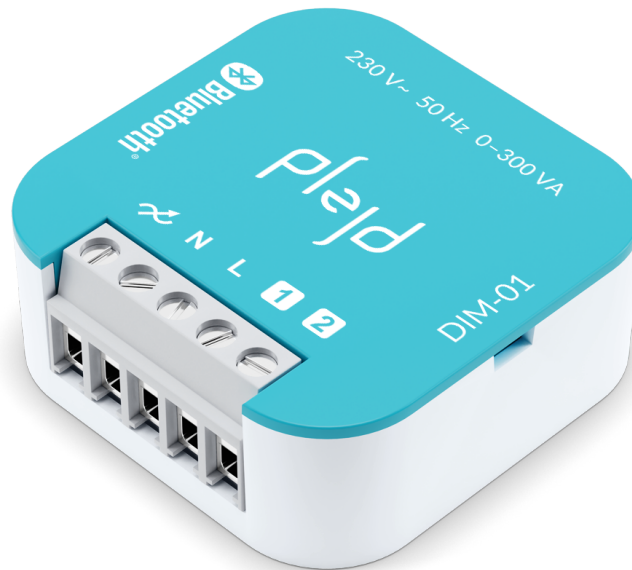




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Chalmers University of Technology

Packaging Automation: A Basis for Production Development at Plejd

Master's thesis in Systems, Control and Mechatronics, MSc

Eliott Ekelund
Emil Isaksson

DEPARTMENT OF ELECTRICAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2026

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MASTER'S THESIS 2026

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A pre study aimed at breaking down the steps needed to automatically fold the packaging, and finding complex elements when moving from a manual packaged product to an automated packaging station.

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Department of Electrical Engineering
Division of Systems and Control
CHALMERS UNIVERSITY OF TECHNOLOGY
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Supervisor: Marcus Hallberg, Plejd & Joel Berg, Plejd

Examiner: Petter Falkman, Division of Electrical Engineering

Master's Thesis 2026

Department of Electrical Engineering

Division of System and Control

Chalmers University of Technology

SE-412 96 Gothenburg

Telephone +46 31 772 1000

Cover: DIM-01: A Plejd 'puck', the product the packing line is planned to handle

Typeset in L^AT_EX

Printed by Chalmers Reproservice

Gothenburg, Sweden 2026

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Abstract

The project focuses on how to turn a manual packaging station into a fully automated packaging station. This is done at the company Plejd where their production of smart pucks is mostly in-house and almost fully automatic with the exception of the packaging station. The packaging station concept and ideas that are developed is meant to be used as a basis for further development of the project and explores different contractors for outsourcing but also what it would take to develop the station in-house. After an investigation of the different possibilities a basis is laid with a recommendation of concepts for how such a station could look. There is also a recommendation for what should be changed in the packaging to make the automation process simpler which would make development easier in-house and also cheaper to outsource.

To be able to evaluate concepts the project utilized Visual Components to visualize the flow of products through the concepts, and test different metrics to layout and evaluate project requirements.

The project found that the choice of concept depends on what Plejd is focusing on and if there is manpower for an in-house project then Plejd should work towards that. It was also found that this projects method or framework could be used for other packaging lines in their factory where different conclusions and data could be reused. It was also found that certain parts of the packaging needs to either be redesigned or completely removed to make the automation process easier.

Keywords: Modeling and Simulation, Packaging, Production System Optimization, Industrial Automation.

Project Acknowledgements

As authors we would like to thank Plejd for the opportunity to make the thesis at their company. We would also like to personally thank Marcus Hallberg and Joel Berg for being our supervisors at Plejd and guiding our work until the very end. We also would like to thank Sandra Kristensson who provided valuable insight into the packaging at Plejd and provided samples for us to use throughout the project. We would also like to thank SKF for the study visit which provided a professional insight into a packaging line that is online in there factory. Finally we would like to thank our supervisor and examiner Petter Falkman who helped us through our thesis with academic knowledge and ideas for the project.

Eliott Ekelund, Emil Isaksson, Gothenburg, June 2026

Personal Acknowledgements

To my parents Björn Ekelund and Petra Nordensvan Ekelund who helped me both professionally but also personally. I would also like to thank my little brother Linus Ekelund who has always been there for me in his own way.

Eliott Ekelund, Gothenburg, June 2026

To my siblings Lina Bergendahl and Simon Isaksson, thank you for your love and support, and for always believing in me. I would like to thank my mother Karin Stenström Isaksson for your guidance, love and support throughout my life. And for always answering my calls home, which helped keep me sane during my studies. And finally in loving memory of my father Lars-Åke Isaksson, thank you for your endless love and support. I would have loved to share this thesis journey with you.

Emil Isaksson, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms and words that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
AMR	Autonomous Mobile Robots
Component	An applied feature for example SCARA robot
CV	Computer Vision
DES	Discrete Event Simulation
DoF	Degrees of Freedom
DL	Deep Learning
Feature	Something that has a function in the system for example a folding mechanism or pick and place operation
IoT	Internet of Things
IQR	Interquartile Range
LLM	Large Language Model
MTBF	Mean Time Before Failure
MTTR	Mean Time To Repair
MVS	Machine Vision Systems
PLC	Programmable Logic Controller
Puck	Plejds most sold product category

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1

Introduction

During the last couple of years there has been a massive disruption to several supply chains around the world. From everything to the pandemic to several wars breaking out making shipments delayed or even canceled. This has given the need for an increase in domestic production of several areas.

One area which has had an increase in production is electronics manufacturing. This has been on the rise for the last 10 years in Sweden [1]. Given this the electronics production companies needs for reliable and fast pace production has increased. The fast development and the limitation of manual labor shows the need for automation and optimization of production flows are higher than ever.

The company Plejd is the leading smart home manufacturer and has been active for over a decade [2]. The production at Plejd are mostly done in-house with both product development and production being done at their headquarters. Plejds core product is the smart device called a smart puck with their production having a significant increase during the last couple of years.

The production line for the pucks are mostly automated with the exception of the packaging station. This is done manually today with prefolded packaging coming to the factory where the pucks are placed manually in a box. The prefolded packaging are seen as wasteful due to the fact that transport of prefolded packaging contains mostly air. Therefore an automated solution where the folding is done in-house is needed to be developed.

1.1 Aim

This project aims to find a framework that can be used to develop packaging stations for production lines. It also aims to develop a concept for a packaging station for the "puck" production at Plejd.

1.1.1 Research Question

- Does every part of the packaging need to be in one cell or is multiple stations needed?
- Is there a possibility of modularity where the system in the future can be used

and adapted into new production lines with different products.

- What problems arrive from the way that the product is currently packaged when moving to an automated solution?
- Can changes be made to how the product is packaged to make the automated solution with the goal of reducing complexity?

1.2 Scope

The project aims to develop a framework and later use that framework on a case study at Plejd for their puck production.

The framework developed will only regard systems with products that weigh less than 20 kg.

In the framework there will be no major prototyping and/or real life testing included and it will only be simulated.

The framework will not handle any palletizing solutions for the packaging or products.

2

Theory

The theory chapter aim to provide readers with the necessary information to understand the technical terms in this thesis paper. It also aims to present the state of the art of packaging production and necessary features.

2.1 Description of a Concept

A concept can be many things in the scope of system development. To narrow it down the project has defined a concept as something that consists of a list of features, layout, technical data sheet and a summary of the evaluation.

2.1.1 List of Features

The first thing when designing a concept is to list all the features. A feature in this sense is something that has a function in the cell for example a folding mechanism or pick and place operation. This is also seen later in the functional analysis section where it is described more in detailed on how this can be done.

Worth noting is that the list does not have to be a regular list it can also present itself as a flowchart for example. The main function of this is to have an understanding of how the concept should work.

2.1.2 Layout

In a concept the layout should be a clear drawing of the different features in the cell. The layout should also roughly be to scale so it is easy to see how much space the different features will take up. It does not have to be exact but it should be close to the real size.

2.1.3 Technical Data Sheet

In the technical data sheet there should be information about the different components that should be in the system. The project defines a component as a feature that is applied for example a SCARA robot.

The data sheet should include a rough estimate of the final data for the component. The data presented should be sufficient for a fairly accurate simulation and evaluation. The data should be based on real life example if it is possible.

If the component is developed in-house or if there is insignificant data where for example a machine needs to be tailor-made then a set of requirements should be set on the machine. These requirements should be so that the flow of the concept will be rather smooth. Further information about the specifics for the machine will be presented in the concept report if this is the case for a component.

2.1.4 Concept Report

The concept report should be a description of the concept and how it works. It should also include a short motivation why the concept works or does not work according to the requirements of the concept.

2.2 Systems Engineering

To approach the problem the project has taken the approach of systems engineering into account. The main footprint of the systems engineering concept was taken from the course "SSY046 Systems engineering" at Chalmers [3].

2.2.1 Functional Analysis

A functional analysis aims to provide a clear understanding of what process should be done in a system [4]. A packaging station will have different operations that need to happen in a specific order which can easily grow in complexity. The problem that the functional analysis aims to do is to organize all the tasks in the station and in what order they should happen. This also helps to highlight potential problems that come with these different tasks which then can be added to a morphological matrix which is described in the chapter below.

2.2.2 Morphological Matrix

After an analysis of the system has been done then a morphological matrix can be designed. A morphological matrix is used to help with development of concepts. The first step is to identify different features in the system. A feature can also be seen as a problem with the system that needs to be solved. When all the features have been identified solutions to those problems are made and put in the matrix. After the matrix is filled new concepts can be found by combining the different solutions. An example of this can be seen in Figure 2.1.

Feature 1	Feature 2	Feature 3	Feature 4
Solution 1	Solution 4	Solution 9	Solution 14
Solution 2	Solution 5	Solution 10	Solution 15
Solution 3	Solution 6	Solution 11	Solution 16
Solution 4	Solution 7	Solution 12	Solution 17
Solution 5	Solution 8	Solution 13	Solution 18

Figure 2.1: Example of a morphological matrix

2.3 State of the Art

The state of the art on a market level was analyzed this section aims to present those findings. First an analysis of how the market handles manufacturing of packaging material is done. Later the machines in the cell is analyzed where it is found that the cells machines can be split into two main features. Those features are a packaging folding machine and a pick and place machine. Lastly a market analysis is done on traceability and quality control of a packaging cell.

2.3.1 Manufacturing of packaging material

This thesis does not focus on the development of packaging materials, however this section aims to explain the production method used for the box that will be used in the Plejd puck case. The process used for the packaging is called die cutting. When using the process of die cutting the operator or machine uses something called a die to cut out a shape in the paper [5]. The die may also have non cutting elements in it to create something called crease lines. These lines create areas which are easier to fold. In Figure 2.2 you can see the cutting line which has cut a trace around the packaging, and the crease lines inside the packaging stencil



Figure 2.2: Pakend - 2015 - Pärnu Museum, Estonia - CC0. [6]

2.3.2 Packaging Folding Machines

On the current market there are several solutions for packaging folding machines. These solutions can be split into two different categories. The categories are robotic solution that usually use a robotic arm to fold the packaging and mechatronic solutions which does not use any robotic arm to fold the packaging which instead uses sequences of linear motions with pneumatic, electric or hydraulic solutions.

What usually is common between the two solution is how the packaging material is loaded. The way that the machines are loaded are with a magazine solution where the packaging material is placed either successively or loaded with some sort of mechanism. When it is loaded the material is then taken from the magazine either from the top or bottom. The most common solution is that it is taken from the bottom.

The robotic solutions that was found usually had the packaging be larger and less complex [7][8][9]. These robots function could be broken down to the robot picking up the packaging and then either having an end effector that folded it in the air or having the robot picking it up with suction cups and then guiding it through a rail that would fold it automatically. At the end of the folding sequence and after the items had been placed in the package these was usually taped with a automatic tape roller.

The mechatronic system on the market usually uses pistons or stamping machines that goes through different geometries to fold the packaging [10] [11][12]. From these solutions the bigger folds on the packaging would be stamped into place while the smaller folds as previously mentioned would be pushed in with a piston. Some of these mechatronic systems would have geometries that the machine would push the packaging through similarly to the robotic solutions.

Some of the mechatronic solutions would also have a step where glue was applied to

the packaging while it was folded through different geometries on a conveyor [13].

2.3.3 Pick and Place Machines

Pick and place is an operation where an object is picked from one position to another. This could be anything from moving an object from one conveyor to another, or picking finished products into a box. This operation is either done by humans or robots based on speed, the complexity of the operation or level of automation. At the time of this report the primary robot types supplied by industrial robot manufacturers such as ABB, KUKA and FANUC are delta, scara, articulated and collaborative robots [14][15][16].

2.3.3.1 Delta robot

The different types of delta robots that was found was usually picking from one conveyor and putting it in a carton or onto another conveyor that both was level to each other. This robot operates at 4 Degrees of freedom (DoF) and is therefore good at simpler pick and place operations.

The pros of this robot is that it is very fast and highly accurate [17]. It also has quite low gross weight and is reliable in the long term.

The cons of this robot is that it can only handle smaller payloads and it has less flexibility [17]. It also has a restricted workspaces and uses complex algorithms to operate it.

