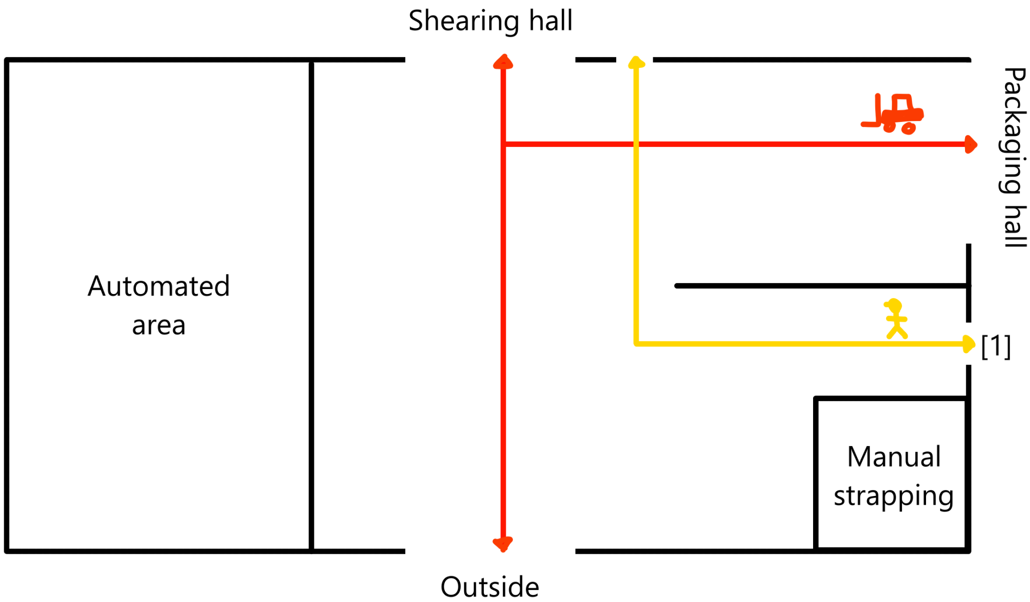


Figure 5.6.1: New and safer layout. Red are forklift traffic and yellow are pedestrians.

The implementation of an automated system would create jobs requiring a high degree of technical knowledge. This would encourage employees to pursue advanced degrees or certifications related to the automated system, to enhance their technical knowledge and advance their careers. In addition these employees would not be limited to working in one single area of the company, but could contribute elsewhere as well. This would increase the versatility of the employee and also increase the value of their contribution.

Table 5.6.1 shows different outputs depending on number of shifts in the week. The tons produced are found by multiplying bundles per hour from the simulations with the amount of hours in one shift, shifts in one week, and 50 weeks. 50 weeks were chosen because production are continued throughout the summer and are a round number. The weight of one bundle on average are rounded of to 1 ton to keep the math simple.

Currently they only work 9 shifts a week. Because of the loud noises coming from the shearing hall the operators need one half hour break every 2 hours. This results in only 6 hour shifts. If the process are automated a soundproof booth can be constructed for an operator to observe from. This would protect their hearing and operators only need 1 hour of break time.

The automated concepts only need 2 operators. With this reduction in workers it now is possible to implement a night shift. Keeping in parallel with how night shifts work at shear 51 the packaging would work almost continuously from Monday 06:00 to Friday 14:00 resulting in 13 shifts. The theoretical maximum output are also represented in Table 5.6.1 marked as 21 shifts in one week which is 3 shifts every day of the week.

Table 5.6.1: Different yearly outputs depending on number of shifts etc.

Process	Shifts a week	Work hours	Per hour	Tons a year
Current	9 shifts	6	15.25	41 175
	9 shifts	7	11.71	36 887
Concept 1	13 shifts	7	11.71	53 281
	21 shifts	7	11.71	86 069
	9 shifts	7	10.23	32 225
Concept 2 & 3	13 shifts	7	10.23	46 547
	21 shifts	7	10.23	75 191

Currently the company estimated that they produce around 46 000 tons a year on average. To achieve this some amount of packaging on overtime are needed when only 9 shifts are run weekly. Regardless of which concept are used. Table 5.6.2 explores further how many tons are packed on overtime and how many hours of overtime the workers are on the job. The *Equation* column shows how the hours of overtime are corrected for break time. This means that the column showing hours of overtime include the time the workers are on break and being paid. The next two columns show a full shift and a half shift and were found by dividing hours by 8 and 4. A full shift of overtime would typically be on a Saturday and a half shift would be done by the evening shift Monday to Thursday from 22.00 to 02.00. All the hours and shifts were rounded off to the closest whole number. In real life , the weekly packing capacity might be a bit lower, since routine maintenance has to be included in the cycle. This is not taken into account since the frequency of this requirement is not known.

Table 5.6.2: Overview of amount of overtime needed to reach 46 000 a year.

	Tons produced	Equation	Hours overtime	Full shifts	Half shifts
Current 9 shifts	4825	$\frac{4825}{15.25} \cdot \frac{10}{8}$	395	49	99
Concept 2 & 3 9 shifts	13775	$\frac{13775}{10.23} \cdot \frac{9}{8}$	1515	189	379
Concept 1 9 shifts	9113	$\frac{9113}{11.71} \cdot \frac{9}{8}$	876	110	219
Concept 1 13 shifts	-7281	$\frac{-7281}{11.71} \cdot \frac{9}{8}$	-699	-87	-

Concept 2 and 3 pack around 46 000 tons a year and are therefor excluded from the overview of overtime. However Concept 1 run on 13 shifts are included and show how many night shifts that are in excess at full production. There is therefor no need to run 87 night shifts. There are only

4 night shifts in one week, Monday to Friday, resulting in 21.75 weeks where no night shift are needed.

Night shifts are more expensive than day shifts and this has not been taken into account previously. If the extra pay night shift gets are 150% of original wages, the additional cost for keeping a night shift are just under 2 million NOK (Table 5.6.3). The table shows all the variables witch are multiplied together and presented under *Yearly Cost*. These numbers are higher than they actually would be, because the wages are derived from an average of the total cost of employees. This would include employer fees, cost of protective clothes and equipment, overtime, and salaries from the already existing night shift. Even with this conservative estimation, 2 million NOK is not enough to get the yearly cost of 10.842 million NOK over the maximum yearly costs of 14.37 million NOK from Calculation 5.2. Concept 1 which do not need to be run on overtime for 21.75 of the 50 weeks of the year will cost just over 1.1 million NOK extra yearly.

Table 5.6.3: Costs of keeping a night shift.

Pay	Extra	Operators	Hours	Shifts	Weeks	Yearly Cost
410	150%	2	8	4	50	1 968 000
410	150%	2	8	4	28.25	1 111 920

The developed concepts take up less space than what is currently in use. This means that it could be possible to scale up the retrieving process. This would increase the overall productivity, but further exploration of the feasibility of this has not been done here and are therefor out of scope.

One aspect that have not been explored due to the limitations of this thesis are the question of alternative locations. It may be be more beneficial to move the packaging to where the cathodes are grown. This is more in accordance with the theory. Now that the new copper facility are up and running there might be some space where the old one was. This would be right next to the nickel production, but evaluating the feasibility of this would require further work.

CHAPTER

SIX

CONCLUSION

Automation is an increasingly more important aspect of modern industry, and an important tool to increase safety of the workplace and health of the employees.

The results from observing the current system, measuring process times, and simulating the system show that the current system has a significant advantage in terms of productivity over the developed concepts. However the production requires a large amount of space, a sizeable number of operators, high variation in process time, and has several bottlenecks in terms of transportation between the work stations. Since the only bottleneck in the developed systems is the robotic arm in the retrieval process, the bundles will not have to wait for the process downstream to complete. In addition since the bottleneck is not spread out over the entire system it is much easier to handle and lessen its impact. The concepts also require fewer operators to maintain operation, and experiences little variation in process times.

The best option seems then to be Concept 1 even though the hourly productivity is less then what the current system provide. By moving from the current 9 shift a week to a 13 shift a week schedule. The yearly productivity will surpass what is currently possible. Because the company views safety as the highest priority automation seems to be a good safety project. Which also brings consistency to production and promotes economic flexibility and benefits.