2.3.3.2 SCARA robot

Similarly to the delta robot the SCARA robots that was found usually picked and placed a from one conveyor and put it into another carton on another conveyor that was level with the other conveyor. This robot also works with 4 DoF and is also good for simpler pick and place operations.

The SCARA robots pros is that it has a rather small footprint and is good for high speed operations [17]. It also is good with operations that is repeatable and has a good price/performance ratio. Another thing is that it has quite few joints which makes it quite easy to manage.

The cons of the SCARA robot is that it has restricted motion and is less flexible than other robotics [17].

2.3.3.3 Articulated Robots

The articulated robots are highly flexible with 6 DoF. Articulated robots are usually used in cells where there are no human interaction due to the fact that there are no safety features that stops the robot in case of collision with humans.

The articulated robots pros are that it has a large workspace with a rather small footprint [17]. It is also very flexible and with a high operating speed as previously

mentioned but not as fast as a delta or SCARA robot.

The cons of the articulated robots are that they are more expensive than its counterparts [17]. It also has more components which makes it more complex to operate.

2.3.3.4 Collaborative robots (COBOT)

The COBOTs were found to be used in lines where human interaction with the line was done. Given that there are humans close to the line these robots are equipped with a safety measure to not hurt humans. These robots are usually highly flexible with 6 DoF.

2.3.3.5 Cartesian/Gantry robot

The Cartesian robot is usually used for very simple lines where similarly to the delta and the SCARA robots the conveyors are level and it picks and places from one conveyor to another. The cartesian robot operates at 4 DoF.

The pros of cartesian robots is that they are quite fast and accurate and can handle heavy payloads [17]. They are also rather simple which makes them easy to handle.

The cons of the cartesian robot is that it has quite a restricted workspace which makes it less flexible than its counterpart [17]. It also has a big footprint which might make it inconvenient in a line with restricted space.

2.3.4 End Effectors

All robotic solutions have one thing in common and that is the need for end effectors. There are two types of end effectors that stand out from the other end effectors and that is suction based and paddles [18].

2.3.4.1 Suction Based

The suction based end effectors work by generating a suction with a vacuum to pick up the load [18]. These are often used in where loads are not very heavy with flat and airtight surfaces. This end effector is also quite agile as if the end effector has quite a small chance of collision.

2.3.4.2 Paddles

This end effector works as a hand would and grasps the item either from above or from the side [18]. Here the max weight of the load is set by the amount of force and friction the different paddles can generate. Given this there might be some damage to the product if the paddles need to do certain lifts. Given the size of the paddles it can also be very collision prone and therefore have a very specific pattern to access the load.

2.4 Level of Automation

When designing a production cell in general there is some things to keep in mind. An especially important detail to keep in mind is the level of automation needed for the cell. For example is the cell going to be human operated in any way or is it going to be fully automated. The level of automation can be seen as how much human interaction is needed for a cell. Where the level of automation is inverse proportional to human interaction needed in the cell. When evaluating the level of automation in a production cell two sides should be considered.

One side is what is going on inside the cell. Will there be operators manually handling the product or will it be a fully autonomous machine handling the product or is it something in the middle.

On the other side is how the cell is interacting with the outside. Will it be manually loading of materials for the robot cell or will there be different kinds of Autonomous Mobile Robots (AMRs) that will be handling the materials that are loaded.

2.5 Layout design

In the literature there are several different layouts for production cells presented. The different layouts that was found can be split into two ways of thinking. The first is how the flow of material is distributed and the other way is the shape of layout.

2.5.1 Flow of Material

The flow of materials can be split into two major categories in a production cell. These categories are serial line segment and parallel line segment [19].

The flow for a serial line segment can be seen as a straight line where the products are going through each machine one by one. This is similar to a queue and this can lead to the system being starved or blocked if there is a failure in one of the machines [19]. The structure of a serial line segment can be seen in Figure 2.3.

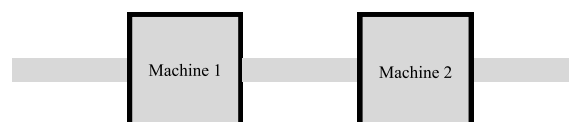


Figure 2.3: Serial line segment flow visualized (Authors own image).

The other type of flow is parallel line segment flow and it works by splitting the flow of materials into two separate lines. On each side of the flow there is the same machines which makes the flow much more efficient due to the fact that the problem of blocking or starving the line is minimized [19]. This parallel line segment flow is visualized in Figure 2.4.

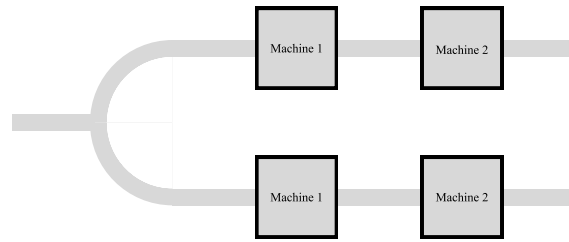


Figure 2.4: Parallel segment flow visualized (Authors own image).

2.5.2 Shape of the layout

In a manufacturing cell there is usually four different shapes of the layout. Those shapes are U-shape, S-shape, straight line and circular shape and can be seen in Figure 2.5, 2.6, 2.7 and 2.8 [20]. From these several more shapes of layout can be made such as a L-shape which is basically two straight lines.

Straight line shaped layout is used when the line is short and rather simple with there usually being a small amount of machines [20]. A S-shape layout is used when you have a longer line that has many stations. An U-shape layout is used for compact designs where there is a need to keep the line small in length and width. Finally a circular layout is used when finished products need to be returned to the starting point of the line.

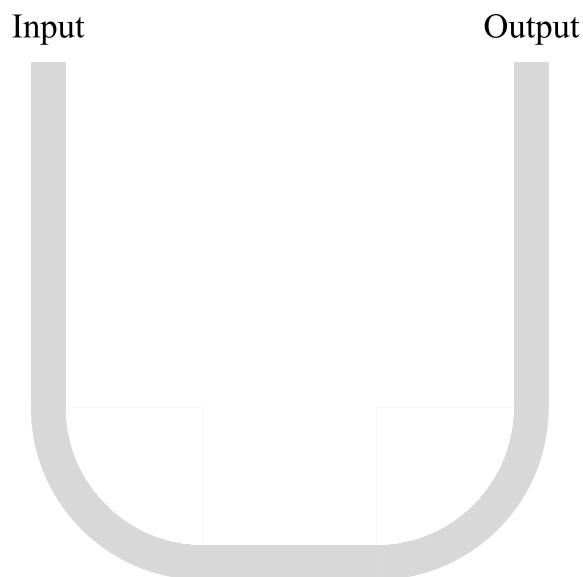


Figure 2.5: A visualization of the U-shape.(Authors own image)

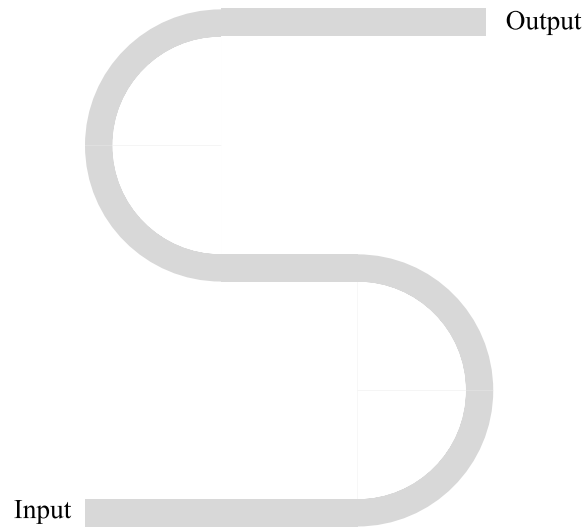


Figure 2.6: A visualization of the S-shape (Authors own image).

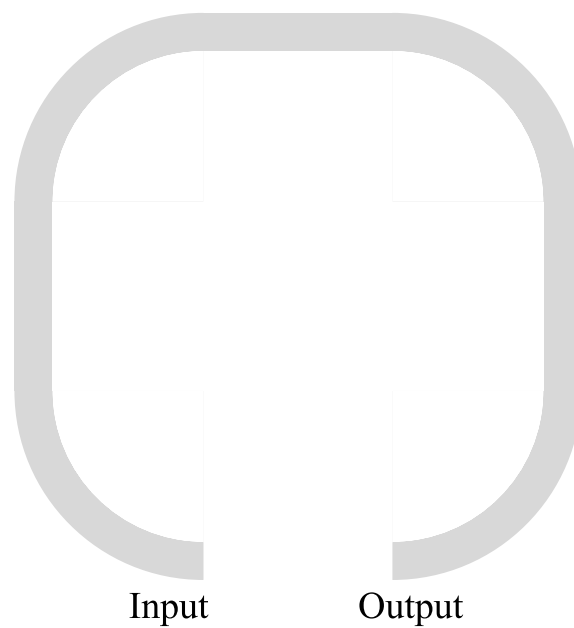


Figure 2.7: A visualization of the circular shape (Authors own image).



Figure 2.8: A visualization of the straight line shape (Authors own image).

2.6 Ergonomic and Safety Design

When designing a production system it is necessary to follow local regulatory standards but also have an ergonomic design for potential operators.

The regulatory standards are different around the world so it is important to find the right one. For example the swedish standards can be found at the swedish institute of standards [21].

If there is a need for operators it can also be a good idea to think about the ergonomic aspect when designing the system. To start that process it can be good to think about where the operators are needed and how they are going to interact with the system. For example if there is an operator working from outside the cell and is loading materials then the loading station should be accommodated so the loading is done in an ergonomic way.

Furthermore when thinking about ergonomics it can be easy to only think about the stress in the body from doing physical labor. This is good to have in mind but there is more factors to an ergonomic design. There is also a need for auditory and visual ergonomics where different light and audio levels have to be taken into account.

2.7 Simulation and Visualization

Simulation and visualization software is used to better understand the flow of entities and how they interact with resources. These flows can be anything from a logistics hub to an airport or in the case of this thesis a packaging station. This chapter aims to provide basic knowledge on the use of simulation and visualization software.

2.7.1 Level of Detail

When developing simulation models, a core component is how detailed the simulation should be. This is because the more simpler the model is the faster it will run [22], and the more complex the calculation the longer it will take to compute. The level of detail in the simulation needs to be determined based on the purpose of the simulation. A highly detailed model could be good for showing how products might flow and be handled by the various machines. While a lower detailed model could be better for simulations on how the system performs during a longer period of time. It is up to the designer of the model to determine what is important for their mission objectives with the model and what tradeoffs are needed.

2.7.2 Discrete Event Simulation (DES)

A common method of simulation in industry settings is the discrete event simulation (DES). Anders Skoogh describes that there are four cornerstones in DES, these are that the model is Stochastic, Dynamic, Discrete and event oriented [23].

Stochastic models introduce a form of randomness with the use of probabilities. These probabilities are based on statistical distributions [23]. Examples of statistical distributions are normal, exponential or uniform distributions. These distributions can be used to model things such as machine breakdowns.

A dynamic model means that the model is not time invariant and that it might give

different results each time you run it[23]. An example of this could be at what time a machine breaks down. If the machine is empty it might not affect the system, and if the machine has a queue it might starve the rest of the system.

A discrete event model is a model that is not continuously recalculating the model and instead recalculates when an event triggers [23]. Events can be things such as when a product arrive to a machine.

An event oriented system are systems designed by humans where changes ar based on discrete events [23]. This is in contrast to change oriented systems which have continuous changes and are often based on formulas from physics and mathematics.

2.7.3 Bottleneck analysis and failure conditions

Another key use for simulation models are for bottleneck analysis. A bottleneck is an operation that limits the flow of products. Since many simulation software's often have visuals that show the position of products in the production system, if there is a pile up of products before a machine then the bottleneck is probably there.

Simulation models are also good for testing different failure conditions and how they might affect the production system. Examples of failure conditions could be the amount of defects (also know as yield), Machine breakdowns and repair times are a few examples [23]. The use of these in the model depends on the aim of the simulation model

2.7.4 Different programs and their use cases

There are many different simulation tools that can be used when designing a packaging station, or any type industrial application. This project has identified two simulation software's that are of interest. These are Tecnomatix Plant Simulation from Siemens and Visual Components. These programs are similar but have a few differences and use cases. Tecnomatix Plant Simulation offers a simulation software that can provide detailed models, but also simpler models that can be used for easy simulations over longer time periods [24]. This good for things such as long time run tests with parameters such as mean time before failure (MTBF) and mean time to repair (MTTR). Visual components offer easy plug and play solutions for machines and robots with good visualization of the flow of products, with the capacity to do longer simulations [25].

Other programs such as blender can be used as they offer good features for doing visualizations but also some simulation in regards to fluids and rigid bodies [26] [27].

2.8 Traceability of Products

According to international standards traceability means that the products history, application or location by recorded identification [28]. This means that there is a need for a system to track each products in a manufacturing setting. This can be

done in various ways and with the rise of industry 4.0 means that more and more companies are using Internet of Things (IoT) solutions for traceability systems [29].