Implementation of an automated solution would give the following benefits to the company.

1. Increase the safety of employees by removing the humans from unsafe areas and reducing traffic inside. A reduction in traffic also means that currently used space are freed up.
2. Because of the reduction in involvement of the packaging the operators can be better protected from hazardous sound levels. This means they require less breaks resulting in an hour more of work.
3. Fewer operators are needed per shift which reduce the cost of labour and allows for implementing a night shift. Because only 2 operators are needed in one shift there would only be 6 employees in total during these 3 shifts. Which are 4 employees fewer than what are currently working in one day.
4. Yearly productivity will increase when implementing 3 shifts a day. This gives the company greater flexibility when receiving orders and reduce lead time and the need for storage.
5. The implementation of an automated system would create jobs requiring a high degree of technical knowledge. Technical knowledge that can be useful other places in the company.

6.1 Further work

Because the company has better access to data and resources it is advised that further research are done about the benefits automation can give the company. This research should better utilize the possibilities of FlexSim to create more accurate simulations. Based on these new results a new evaluation should be done with the concepts from this project and new designs that are more specialized. This future project should test whether gravity is a reliable method of extraction when retrieving 11 cathodes simultaneously.

One aspect that have not been explored due to the limitations of this thesis are the question of alternative locations. It would be more beneficial to move the packaging to where the cathodes are grown. This would also be more in accordance with the theory. Now that the new copper facility are up and running there might be some space where the old copper packaging was, or other sites at the facility. This would be right next to the nickel production. Evaluating the feasibility of this solution are needed in future projects.

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APPENDIX

A

FLEXSIM

A.1 FlexSim 2023

FlexSim 2023 is a discrete-event simulation software developed by FlexSim Software Products Inc. It was initially released in 2003, and has since been continuously updated. It is capable of modelling systems from manufacturing to healthcare in a 3D environment (FlexSim 2023).

A.2 FlexSim 2023 Simulation

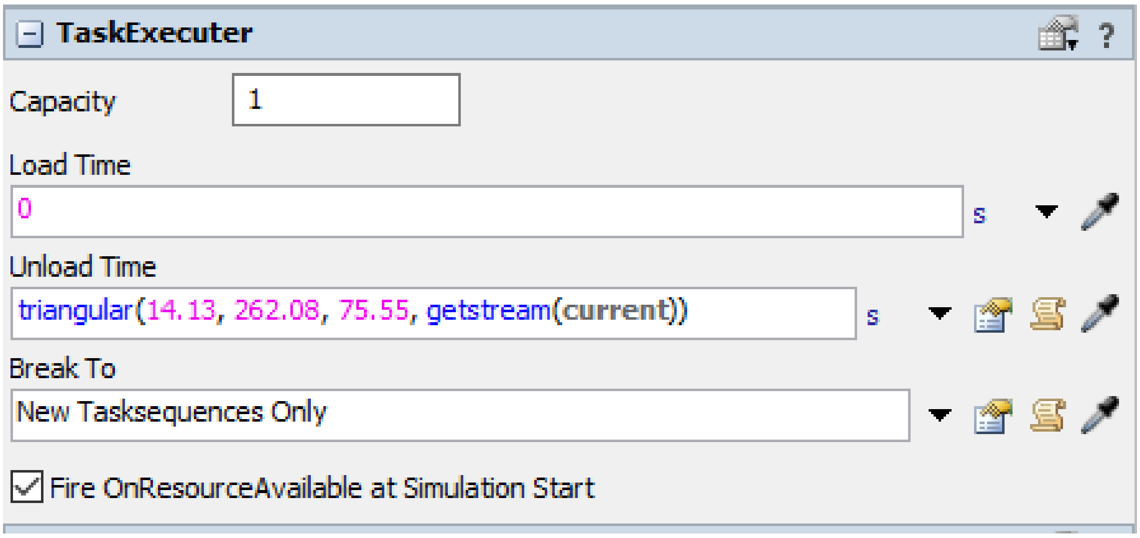

Figure A.2.1: Forklift A Setup in FlexSim 2023

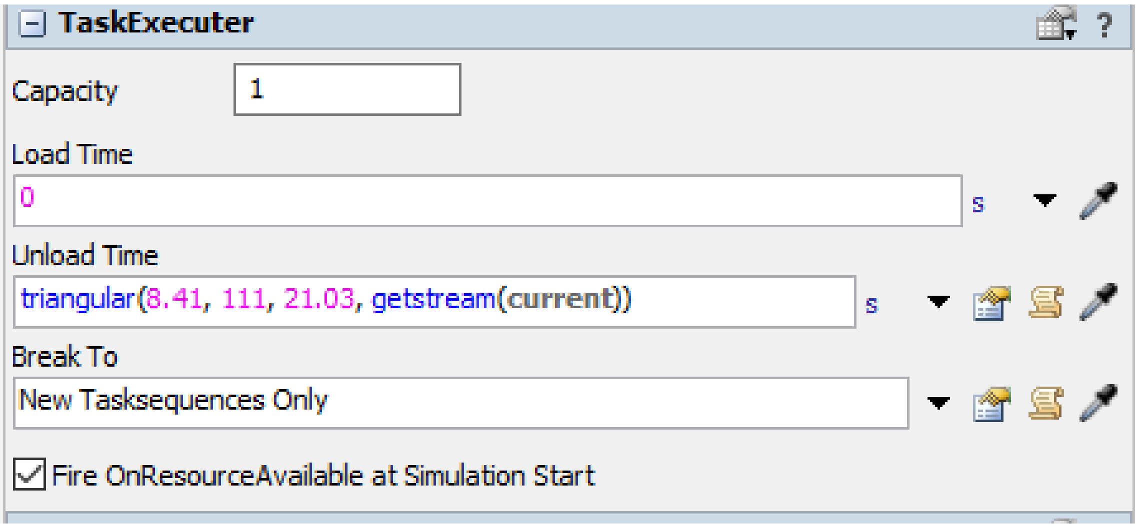

Figure A.2.2: Forklift B Setup in FlexSim 2023