The traceability of a product can be split into two major categories of direct and indirect marking [29]. The direct marking is when the products surface is marked and this can be done by either applying some type of paint or engraving a marking with a laser. Indirect marking is when a separate part is applied to the product as an identifier this can for example be a label of various materials. In recent years it is also become more to use RFID which is also seen as an indirect marking method.

2.9 Quality Control of Products

Quality control is used to keep the quality of the product at a desired level [30]. It by works by gaining feedback from a certain characteristic of the product and then looks for any deviation from the standards in those characteristics.

The most common way to do quality control on products today is through combinations of IoT solutions [31]. This can include Computer Vision (CV), Machine Vision Systems (MVS), Machine Learning (ML) and Deep Learning (DL).

Both ML and DL are part of the umbrella term Artificial Intelligence (AI) [31]. The way it works is using existing data from the manufacturing line and trains on it using DL and ML techniques. If there is no existing data a way to gather that data needs to be set up where for example an operator or technician needs to manually gather data for the different models. ML and DL is often used in combination with CV where algorithms are used are train on certain images and then image recognition is used to find defect products.

Another way to implement quality control with IoT solutions is to use a MVS. MVS uses image processing to find faulty products through a set of rules and parameters [31]. The main components of a MVS is illumination, image capturing and image processing. The way it works is that the image is capture and is transformed into a set of numbers which can be analyzed using image processing algorithms.

For CV to work well a good level of illumination is needed for the image capturing to have a high quality image.

3

Methods

The project follows the following framework that was developed during the project. The framework can be seen in the flowchart seen in Figure 3.1.

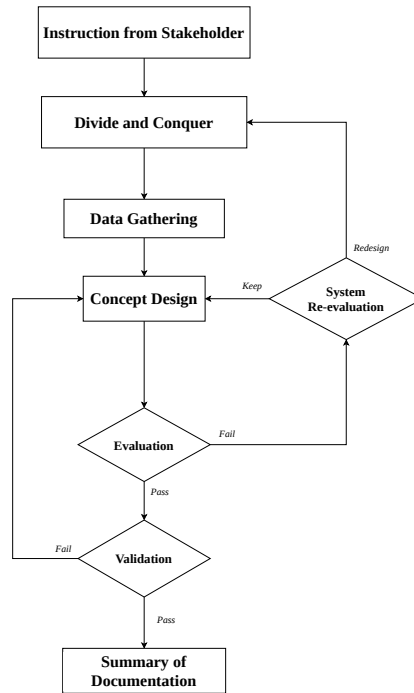


Figure 3.1: A flowchart of the framework presented (Authors own image).

The different components seen in Figure 3.1 will be described in this section.

3.1 Instruction from Stakeholder

The first stage of the framework is the instruction from stakeholder stage. During this stage the different specifications are given and discussed with the stakeholder. These specifications could be anything from the total size of machines or stations

to the expected throughput of the station. Factors such as time is also crucial. Detailed information from the stakeholder is important to ensure an aligned vision between developer and stakeholder [32].

A stakeholder is defined in this framework as the party that issues the project. This can be everything from a boss, teacher or even an external party like another company wanting a system.

Once an agreement with the stakeholder is reached the project can move on to the next stage.

3.2 Divide and Conquer

During the divide and conquer stage it is all about breaking down the problem. This is done with a functional analysis. To make the functional analysis easier it is a good idea to manually fold the packaging a few times to really understand the different steps.

After the packaging has been analyzed it is a generally a good idea to start from a high level and breaking the packaging into the most basic functions. The understanding of the basic functions can be seen as a black box but for the start of the divide and conquer phase it can be good to really understand what functions are needed.

After the different basic functions have been found the black boxes can be opened up and treated as their own problems where a functional analysis can be done with each black box. During this part of the process it can be good to find the different features needed.

An example of the whole process can be that the black box is initial folding and a feature in that can be folding of carton.

3.3 Data Gathering

After the divide and conquer phase the next phase is data gathering. This phase aims to improve the knowledge of the project and to then later use the data gathered in decision about the different subsystems during the concept design phase.

When gathering data it can be a good idea to have a spreadsheet where the data is put where it can be evaluated. Here it can be good to use different statistical methods to evaluate the different machines to gain an understanding about the different metrics to gain insight in the decision making process for the different machines.

During this process there might be some contact with different companies and then it can be a good idea to have an open and clear dialog about intent.

During this stage there might be revelations about different machine needed to be tailor-made to the product. If this is the case then sufficient amount of data can be difficult to collect. Here it can rather be good to gather data about different companies that make these type of solutions and investigate if they can make machines that are tailor-made to the product in the project.

If there is tailor-made machines needed for the project then there should also be a clear set of requirements that can be used to find tailor-made machinery from the companies found.

3.4 Concept Design

The next phase is called the concept design phase and during this phase the concept is developed. This phase is the start of an iterative process where if a process fails the process starts over here.

The first step of this phase is to make a conceptual layout design. The conceptual layout design should have a rough sketch of how the layout will be arranged. In a conceptual layout design there is no need for exact measurements but it should be based in some reality. Here it can be a good idea to consult in the data gathered to have an insight in the proportions for the different machines.

The next step in this phase is to create or evaluate a morphological matrix. If it is the first time entering this phase then it is a good idea to create a morphological matrix for the different subsystems found in the divide and conquer step. If it is not the first time entering this phase it can be a good idea to reevaluate an existing morphological matrix or it can be a good idea to found a new solution in the existing morphological matrix. When making the decisions it can be a good idea to look at the data and try to find something that seems to fit the specified metrics. Worth noting is that the matrix should have solutions that are rather open ended. So for example if the subsystem is a pick and place operation the solution should be which type of machine should be used not which model of machine.

After the morphological matrix is done it is time for feature application. During this step the different solution or features found should be applied to the conceptual layout. The end result should a layout with an added level of realism where it is roughly to scale.

3.5 Evaluation

During the evaluation phase the concept design is evaluated analytically. During this phase the requirements found from the stakeholder is evaluated and if they are not met then the processes goes back to the concept design phase where a new solution is needed to be found.

Worth noting during this phase is that the evaluation of the requirements are absolute and if one fails the entire project goes back to the concept design phase.

Another thing worth noting is that the requirements provided by the stakeholder should be clear and should give a fair representation of features that should be evaluated. For example a clear metric could be lead time of the system or area of the footprint.

3.6 System Re-evaluation

If the evaluation phase is failed then the next step is system re-evaluation. During this phase the system should be questioned and re-evaluated. During this phase there is two major points of order to re-evaluate. The first point is packaging design and the other point is the overall system.

If the evaluation is failed then the first step is to evaluate if the packaging need any changes. Here it is a good idea to look into the limitations of different machinery or if there is just a need to scale down complexity for application of autonomous solutions.

The second step is to evaluate the current system. During this phase the system requirements are evaluated and discussed with a stakeholder. This can be for example the level of automation or the footprint.

3.7 Validation

If the evaluation is passed then the next phase is validation. As the name suggests the concept is validated here and it is done so using simulation software. This software can be everything from different rendering software to discrete event simulation (DES) software.

The goal of the validation is to validate that the flow is possible. Therefore the software need to have some sense of realism with a physical engine.

As with the evaluation phase if the concept fails any requirement then the process goes back to the concept design phase.

3.8 Summary Documentation

Once the concept passes both evaluation and validation the concept is finished and can be presented. During this phase the concept should be presented according to what a finished concept needs to include and can be found in Section 2.1.

4

The Plejd Puck Case

To apply the framework that has been described in Chapter 3 a case was made at an electronics company in the Gothenburg area. The stakeholder was the electronics company called Plejd and they provided a set of specification for this station. In this chapter Plejd will be referenced to as the company.

4.1 Instruction from the Company

The technical requirements that the electronics company gave can be seen in Table 4.1.

Technical Requirements			
Lead Time (s)	Setup Time (s)	Refill Time (s)	Footprint (m^2)
5	600	120	16

Table 4.1: A table that shows the technical requirements for the different concepts.

There was also a requirement that there was a rather high level of automation inside the station with a potential operator working from the outside inputting and offloading materials and products.

There was a request by the company to have the different components in the system to be from companies that were able to do maintenance on the components. This was needed to mitigate the need for in-house resources being used to maintain the components. This was however only a request and if there is a need for either a machine with no maintenance support or the need to develop in-house solutions then that was okay with the company.

4.2 Bill of Materials



Figure 4.1: All the parts that go into the packaged product (Authors own image).

In Figure 4.1 all the different components that make up the packaged product can be seen:

- The sleeve that wraps around the packaged product can be seen in top left of Figure 4.1
- The smart puck product can be seen in the top middle of Figure 4.1
- The die cut trace that folds into the packaged box can be seen in the Right part of Figure 4.1
- The three different stickers and leaflets can be seen in the lower left part of Figure 4.1

4.3 The Current Packaging

The current packaging has several steps and is as previously mentioned assembled by hand. An image of the unfolded packaging can be seen in Figure 4.2.



Figure 4.2: A picture of the Puck packaging unfolded (Authors own image).

The current assembly process of the packaging is divided into six steps and can be seen in Section 4.4 in Figure 4.4. The packaging however can be seen as it is in four different states. Those states are raising of packaging, folding of insert, top folding and sleeve applicator. These states can be seen in Figure 4.3.



Figure 4.3: A picture of the four folding states (Authors own image).

4.4 Problem Identification

As mentioned in the framework the problem at the electronics company was broken down to the basic functions in the form of black boxes. This can be seen in the flow chart in Figure 4.5.

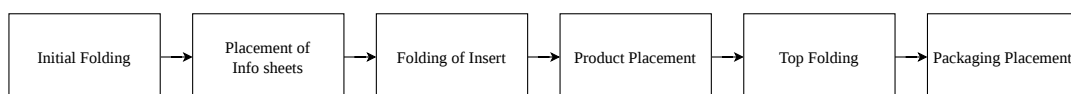


Figure 4.4: Flow chart of a high level analysis of the system (Authors own image).

Once the black boxes of the basic function had been identified the different black boxes was opened up and treated as their own systems to be broken down. After each system has been broken down they can then be combined again in one big system. This will be the full functional analysis and can be seen in Figure 4.5.

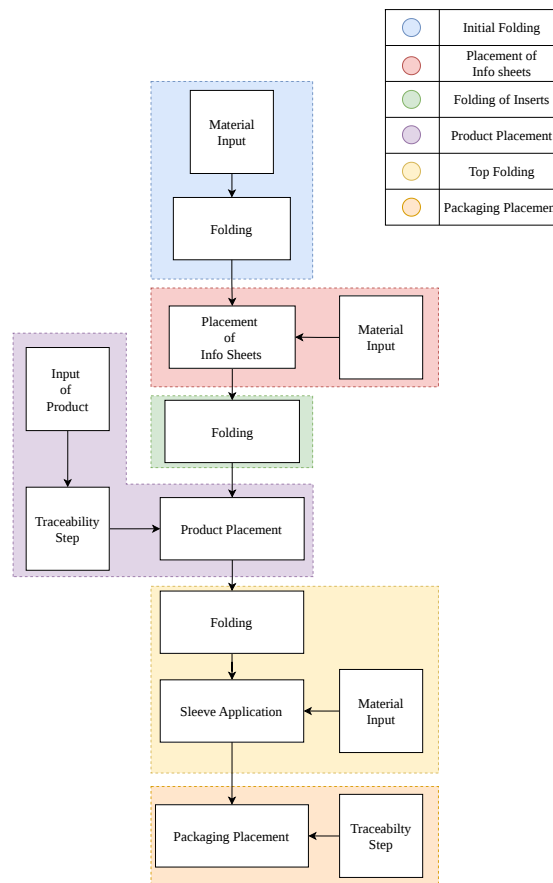


Figure 4.5: Flow chart of the low level analysis of the system (Authors own image).

The project does however leave out one component of the functional analysis and that is quality control and this is due to there needing to be some sort of quality control at all of the features and the project deemed it outside the scope.

4.5 Concept Evaluation

The concept evaluation will be the first step in the two step process of determining the possibility of implementation of the concept. After a concept has been designed

with the help of the morphological matrix then it will be evaluated. Examples of evaluation could be discussing the solution with more experienced people or it could be finding a clear contradiction in the work that has been done.

4.6 Concept Validation

For validation the software that was picked was Visual Components. The main reason Visual components was used in this project was due to the fact that it can simulate both physical aspects but it can also give a rather accurate insight in the different cycle times. This is rather important to truly validate a solution.

The primary reason for the use of simulation models in this project will be to visualize the flow of products. This means that a more detailed model is preferable in this case.

When simulating in Visual Components the simulation time was set to be one 40 hour work week.

5

System Analysis

In the company case there was two major features that was analyzed and data was gathered about. Those features were industrial robots and packaging machines. There was also other features taken into account but those was analyzed on a high level to gain understanding. This chapter aims to present findings about industrial robots, packaging machines and high level information about the rest of the features in the project.

5.1 Layout Design

As mentioned in Section 2.5.2 there are several different layouts when designing a production station or system. This project explores U-shape, S-shape and L-shaped designs. It is also worth noting that all of the line has a serial material flow. This is due to the fact that this is what Plejd uses today and therefore the parallel flow was disregarded for the projects designs.

The first layout that was explore was the U-shaped layout which worked well when there was need for both compact but also area for operators to work. This meant that the area in the middle could be used as a work area for an operator. One of the problems with this is that there is no place for easy placement of materials close to the stations and it would need to be outside of the "U".

The second layout was the S-shaped layout which is even more compact than the U-shaped layout. This layout suffered from lack of accessibility to the machines for operators. And it would also mean that there would be problems for close by access to the materials. It was also found that if there is not that many stations in the system it is easy that it becomes a more compact "U" design and for this project this was the case. For this reasons concept with an S-shaped layout was disregarded and U-shaped layouts was used instead.

The last layout that was explored was the L-shaped layout. This layout is less compact than the other layout but it has rather easy access to the different stations for the operators. This layout also has the possibility to add racks of material next to each refill station which makes refill easier for operators and adds the possibility for easier AMR integration.

5.2 Industrial Robots

The company case needed to have different robots that did various tasks. For example it needed to do pick and place operations but also it may needed to raise cardboard boxes for shipping. Therefore data was gathered for these different robots from producers of robots that deemed necessary to outsource. The only robot type that was deemed not needed to be outsource was the gantry crane. This decision was made due to there being in-house competence for development of these types of robots.

The companies that were the data was gathered from were IGUS, KUKA, ABB, Universal Robots. The data points can be seen in Figure 5.1.



Figure 5.1: A visualization of the reach and price data collected with Reach on the y-axis and Price on the x-axis (Authors own image).

From these data points a range can be set up for the different robot types. To keep the ranges as accurate as possible potential outliers in the data was removed with the interquartile range (IQR) [33]. This works by removing any data points that does not hold the Equation 5.1.

$$Q_3 + (Q_3 - Q_1) \cdot w_1 > p_n > Q_1 - (Q_3 - Q_1) \cdot w_2 \quad (5.1)$$

Where Q_1 and Q_3 are the first and third quartiles and w_1 and w_2 are arbitrary

weights to decide the level of outlier rejection and p_n is each of the data points.

The ranges without the outliers can be seen in Figure 5.2.

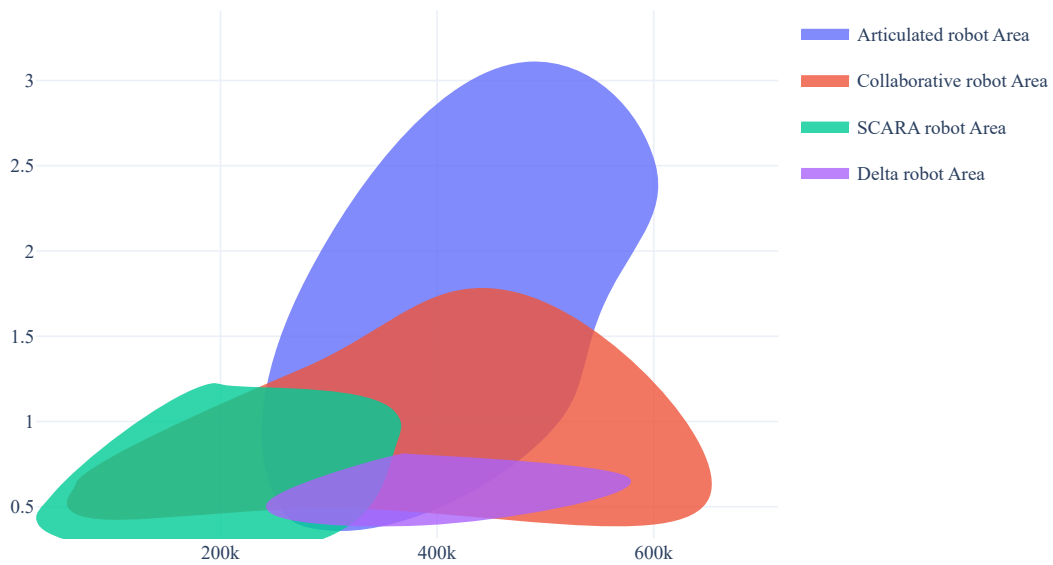


Figure 5.2: A visualization of the range of reach and price data collected with Reach on the y-axis and Price on the x-axis (Authors own image).

From the data points and range it can be seen that SCARA robots are the most cost effective at short range while the articulated robot is more flexible in different ranges. For the company case this meant that the SCARA robot was mostly chosen when there was a pick and place operation with low reach necessary.

For certain pick and place operations that could be split into different steps there was an idea to implement a gantry robot. As previously mentioned this would be developed in-house and given the expertise at the company the project does not further investigate this for them.

For the project there is quite a short range pick and place motion with a rather low weight so the project decided that a SCARA robot was the most cost effective solution.

5.3 LLM Approximation

An alternative approach to data gathering was done where if there was an issue in finding data about certain features or components due to secrecy or tailor-made machines the data would be gathered from Large Language Models (LLMs).

The way this works is by asking several models the same prompt and basing the data on an average of what the models output.

Worth noting is that LLMs have a tendency to hallucinate so trusting them completely is not recommended but it can be a good to gain an understanding of certain data needed.

This project will use LLM approximations to gain an understanding of the footprint of each packaging machines with the understanding that the machine size can deviate from the real packaging machine sizes.

5.4 Packaging Machines

During the project it was found that packaging machines are not standardized and will need to be tailor-made for the project. This meant that there is no standardized data to present.

From the functional analysis there are four components that were needed to be investigated. The components that were investigated were an initial folding machine, an insert folding machine, a top folding machine and a sleeve handling machine.

Due to the packaging machine needing to be tailor-made it was decided to investigate if the packaging machines needed to be outsourced, developed in-house or reconsidered due to packaging changes. This chapter brings up the possibilities of outsourcing and developing in-house while Section 5.6 will discuss potential packaging changes that can be made for an easier automation process.

5.4.1 Experience Related to Developing In-house Solutions

Plejd is a company with an automation team whose jobs focus on maintaining and developing automation inside the factory. These range from semi automated stations to fully automated stations. This section aims to bring forth some of their experiences and later put them into context of designing and developing an in-house solution for the packaging station.

In Plejd's factory there is an automated production line that has been developed in-house as previously mentioned. In that line there is a lot of pneumatic actuators that control the different operations. Especially where there is a need for straight motions that does not need that much control. There are also electrical actuators. These are used when there is a need for non straight motion. The parts of the line where there was assembly with precision and a so called "finger tip feeling" was

needed was especially hard.

Furthermore it was found that projects developed in-house have a shorter Time to Production (TTP) than a project that would be outsourced. A project at Plejd at this size would take somewhere between 20-40 weeks to finish. This only includes the development of the machines, any packaging changes that might be necessary is not included in that time frame. Worth noting is that Plejd does not have any experience in packaging automation from before which might add to the time needed to develop such machines. It should also be noted the developing machines in-house does run the risk of encountering growing pains, especially when it is in a new area of automation.

As previously mentioned Plejds automation team usually develops machines where electronic testing is required and expensive testing equipment is needed. For a packaging machine this is not needed and will save money and maybe time compared to previous projects depending on how they decide to implement it.

After analyzing previous project from Plejd it is clear that there is a capability of developing the cell in-house. It should only be developed in-house if there are time and resources in manpower for the project. Plejd mentioned that a project similar to this one would take a team of two to three people working full time which may take away manpower from other projects at the company. This is a trade off that the project leaves to Plejd to make and in the concept design this will be seen.

5.4.2 Outsourcing Possibilities

Plejd wanted to preferably use contractors from Europe and Sweden. This is due to them wanting to have some sort of outsourced service agreements where an external contractor can service the potential machines. Plejd also wants to favor European and local markets. As there are many suppliers in Europe the project chose to focus on investigating contractors from Sweden.

When investigating contractors in Sweden several companies was found that made similar packaging machines to the once needed [10][34][35][36]. Some contractors also seemed to have the possibilities of developing a tailor-made station for Plejd which is needed for the project.

To gain some sort of understanding of the contractors capability a carton erector was investigated to see how fast the different contractors could raise different cartons. From this it was found that the different carton erectors could achieve a produced carton in less than four seconds [10][34][35][36].

When investigating some parts of the packaging design was found not to be done commercially very often. One of those parts was the insert folding which was even rare to find any solution in the world. This means that it needs to be tailor-made and due to the complexity and the need for a lot of "finger tip feeling" in the process it should be considered to be outsourced. For designs like these where it is very niche there are often contractors that will completely make tailor-made machines

given a packaging design [37][38][39].

When investigating the packaging placement operation it was found during a study visit to SKF that packaging placement is often combined with palletizing. There an articulated robot worked by picking up finish packaged products and putting them in an equivalent to a brown box. Once a box was full it was placed on a pallet with the same articulated robot. Similar system design was also found from other contractors where the palletizing and packaging placement is in one cell [40]. This means that it can be seen as a whole system and could and leads to more complexity in the system. Therefore it was found to either keep it manual with operators doing it or outsource this problem.

5.5 Minor Features & Components

Throughout the project it has been made clear that there are features that will be used in the project that have a minor impact on the evaluation of the system. This was decided to just include as a future analysis for the continuance of this project from the company side.

The minor features in the functional analysis was the material input, traceability step, material movement and quality control. These will shortly be described in this chapter.

From what has been seen in previous packaging machines in Section 5.4.2 there is often a magazine used for material input. It often loads with some sort of suction cups and grabs one piece of carton at a time to load into the machine.

For future work in traceability and quality control it can be a good idea to check Section 2.8 and 2.9 for inspiration and see how it is handled on the market today. Given the market CV, MV and RFID seems especially prominent due to their flexibility and simplicity.

At the company there is a way of moving materials with a conveyor system. There are many ways of doing it and in the simulation some assumptions are made on the speed which is described more in Section 5.7.1.

5.6 Packaging Redesign

In Chapter 4.4 a flow chart was presented. This flow chart is based on the current packaging, which contain elements that could prove hard in an automated packaging solution. Elements such as the sleeve could prove difficult due to the low tolerance between the sleeve and the package that contains the product. The sleeve also creases easily when trying to mimic the motions of a potential robot.

There are also new EU directives being planned to reduce the percentage of air inside the packaging [41], which could potentially force Plejd to redesign the packaging.

This subchapter aims to bring fourth ideas on changes in the packaging and how this could affect the complexity of the automated packaging station. Many ideas and problems that are brought up here were gathered from analyzing and folding the current packaging, but also discussing with supervisors etc.

5.6.1 Folding and Locking of the Top Lid

Removing the sleeve could prove an interesting concept as this would the reduce the need for a specific machine for this operation. However there is one problem with removing the sleeve. When the sleeve is removed then nothing is locking down the top lid as can be seen in figure 5.3.

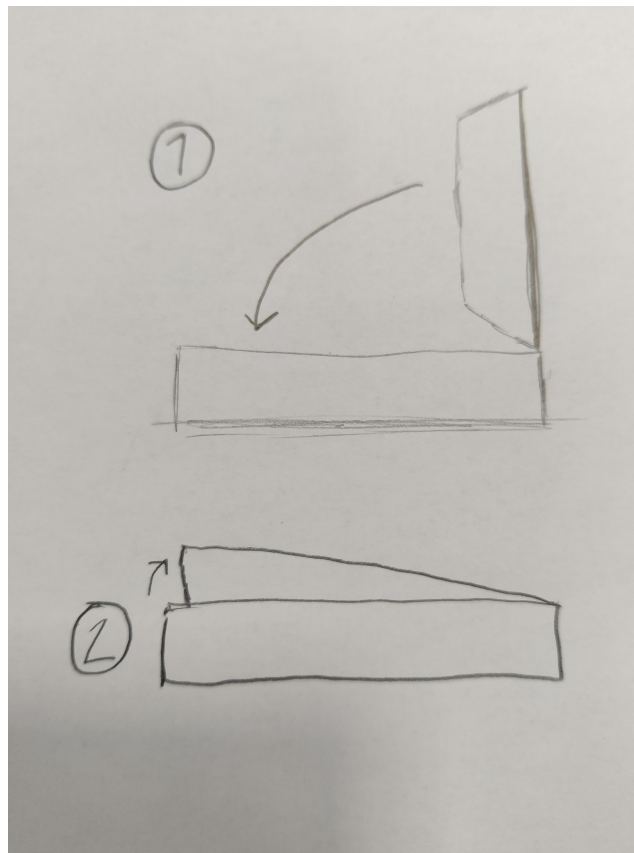


Figure 5.3: An illustration of a box that does not contain a locking mechanism for the top lid (Authors own image)

The problem that might arrive with the top lid not being secured is that the product could fall out during the packaging process or during transport to the retailer. The project has identified 3 potential solutions to this problem. The first is to add some form of adhesive, either in the form of a sticker or glue to hold the top lid down. This method was seen in use during a study visit to SKF where it was used to close the top lid of their product packaging. The method used was a hot glue sprayer that applied a layer of glue that then was used to seal the top lid of the product. This seemed to work well but does require maintenance since glue can potentially

clog or spray into parts it should not be.