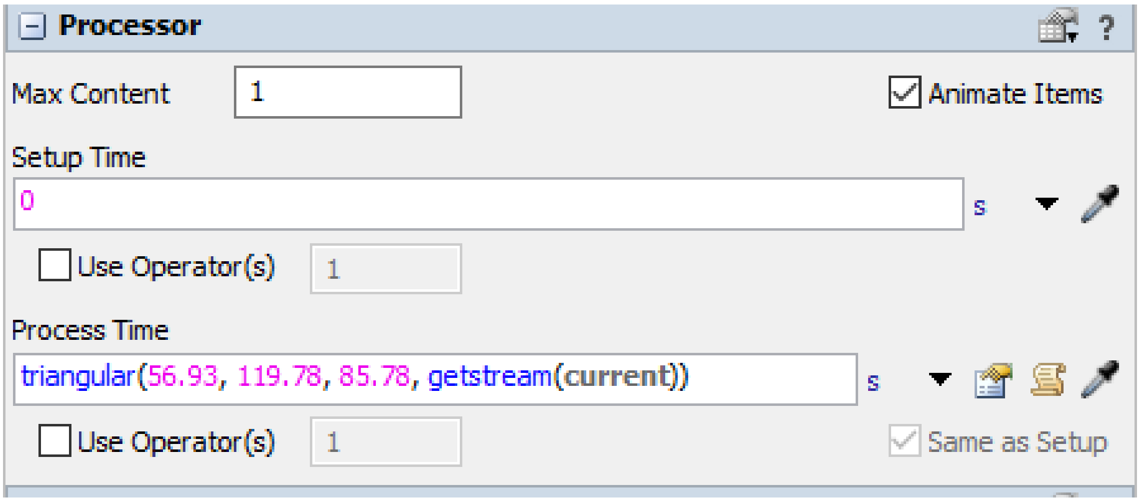

Figure A.2.3: Strapping Setup in FlexSim 2023

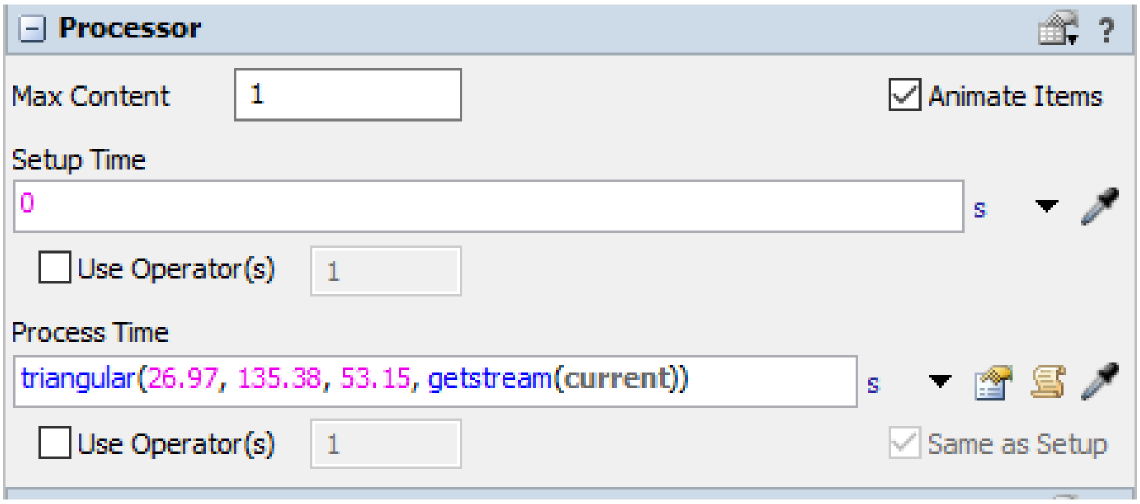

Figure A.2.4: Registration & Weighing Setup in FlexSim 2023