Another solution is to add another panel to the end of the top lid with two smaller panels connected to the side. These smaller panels could then slot into the original packaging, effectively resulting in a locking mechanism as can be seen in Figure 5.4.

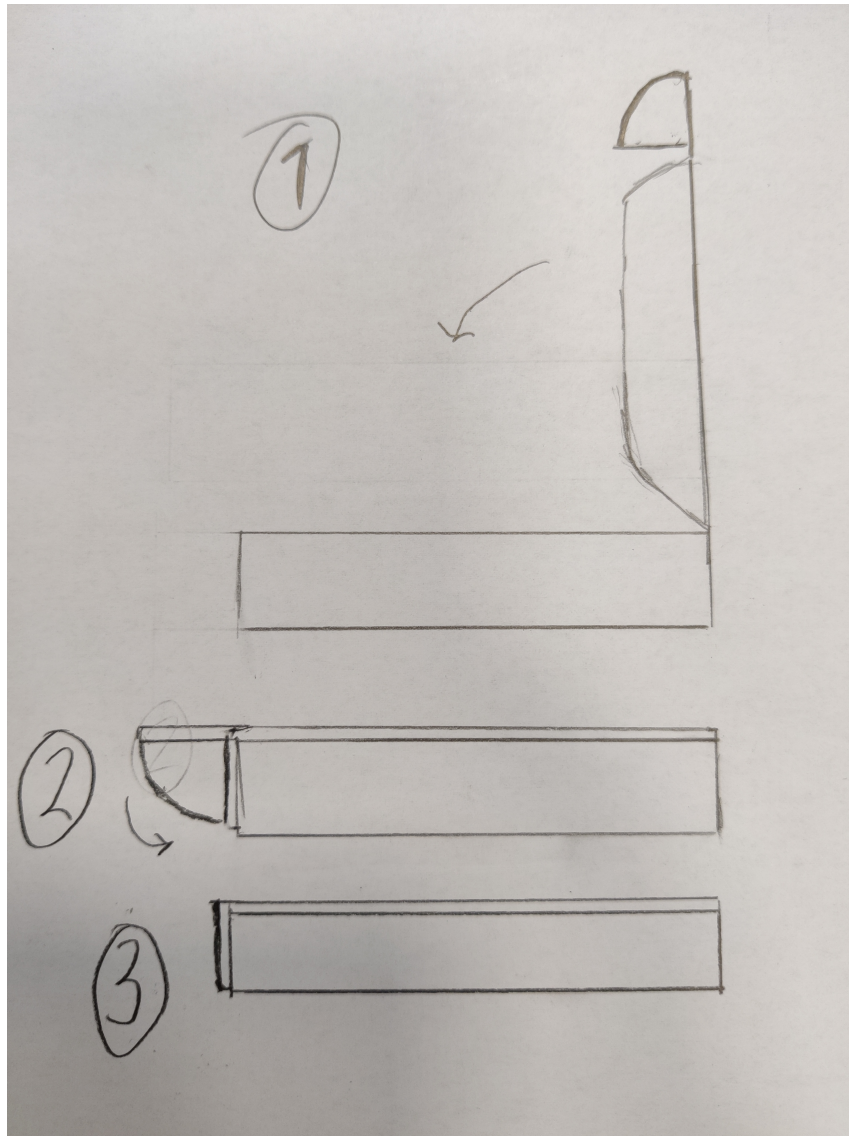


Figure 5.4: An illustration of a box that does not contain a locking mechanism for the top lid (Authors own image)

Should this design be implemented then the sides of the packaging would need to be redesigned as in their current form the margins are too slim to be able to slot in side panels easily.

The third solution is to have a combination of both the adhesive and the top lid with locking side panels. With the adhesive in this case being some sort of sticker. The sticker also gives the bonus of proving that the product has not been open since

it was packaged at the factory.

The sleeve also provides the function of being used to hang the products inside retail stores. Should you remove the sleeve this would need to be replaced. An example of a solution could be to have part of the packaging be able to be "torn off" to allow a hole for this type of operation.

5.6.2 Redesigning the Insert

In the current packaging, the insert is part of the die cut box trace. This means that a complex folding procedure is needed. The process for folding of the insert in can be seen in Figure 5.5, 5.6, 5.7 and 5.8.



Figure 5.5: The front and side view of the packaging without the insert folded (Authors own images).

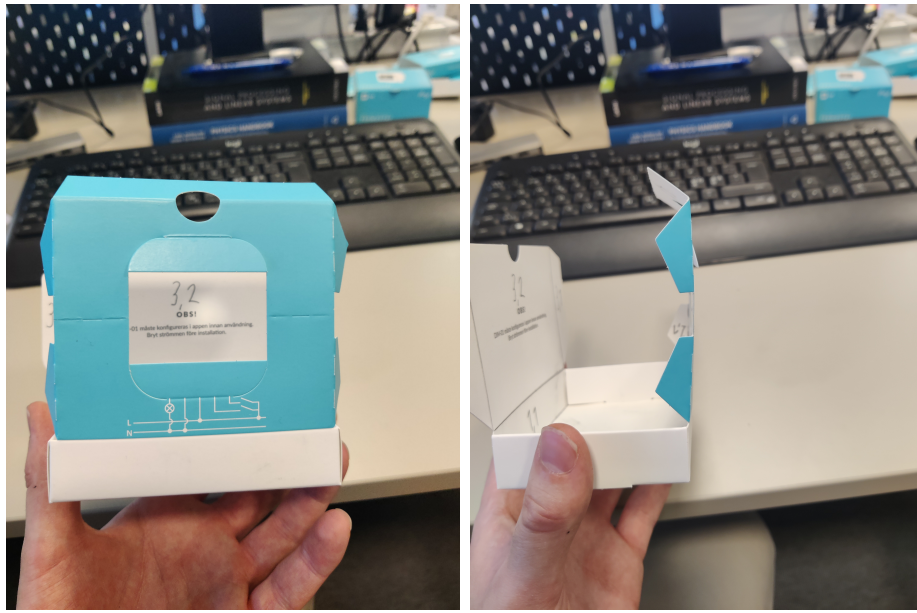


Figure 5.6: The front and side view of the packaging with the side panels folded (Authors own images).



Figure 5.7: The front and side view of the packaging with side panels folded and insert bended to be able to slot into the packaging (Authors own images).



Figure 5.8: The front and side view of the packaging with a completely folded insert (Authors own images).

As can be seen in the series of images above the process to go from trace to folded insert is fairly complicated, and tests of folding it manually showed that it can be a bit tricky even for humans. This means that automating this process could prove quite difficult as the operations requires many movements to be done simultaneously. The insert cannot be removed however without changes to the total size of the packaging as the core function of the insert is to keep the puck in place. The project has found two potential solutions to this problem.

The first solution is to reduce the complexity of the insert. Examples of this could be to remove side panels which would reduce the numbers of operations needed. Removing the operation of having the insert be bended to fit in the packaging could also reduce complexity.

The second solution is to remove the insert from the trace entirely and replacing it with an external insert in either paper or foam material. This would transform the insert folding step to a pick and place operation. This could either be in the form of its own pick and place station or combined with the current pick and place operation. This would require some form of feeding mechanism for the robot which adds another refill step for the operator.

5.6.3 Changes to the Sticker and Leaflets

Changing the stickers and leaflets could prove beneficial to the total packaging system depending on the changes made. In its current form there are one sticker and two leaflets that needs to be placed in the packaging requiring the operation of either a pick and place robot or a card feeder machine. These machines needs to be refilled by an operator, effectively increasing the time needed both for keeping the

system running and resetting the system for a new version of the product.

One possible change to this problem could be to change from paper cards to a QR code on the inside of the packaging. The QR code would provide both the installation guide and the getting started guide. The sticker is a crucial part as it is placed on the electrical box. This means that it cannot be removed in favor of a QR code like the other leaflets. A potential solution could be to have the sticker be part of the inside of the packaging, which would remove the need of a dedicated card placing station.

5.6.4 Changes to the Material

The current material used for the packaging works good for folding with movements made by a human. However tests of folding the boxes showed that it often does have a tendency to not stay upright. This is not a problem for a human operator. However this could become a problem for a machine should a piece move out of position which could result in the folding operation failing. If the operations are done in a fast enough sequence this will probably not be a problem. However if the material is changed to allow for the folds to stay more in place then there might be a reduced risk of folds failing to stay in the dedicated position. This is mostly important should you need to transport the packaging in a specific folded position from one operation to another, with the folds not shifting position.

5.7 Simulation

This section describes the different simulations that was done during the project.

5.7.1 Assumptions Made

Since the simulation is not based on a current existing system some assumptions are needed in regards to the cycle times of the machines and the speeds of the conveyors. The machines in question are the different components in the concept. These components are the machines for the folding of the packaging, the pick and place robot and the card feeder operations. The cycle and transport times of these operations will be based on open source information from company sites, the only difference is the packaging machines that will have a cycle time of maximum 5 seconds which is the demand from Plejd.

Each individual card feeder will have a cycle time of 0.2 seconds. This is based on a card feeding machine from ifeeder which can supply 300 cards per minute [42]. The SCARA robot will have a cycle time of around 1 second since this is what is stated in a YouTube video from Fanuc showcasing the capabilities of their SCARA robot [43]. The different conveyors of the concepts will use a speed of 2 meters per second which is the max speed on a x65 conveyor from Flexlink [44].

5.7.2 Tests and Choice of Simulation Software

The simulation was built with two principles in mind. The first is to be able to visualize the flow of products and the space that the different stations occupy. The second is to test how robust the system is when faced with lower yield rates and how to counteract these, with yield in this context being the percentage of products that exit each machine. This means that this project prefers a program that can do both tests. In Chapter 2.7.4 two different simulation software's were presented. Visual Components was chosen for its easy plug and play robotics and machines, and good tools for visualizing the flow of products. The company also had experience in the use of Visual Components which also affected the choice of software.

Since there is not much public information available on yield values for commercial packaging machines the project chose to estimate some values that could be of interest. The values chosen was 95%, 97% and 99% since they cover a large area of plausible values. Discussions with our supervisor highlighted that values lower than these would be deemed to wasteful. The yield test will be done by testing all the different combinations of percentages on the four different packaging machines. This is to test how robust the system is at different yield values and where the bottleneck appears to form. The simulation time will be 40 hour to represent a work week. The values that will be studied are Total products produced (Total Prod), mean products per minute (PPM Mean) and the utilization of the different packaging machines. A reference value will also be used where all the yield values for the machines are set to 100%. A total yield value will also be calculated by multiplying the different yield values of the machines for each test. This value will then be multiplied by the reference value and compared to the Total Prod to see if total yield is accurate in its value. The total combinations of yield values on the machines is 3^4 which means there will be 81 yield tests in total. Since the company gave the requirement of 1 product per 5 seconds which translates to 12 PPM. The project chose to only simulate on one type of layout which was the L-shape layout, because it had the lowest transportation distance in regards to the conveyors. The reason for only simulating one layout is that the tests takes around 5-10 minuets each, and the project deemed that difference in layout would not produce drastic enough changes to justify triple the amount of current simulations. The simulation model did not include any MTBR or MTTR values since the simulation model only uses 40 hour, and an industry standard cartoner can have an MTBF of 200-400 hours [45].

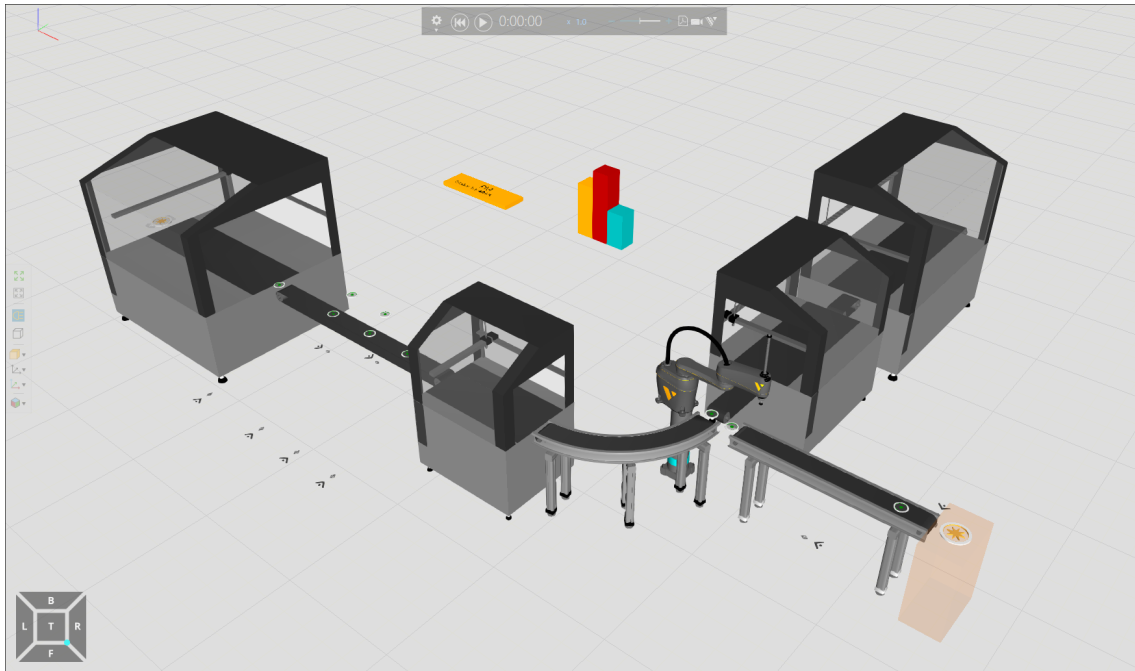


Figure 5.9: Image of the simulation model used for testing (Authors own image)

Should the system not be able to reach 12 PPM then the project will extend the testing. In this case it will be to reduce the different cycle times on the machines or increasing the flow of puck products.

5.7.3 Simulation Result

From Table A.2 the results of the yield can be seen. There are a few general findings that can be observed. When doing the tests it was observed none of the cases (not even the reference case) was able to reach the desired PPM of 12. Generally the lower the total yield of the system the more noise there was in the PPM measurements with values as low as 4 PPM in some cases. What could be seen is that a higher total yield value often lead to a more tight spread in PPM. This can be seen in the images bellow:

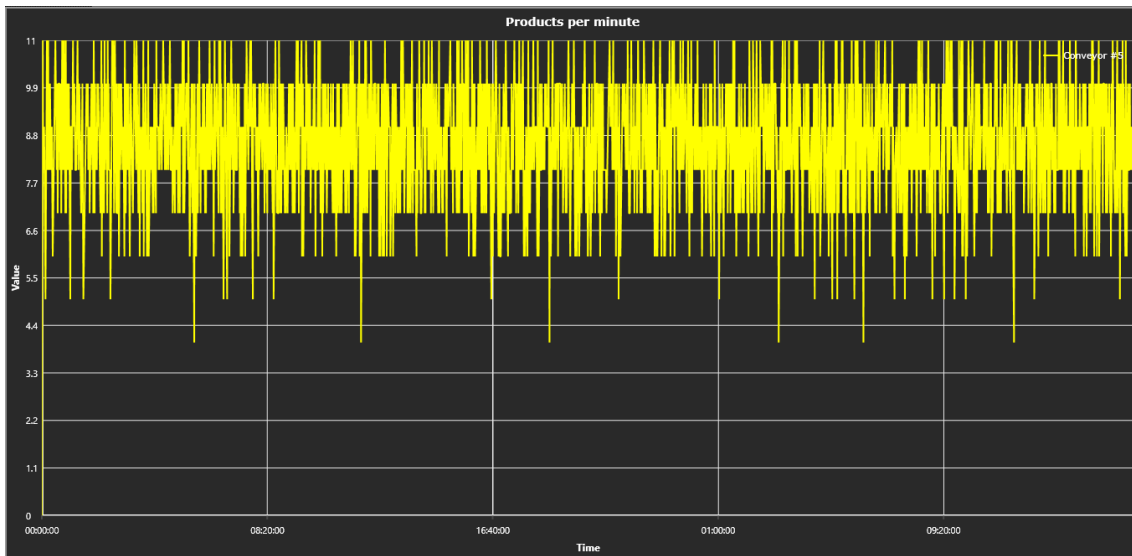


Figure 5.10: PPM for the system with a total yield of 81.45% on all the packaging machines (Authors own image)

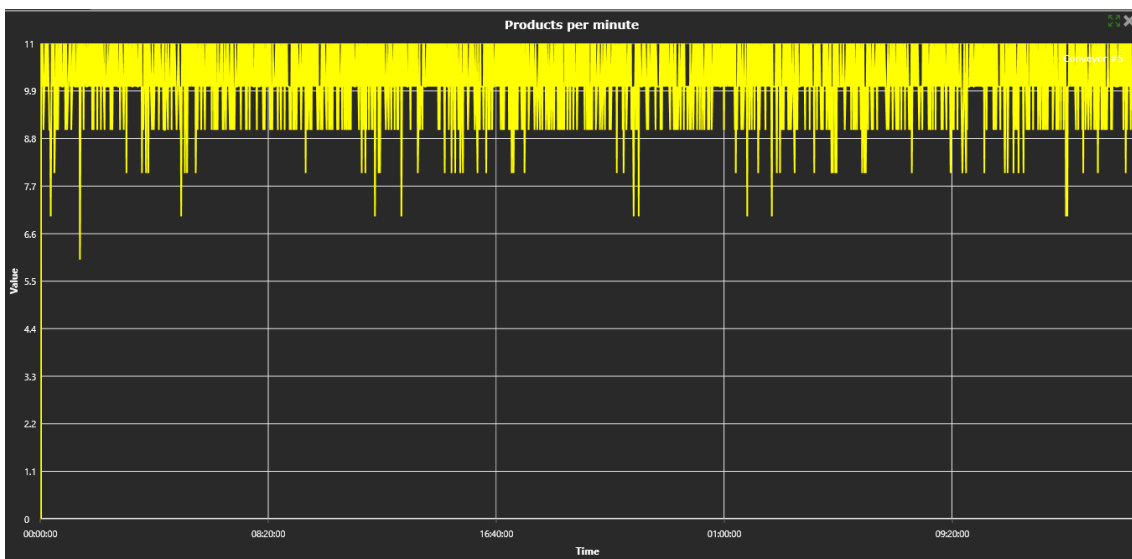


Figure 5.11: PPM for the system with a total yield value of 96.06% on all the packaging machines (Authors own image)

In every yield simulation there was a pile up of puck products at the pick and place operation where the puck is placed into a box. This meant that there was a bottleneck somewhere in the system, and since none of the test showed PPM over 12 the project choose to do some tests to try and identify what could be done to increase the PPM and reduce the bottleneck at the test station.

The results from the tests in regards to the bottleneck can be seen in Table A.1. The tests were done where different machines cycle times were reduced to see the impact on the system. When reducing the cycle times of the packaging machines to four

seconds then the bottleneck was now not at the conveyor from the test station, but instead there was a pile up of packages before the pick and place operation. However the PPM was still under 12. To try and get the PPM value above 12 the project increased the flow of pucks to one every 4.5 seconds. This increased the PPM to over 12 however there was again a pile up at the conveyor from the test station. This pile up was again combated by reducing the cycle times on the packaging machines (3 seconds and 1 second cycle times gave the same PPM value). This means that the packaging machines should have a faster cycle time to than the amount of pucks that flow into the system to reduce the risk of a bottleneck in the puck flow which could potentially create bottlenecks in earlier parts of the production line.

6

Results

This section aims to present the different concepts that was developed in the project. All the concept is based on the morphological matrix seen in Figure 6.1 and could have variants of itself where most of the characteristics is similar but it deviates slightly. The technical data for the different concepts are presented in Section 5. An experimental design section is also provided that is a series of changes the project would recommend doing to lower complexity.

Furthermore it was found that the technical requirements from Plejd presented in Section 4.1 could be inherited to the development of the realization of the project.

Layout	S-Shaped	U-shape	L-shape				
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	Outsource
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.1: The morphological matrix for the system. (Authors own image)

6.1 Concept 1

The first concept and its variant is a L-shaped design. The morphological matrices can be seen in Figure 6.2 and 6.3.

Layout	S-Shaped	U-shape	L-shape				
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	Outsource
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.2: Concept 1 Variant A, L-shaped with operators manually handling brown boxes. (Authors own image)

Layout	S-Shaped	U-shape	L-shape				
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	Outsource
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.3: Concept 1 Variant B, L-shaped with outsourced brown box handling. (Authors own image)

An approximate layout drawing of the concept can be seen in Figure 6.4. This is also the drawing for concept 3 which is presented further down.

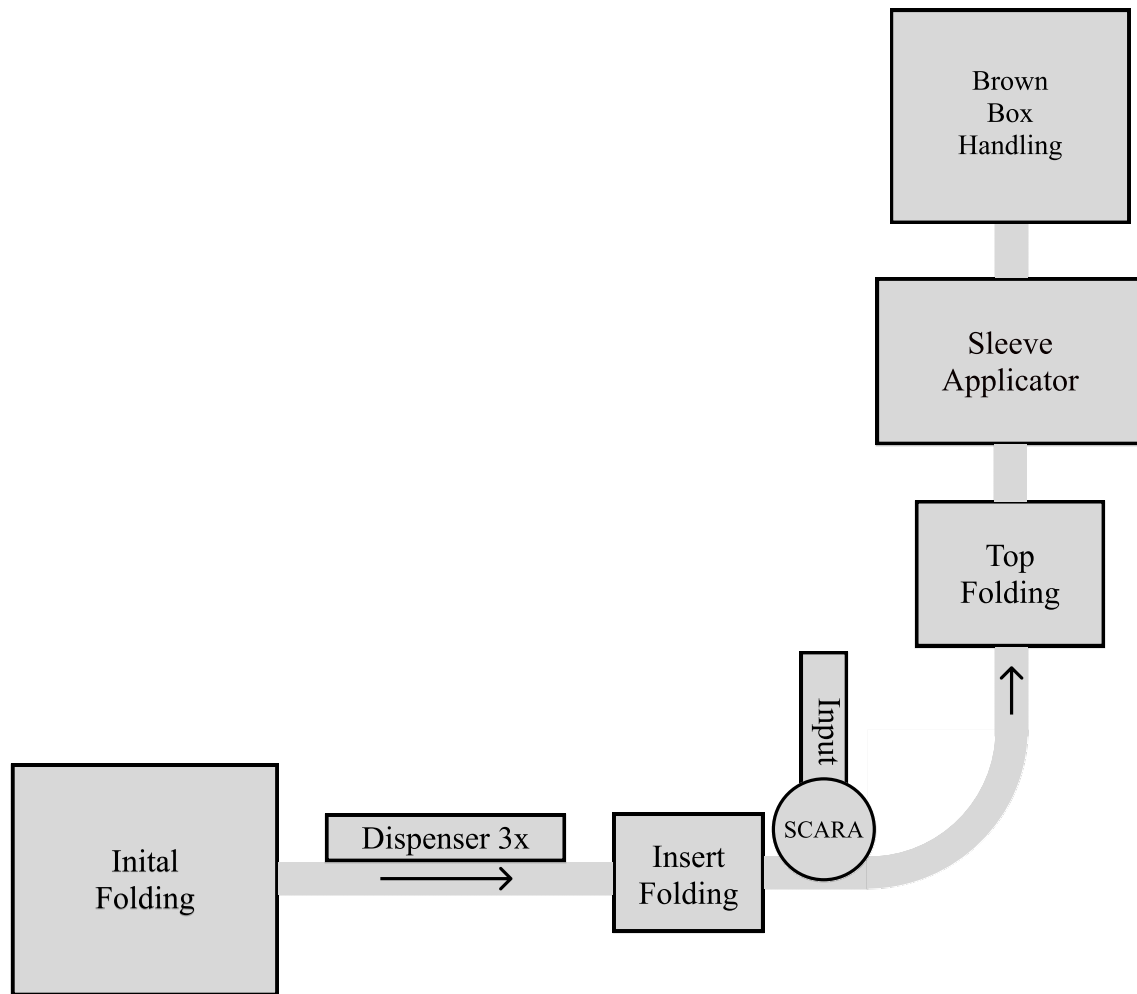


Figure 6.4: An approximate drawing of Concept 1 and 3s layout. (Authors own image)

6.2 Concept 2

The second concept has similar components to it as the first concept with the change of the layout. The second concepts layout is an U-shape design and the morphological matrices can of the two variants can be seen in Figure 6.5 and 6.6.

Layout	S-Shaped	U-shape	L-shape				
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	Outsource
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.5: Concept 2 Variant A, U-shaped with operators manually handling brown boxes. (Authors own image)

Layout	S-Shaped	U-shape	L-shape				
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	Outsource
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.6: Concept 2 Variant B, U-shaped with operators manually handling brown boxes. (Authors own image)

An approximate drawing of the concepts layout can be seen in Figure 6.7.