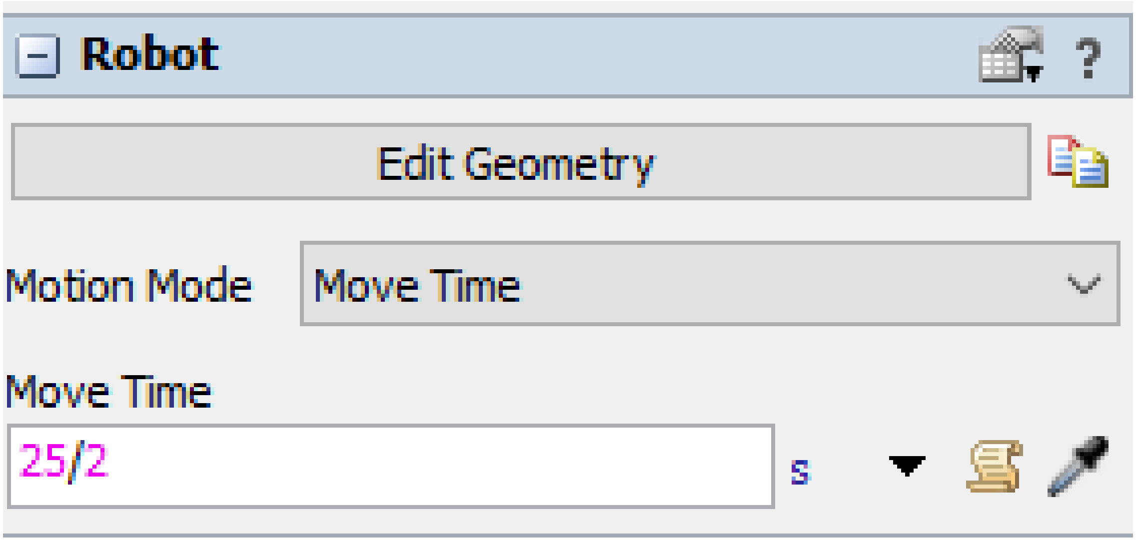

Figure A.2.5: Setup of the robotic arm (Concept 1) in FlexSim 2013

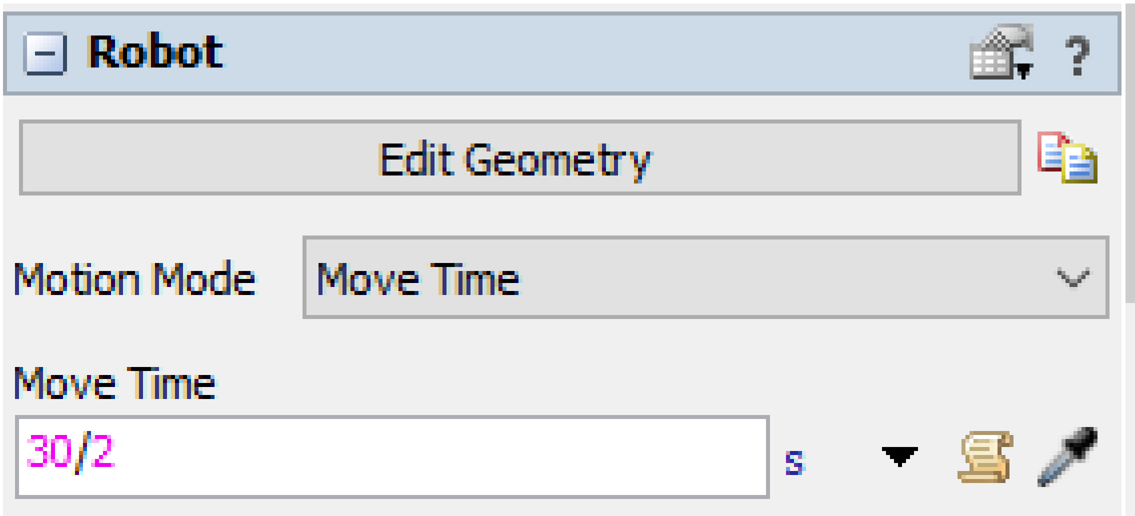

Figure A.2.6: Setup of the robotic arm (Concept 2 and 3) in FlexSim 2013