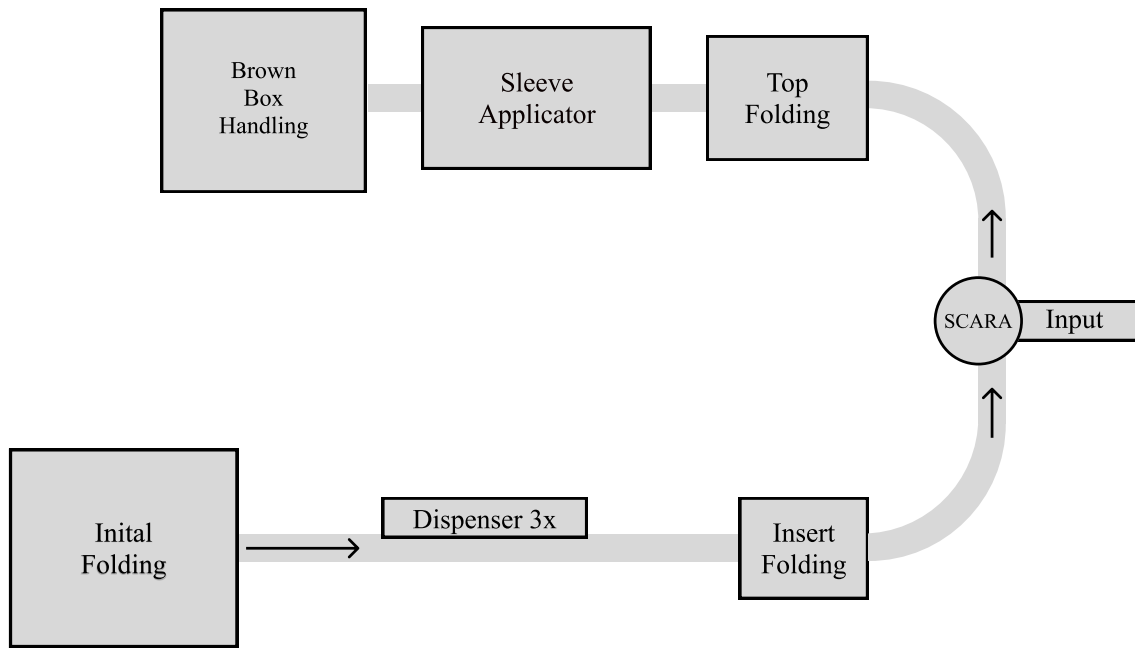


Figure 6.7: An approximate drawing of Concept 2s layout. (Authors own image)

6.3 Concept 3

Concept number three and its variants explores the possibilities of in-house solutions. The morphological matrices of concept 3 can be seen in Figure 6.8 and 6.9.

Layout	S-Shaped	U-shape	L-shape				
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	Outsource
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.8: Concept 3 Variant A, L-shaped with operators manually handling brown boxes. (Authors own image)

6. Results

Layout	S-Shaped	U-shape	L-shape				
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	Outsource
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.9: Concept 3 Variant B, L-shaped with outsourced brown box handling. (Authors own image)

The layout for this concept is the same as concept 1 and can be seen in Figure 6.4.

6.4 Experimental Design

Layout	S-Shaped	U-shape	Straight Line	L-shape			
Initial folding	Outsource	Mechatronic Push System	Mechatronic Stamp System	COBOT			
Placing of info sheet	Chute with pretaped info sheets	SCARA	DELTA	Gantry	Card Dispenser	Articulated Robot	Redesign
Folding of insert	Outsource	Mechatronic Push System	Redsign	Remove	In Combination with Product Placement		
Product placement	SCARA	DELTA	Articulated Robot	COBOT	Gantry		
Top folding	Outsource	Mechatronic Push System	Modified conveyor	COBOT	Articulated Robot		
Sleeve handling	Outsource	Mechatronic Push System	Remove	Redsign	COBOT		
Packaging placement	SCARA	DELTA	Operator doing it manually	Articulated Robot	COBOT	Gantry	
Brown Box Raising	Operator does it	Articulated Robot	COBOT	Mechatronic System	Outsource		

Figure 6.10: Experimental design of the packaging system based on changes presented in Section 5.6. (Authors own image)

Figure 6.10 shows the morph matrix of how the project believe a concept could look like based on changes presented in section 5.6. The green boxes are similar to the morph matrices of previous concepts. The yellow is meant to symbolize things that should be considered or added later

6.4.1 Prototype design

In Figure 6.11 a test design can be seen based on the morph matrix made in



Figure 6.11: The front and side view of the modified packaging. This packaging has removed the sleeve in favor of an extra panel with side panels use to lock down the top lid. The insert is replaced with an insert that is not angled allowing for an easier motion of folding. (Authors own images)



Figure 6.12: The left image shows the example design with the insert folded and the lid open from the front. The right image shows the same but from the side. (Authors own images)



Figure 6.13: The image shows how the example box looks like with the insert not folded into the packaging. (Authors own image)

7

Discussion

This chapter goes into detail about the different concepts developed and why the choices was made. It also discusses future works and how to continue the project and what to keep in mind when doing so.

7.1 Concept Reasoning

This section aims to present a reasoning behind the different concept and explore why the different choices was made. It also answers if the concept upheld the requirements for the project and also presents any insight that the concept might have given the project in full.

All the concepts has a similarity and that is that they have two different variants that are fairly similar. All of the variants are about how the brown box handling should be done and it is due to the complexity mentioned in Section 5.4.2.

7.1.1 Concept 1

The first concept explores an L-shape layout with most of the machines being out-source with the exception of placing of info sheets and product placement. The main reasoning behind outsourcing is if there is not enough man power to develop a solution in-house an outsourced solution can be a good idea. It was also found that an L-shape layout worked quite well where there is a lot of space around the line where there can be material handling for operators. There is also a possibility for material handling solutions such as AMRs to feed and materials. The L-shaped design also handled material transport between stations well due to the fact that the corners could be made rather compact and space utilization on the line was easier than in other layouts.

7.1.2 Concept 2

Concept 2 is similar to concept 1 with the change that it has a U-shape layout. The U-shape makes it so that this concept can be more compact at the cost of material handling for operators and potential AMRs. It was also found that the cycle time for this layout was slower than the L-shape layout. This was due to the need for longer transport of materials between machines which than slowed down production

for this case. Given that it was decided that the U-shape layout failed the test and was disregarded. Similarly any design that involved a S-shaped layout would be disregarded due to similar issues being found in those designs.

7.1.3 Concept 3

The third concept has the same layout as concept 1 but instead of outsource the concept for build the machines an in-house solution is made instead. This should be done if there is manpower given that the competence of the products stays in the company and Plejd will then own the knowledge of the machine and capability of fixing it. All the choices of machine types are made given the state of the art which can be seen in Section 2.3.2.

7.1.4 Experimental Design

The last concept that is presented is called experimental. This is because this concept implements parts such as redesign which means to change the packaging in ways to make the complexity of the automation task easier.

The experimental concept starts with the choice of design. For this the L-shape was chosen for its open spacing allowing for materials to be kept close to machines, while still keeping a fairly compact area for the machines. For the initial folding step the project believes that outsourcing this would be beneficial since there are many companies that make these types of machines and the operation seems to be fairly standard in its folding stages.

The placing of the info sheets is believed that some form of of card dispenser is the best choice. When discussing with the company they voiced concerns with picking the info sheets with robots using suction cups. However the option of redesigning and making it so the sticker is part of the inside of the packaging and the leaflets be a QR code instead should be considered as this would remove the placing of info sheet step completely, effectively reducing the total complexity of the system.

The insert in its current form is complex in an automation standpoint as it requires a bend to be able to fold it into the packaging. Changing this design to a design that does not require bending would help with making the product easier to automate. Making the insert a separate product made from either paper or some sort of foam material is also a possibility, which would make this a pick and place operation instead of a folding operation, which the company has experience in. However this would require the feeding of this insert material to the pick and place operation. This means that it adds another step for the operator which could increase the setup time.

For product placement it is still the SCARA robot that is chosen. This is because the picking and placing of the puck is an operation that will only need 4 degrees of freedom. The SCARA robot is fast for these types of operations while not requiring special mounting such as the Delta robot.

In this experimental design the sleeve would probably be removed which means that the top folding step will be more advanced. This means that the top lid will probably contain more parts so that it can either be locked using side panels, or using adhesives to close it. The project believe that side panels would probably be preferable. This means that the packaging would be needed to be modified to allow this. Using glue to close the box is a good idea, however using glue does require more maintenance. Some form of adhesive in the form of a sticker is recommended to add another insurance that the top lid does not open, and it gives insurance that the product has not been opened. Worth noting here is that should the sleeve be removed then some solution is needed to be able to hang the product in retails stores as this was done by the sleeve. Maybe designing the packaging with a hole that fold out could be a solution for this.

The project did not focus on palletizing operations as this was seen as outside the scope of this project. The study visit at SKF showed that combining the product placement step with palletizing using an articulated robot could be an interesting solution. This means that the project sees two potential path for this operation. Since there is going to be an operator for this packaging system, the project believes that they might be able to do the folding of brown boxes and placing of products as this operation should be fairly fast. This can be implemented fairly easy as this is similar to the current operations in the packaging station at the company. However if an articulated robot that does both product placement and the palletizing operation could prove beneficial as this frees up more time for operators to do other tasks. The robot could also do the raising of the brown boxes for the product placement step. This combined operation is fairly complex however and will need a lot of space.

7.1.5 Prototype design

The design presented Figure 6.11-6.13 showed a prototype package. This prototype was to test the possibility of removing the top lid and replacing it with side panels that lock into the sides. The design does not feature an adhesive sticker which could be useful to ensure the lid is closed and the product has not been modified since it was packaged. The design also has a modified insert where the bend was removed. This was to reduce the complexity of the folding motion for the insert while still keeping the insert.

This design showed promise but is far from the final version. The side panels for locking the top lid work good but for an automated process it needs more spacing to allow for easy slid in of the side panels. Otherwise the operation will be to hard to execute which would result in a bad yield rate.

The removal of the sleeve would reduce the complexity of the product since there need to be one less machine. However this increases the complexity of the top lid closing. But the project believes that closing the top lid using locking side panels or adhesives is easier than threading on a sleeve. Since the sleeve plays a role in locking the top lid in the current format of the design the margins for threading it onto the packaging is very small. It is believed that these margins will be hard

when automating the process.

7.1.6 Concept Recommendation

We recommend either concept 1 or 3. This will depend on what the company values when this project shall be realized. Having everything outsourced will free up resources. However the development will be more expensive and might take longer as there needs to be a lot of back and fourth between the different companies. Depending on the contractor of the system, the insight might not be the same as an in-house system or might even require the need of technical staff from the developing company to fix potential problems that arrive.

However developing this in-house is also a possibility. Developing the system in-house gives more insight into the system. However when developing systems in-house, especially in a new area, there is a risk of growing pains in the system. Developing this in-house would almost certainly be cheaper than outsourcing the project, and could potentially go faster as there will be less back and fourth between companies.

There is also two different variants of each concept with variant A being manual brown box handling while variant B is outsourced machinery for brown box handling. This was done due to the fact that in similar projects brown box handling and palletizing is done in the same step. Here the project recommends to outsource this step due to the fact that it can be decoupled from the rest of the project easier. The reason it is easier is because there is a finished product between these steps and the brown box handling part can be seen as its own system because of that. Variant A could work for awhile but it would slow down the system and eventually there would be a need for an automatic station here too.

7.2 Future Works

This section describes the simulation results and what simulation should be done next. It also explores the different function that was not included in the system and was referred to as minor features and components in Chapter 5. Finally it describes how to move forward with this project and what to think about when a continuance of the project is done.

7.2.1 Simulation results and further simulation

The project chose the L-shape design since this was the design that required the minimum amount of meters of conveyors, while still keeping the area open for operators to move around easily around the machines. During the simulations it was observed that the conveyors did not have any greater impact on the performance of the system. The reason for this is believed to be the high transport speed of the reference conveyor from Flexlink which had a top speed of 2 m/s. And while it is possible that the system can use this speed, a more realistic value would probably be

around 0.5-1 m/s. With a reduced speed the more important it is to try and minimize the amount of meters of conveyors used. While reduced speeds would probably not affect the L-shape design since it already does not have many conveyors, designs such as U-shape will be highly affected since they require a lot of conveyors for the operator to move inside the U shape.

The yield rates that were used were 95%, 97% and 99%. The project was not able to find any yield values provided by companies. It is believed however that these values cover a broad enough area of potential defects, and helps give insight into the demands that should be on the machines.

For continuation of this project some form of simulation of the handling of brown boxes and the placement of products inside brown boxes. The study visit at SKF showed that a combination of product and palletizing in the same cell. Should the simulation work continue then this area could prove to be interesting. What would be interesting is simulating one or two articulated robots that first fold a brown box and scans it. Then the robot places the finished products inside the brown box. This could be a complicated process should the product packaging not change since the sleeve contains a mounting part that extrudes from the packaging for hanging in commercial stores. This means that the the product packages needs to be place in a "alternating order".

Developing a deeper and more advanced simulation model with things such as humans moving around in the simulation mimicking the actions of operators could be interesting. Especially when it comes to observing actions such as refills or preparing the station for new products. However the project did not find this necessary in this stage of the project. However should you want to start integrating more "smart" systems into the factory such as AMR or AGV then a more deeper simulation could prove useful.

7.2.2 Quality Control and Traceability of Products

Quality control and traceability has been left out of the scope to limit the projects size. For future work on the project is is needed to make the system work. Today at Plejd they have an operator that scans the puck and the brown box packaging manually. This step also serves as a quality control step due to the fact that the operator also does an ocular inspection. For a functional fully functional system this also needs to be automated. For quality control this means to either implement a CV or MV solution that will inspect each packaging thoroughly to find any defects either made by the machine or the materials contractor.

Plejd currently uses a wholesale system where Minumum Order Quantity (MOQ) is placed and therefore the individual packaging is not traced but rather an entire brown box. This works well and rather easy in a manual flow but in an automated flow where there are several steps in between it creates problems. A solution to this can be to use RFID tags on the product where it can be scanned through the packaging when it enters the brown box and solve the problem that is created. This is however only one solution but the continuance of this project needs to keep this

in mind.