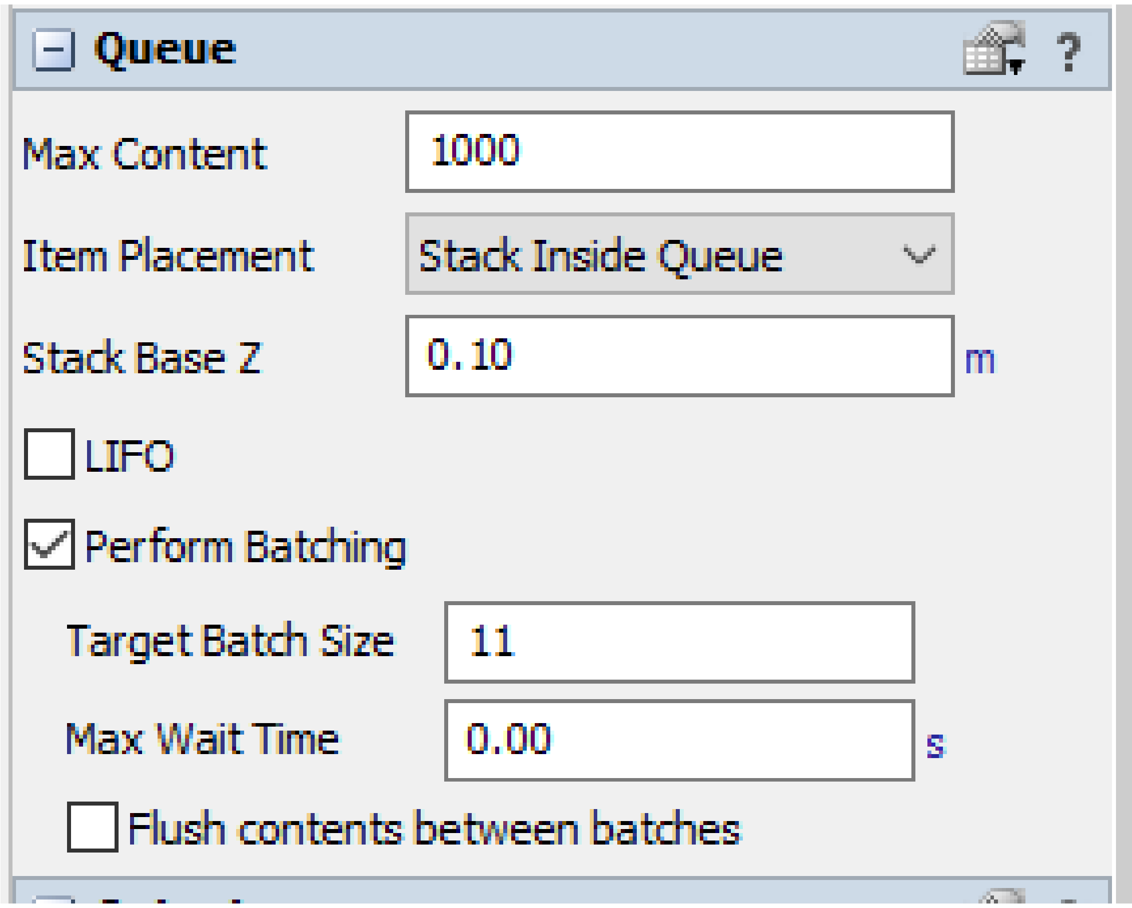

Figure A.2.7: Setup of the queue in FlexSim 2013

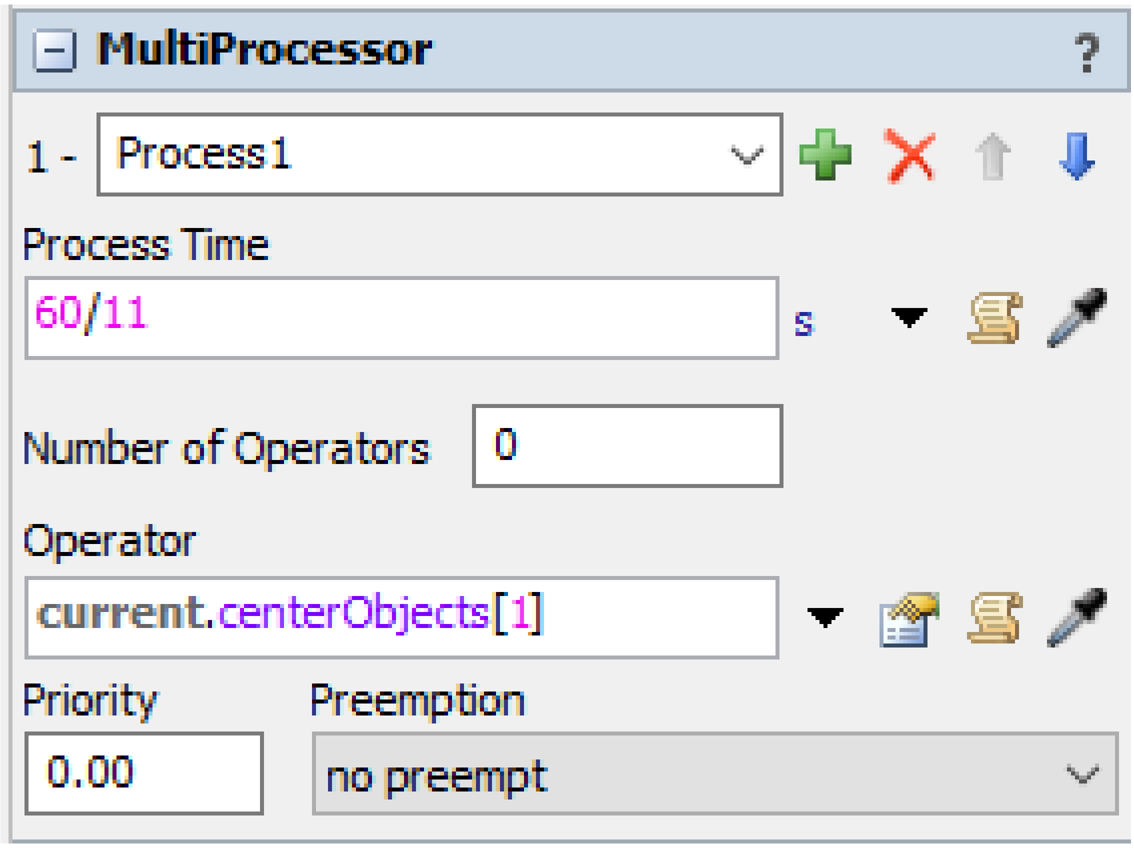

Figure A.2.8: Setup of the multiprocessor (Process 1) for the concepts in FlexSim 2013

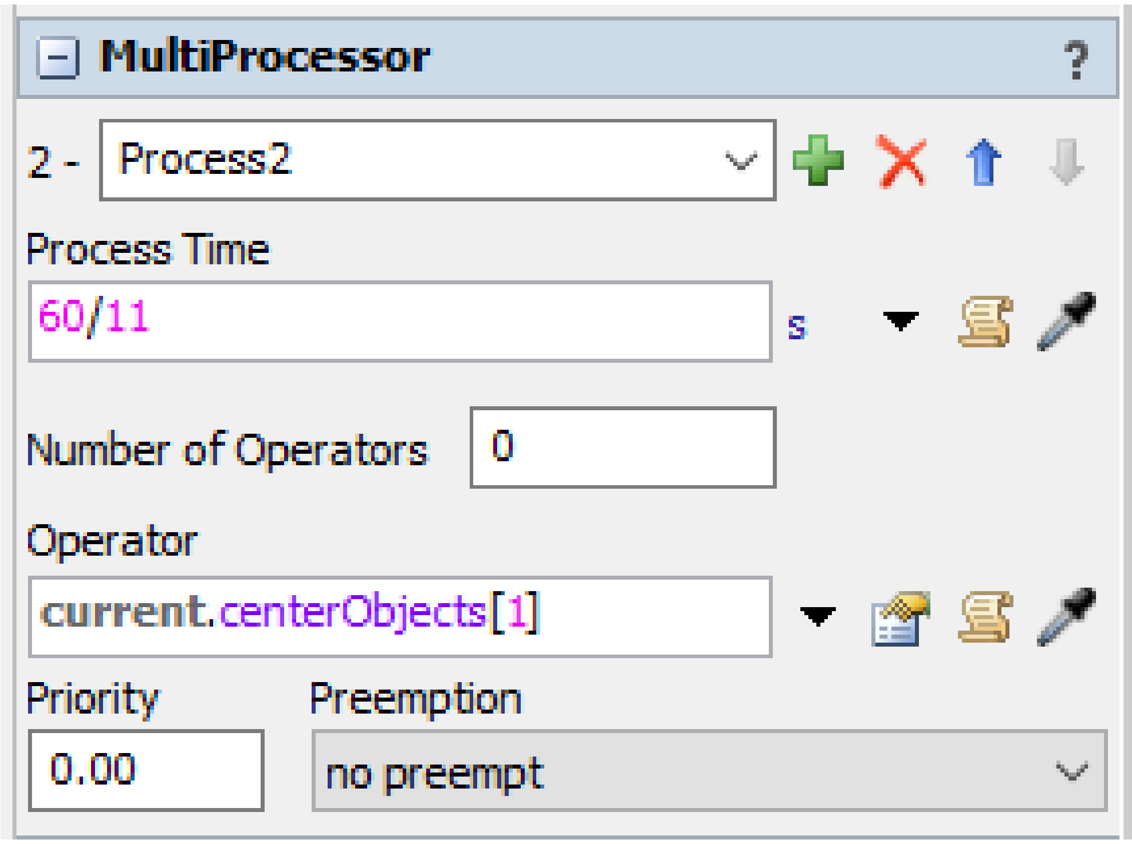

Figure A.2.9: Setup of the multiprocessor (Process 2) for the concepts in FlexSim 2013

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