7.2.3 The way forward

So what is the next step of this process? Since the project is still in a very early phase with no time critical moments currently, we believe that the packaging should be the first focus. These changes should focus on both making the packaging process easier to automate, but also making the packaging in line with the new EU directives in regards to the amount of air inside the packaging. A recommendation here would be to communicate with automation companies to gain a better understanding what they require should you wish to outsource this project.

When the design of the packaging is finished then a new functional analysis should be done to determine the processes needed to go from trace to finished product. It is recommend however doing this functional analysis in tandem with the design process of the packaging. This new functional analysis should go deeper into things such as how quality control should be handled and the traceability of the products. Here you should also try to determine how you want the flow of products in your system and the general layout of the machines. Generally the more details you have in regards to things such as cycle times

When the packaging is done and a new functional analysis is finished then it needs to be determined on what processes should be developed in-house and what should be outsourced. This will be a process that depends on the current situation of the company. If this packaging integration is done at a time of high workload for the automation team in other projects, then it might be worth having this be outsourced to a packaging company. Having the project be outsourced will probably be expensive. Developing some of the processes in-house could both be beneficial as it would probably be cheaper and allow for more experience in automating processes in regards to packaging should you want to automate the packaging of another product in the future. Developing some parts in-house while outsourcing other parts is also and will depend on the complexity of operations and the resources available at the company for these type of automation tasks.

8

Conclusion

The conclusion aims to answer the research questions asked in Section 1.1.1. As a reminder the questions are:

- Does every part of the packaging need to be in one cell or is multiple stations needed?
- Is there a possibility of modularity where the system in the future can be used and adapted into new production lines with different products.
- What problems arrive from the way that the product is currently packaged when moving to an automated solution?
- Can changes be made to how the product is packaged to make the automated solution with the goal of reducing complexity?

The packaging station can be considered as one cell with several stations inside of it. This is why during the concept recommendation step that it is considered to either outsource or build in-house for the entirety of the system. It could be argued that it should be in two cells with one of the cells being the palletizing system but this was outside of the scope of the project and further investigation is needed to draw this conclusion. This answers the first research question as there is only need for one cell at the moment with the potential of needing two if palletizing is added.

The second research question was if there is a possibility for modularity. The modularity aspect of the solution comes in the form of the framework where if another packaging line needs to be developed the framework can be used for future projects. The conclusions from this project can also be used for further developments of other production lines. There is also some key take away such as data gathering for different machines and contractors that can be used for future projects.

The third research question focuses on elements in the current packaging that could become a problem. It was found that the sleeve and the folding of the insert are the main components that could prove to be difficult when moving to an automated solution. The threshold between sleeve and packaging makes it hard to mount and could potentially crease to packaging. The insert in its current form contains a bend that would be hard to automate as it would require a complex sequence of motions to fold it into the desired shape.

The fourth and final research question concerns what changes could be made to the packaging with the aim of reducing complexity. Similar to research question three it would be to remove the sleeve and changing the insert. A prototype of this can be seen in Section 6.4.1.

Outside of the research questions it was found that when designing an automated packaging system there are many parts that needs to be considered. However what was found is that having a clear understanding of the packaging, and the crucial components of it is essential. Changes to the packaging should also be considered based on ease of automation, use of the packaging and potential laws in the future also needs to be considered when moving to automate the process. The level of automation will also prove a crucial parts in how advanced your system needs to be.

When trying to implement the system the packaging needs to be in a finished state as changes to the packaging could turn the developed system completely upside down. This means that pre-studies before implementation is crucial and cross team communication essential for realizing these types of projects.

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A

Appendix 1

Init. Fold Time (s)	Insert Fold Time (s)	Top Fold Time (s)	Sleeve App. Time (s)	Yield Rate	Total Products	PPM over 40h
4	4	5	5	97%	26195	10.91
4	4	4	4	97%	27022	11.26
4	4	4	4	99%	28206	11.75
3	3	3	3	99%	28229	11.76
4	4	4	4	99.5%	28500	11.88
4	4	4	4	100%	28782	11.99
4	4	4	4	99%	29721	12.38
3	3	3	3	99%	31330	13.05
1	1	1	1	99%	31316	13.05

Table A.1: Production results by folding cycle time

A. Appendix 1

Init. Fold	Insert Fold	Top Fold	Sleeve App.	PPM Mean	Total Prod.	Diff	Yield	Init. Util.	Insert Util.	Top Util.	Sleeve Util.
95%	95%	95%	95%	8.63	20707	49.88	81.45%	88.61%	84.08%	79.88%	75.85%
97%	95%	95%	95%	8.81	21151	42.86	83.17%	88.52%	85.92%	81.66%	77.56%
99%	95%	95%	95%	8.99	21579	51.85	84.88%	88.53%	87.64%	83.20%	79.03%
95%	97%	95%	95%	8.82	21166	27.86	83.17%	88.61%	84.22%	81.79%	77.52%
97%	97%	95%	95%	9.02	21646	5.95	84.92%	88.58%	85.98%	83.41%	79.18%
99%	97%	95%	95%	9.19	22055	31.24	86.67%	88.55%	87.61%	84.97%	80.56%
95%	99%	95%	95%	8.99	21578	52.85	84.88%	88.27%	89.21%	88.13%	79.06%
97%	99%	95%	95%	9.20	22087	0.76	86.67%	88.58%	85.94%	85.05%	80.88%
99%	99%	95%	95%	9.38	22508	33.62	88.45%	88.55%	87.69%	86.78%	82.29%
95%	95%	97%	95%	8.81	21155	38.86	83.17%	88.61%	84.15%	79.99%	77.67%
97%	95%	97%	95%	9.01	21632	8.05	84.92%	88.58%	86.04%	81.85%	79.33%
99%	95%	97%	95%	9.17	22007	79.24	86.67%	88.55%	87.71%	83.36%	80.79%
95%	97%	97%	95%	9.01	21629	11.05	84.92%	88.29%	79.95%	81.04%	79.25%
97%	97%	97%	95%	9.21	22115	19.37	86.70%	88.58%	85.92%	83.31%	80.90%
99%	97%	97%	95%	9.40	22555	3.79	88.49%	88.55%	87.61%	84.94%	82.43%
95%	99%	97%	95%	9.19	22058	28.24	86.67%	88.29%	79.95%	89.21%	80.79%
97%	99%	97%	95%	9.41	22579	27.79	88.49%	88.58%	85.90%	85.01%	82.55%
99%	99%	97%	95%	9.59	23014	2.18	90.32%	88.55%	87.61%	86.69%	84.10%
95%	95%	99%	95%	9.00	21603	27.85	84.88%	88.61%	84.19%	80.10%	79.16%
97%	95%	99%	95%	9.18	22040	46.24	86.67%	88.58%	85.90%	81.54%	80.72%
99%	95%	99%	95%	9.36	22457	84.62	88.45%	88.55%	87.65%	83.27%	82.39%
95%	97%	99%	95%	9.20	22081	5.24	86.67%	88.13%	88.98%	88.99%	80.80%
97%	97%	99%	95%	9.38	22520	31.21	88.49%	88.52%	85.88%	83.22%	82.38%
99%	97%	99%	95%	9.58	22986	30.18	90.32%	88.55%	87.59%	84.95%	84.06%
95%	99%	99%	95%	9.37	22480	61.62	88.45%	88.61%	84.00%	83.14%	82.23%
97%	99%	99%	95%	9.60	23043	26.82	90.32%	88.58%	85.86%	84.95%	84.06%
99%	99%	99%	95%	9.79	23489	1.74	92.18%	88.55%	87.64%	88.69%	85.77%
95%	95%	95%	97%	8.81	21144	49.86	83.17%	88.61%	84.08%	79.88%	75.85%
97%	95%	95%	97%	9.00	21595	45.05	84.92%	88.58%	85.92%	81.66%	77.56%
99%	95%	95%	97%	9.19	22053	33.24	86.67%	88.55%	87.64%	83.20%	79.03%
95%	97%	95%	97%	9.01	21616	24.05	84.92%	88.13%	89.21%	79.80%	77.52%
97%	97%	95%	97%	9.20	22083	12.63	86.70%	88.58%	85.98%	83.41%	79.18%
99%	97%	95%	97%	9.38	22511	40.21	88.49%	88.55%	87.61%	84.97%	80.56%
95%	99%	95%	97%	9.20	22073	13.24	86.67%	88.27%	89.21%	88.13%	79.06%
97%	99%	95%	97%	9.40	22556	4.79	88.49%	88.58%	85.94%	85.05%	80.88%
99%	99%	95%	97%	9.57	22964	52.18	90.32%	88.55%	87.69%	86.77%	82.29%
95%	95%	97%	97%	9.01	21629	11.05	84.92%	88.61%	84.15%	79.99%	77.67%
97%	95%	97%	97%	9.21	22098	2.37	86.70%	88.58%	86.04%	81.55%	79.33%
99%	95%	97%	97%	9.38	22511	40.21	88.49%	88.55%	87.71%	83.36%	80.79%
95%	97%	97%	97%	9.21	22098	2.37	86.70%	88.29%	79.95%	81.03%	79.25%
97%	97%	97%	97%	9.41	22578	17.20	88.53%	88.58%	85.92%	83.31%	80.90%
99%	97%	97%	97%	9.60	23040	14.03	90.35%	88.55%	87.61%	84.94%	82.43%
95%	99%	97%	97%	9.40	22555	3.79	88.49%	88.61%	84.15%	83.31%	80.79%
97%	99%	97%	97%	9.60	23037	11.03	90.35%	88.58%	85.90%	85.01%	82.55%
99%	99%	97%	97%	9.79	23498	2.74	92.22%	88.55%	87.61%	86.69%	84.10%
95%	95%	99%	97%	9.21	22097	10.76	86.67%	88.61%	84.19%	80.01%	79.16%
97%	95%	99%	97%	9.39	22526	25.21	88.49%	88.58%	85.90%	81.54%	80.72%
99%	95%	99%	97%	9.58	22986	30.18	90.32%	88.55%	87.65%	83.27%	82.39%
95%	97%	99%	97%	9.40	22566	14.79	88.49%	88.13%	88.98%	88.99%	80.80%
97%	97%	99%	97%	9.60	23035	9.03	90.35%	88.58%	85.88%	83.22%	82.38%
99%	97%	99%	97%	9.79	23494	6.74	92.22%	88.55%	87.59%	84.95%	84.06%
95%	99%	99%	97%	9.57	22977	39.18	90.32%	88.61%	84.00%	83.14%	82.23%
97%	99%	99%	97%	9.80	23509	8.26	92.22%	88.58%	85.86%	84.95%	84.06%
99%	99%	99%	97%	9.98	23963	22.29	94.12%	88.55%	87.64%	86.69%	85.77%
95%	95%	95%	99%	9.00	21588	42.85	84.88%	88.61%	84.08%	79.88%	75.85%
97%	95%	95%	99%	9.20	22076	10.24	86.67%	88.58%	85.92%	81.66%	77.56%
99%	95%	95%	99%	9.38	22522	19.62	88.45%	88.55%	87.64%	83.20%	79.03%
95%	97%	95%	99%	9.20	22075	11.24	86.67%	88.13%	89.21%	79.79%	77.52%
97%	97%	95%	99%	9.41	22572	20.79	88.49%	88.52%	85.98%	83.41%	79.18%
99%	97%	95%	99%	9.58	22989	27.18	90.32%	88.55%	87.61%	84.97%	80.56%
95%	99%	95%	99%	9.39	22537	4.62	88.45%	88.27%	89.21%	88.13%	79.06%
97%	99%	95%	99%	9.60	23038	21.82	90.32%	88.58%	85.94%	85.05%	80.88%
99%	99%	95%	99%	9.77	23445	45.74	92.18%	88.55%	87.69%	86.77%	82.29%
95%	95%	97%	99%	9.21	22113	26.76	86.67%	88.61%	84.15%	79.99%	77.67%
97%	95%	97%	99%	9.41	22593	41.79	88.49%	88.58%	86.04%	81.58%	79.33%
99%	95%	97%	99%	9.58	23002	14.18	90.32%	88.55%	87.71%	83.36%	80.79%
95%	97%	97%	99%	9.41	22582	30.79	88.49%	88.29%	79.95%	81.03%	79.25%
97%	97%	97%	99%	9.61	23062	36.03	90.35%	88.58%	85.92%	83.31%	80.90%
99%	97%	97%	99%	9.79	23499	1.74	92.22%	88.55%	87.61%	84.94%	82.43%
95%	99%	97%	99%	9.60	23035	18.82	90.32%	88.61%	84.15%	83.31%	80.79%
97%	99%	97%	99%	9.81	23545	44.26	92.22%	88.58%	85.90%	85.01%	82.55%
99%	99%	97%	99%	9.99	23971	14.29	94.12%	88.55%	87.61%	86.69%	84.10%
95%	95%	99%	99%	9.40	22567	25.38	88.45%	88.61%	84.61%	80.01%	79.16%
97%	95%	99%	99%	9.58	22999	17.18	90.32%	88.58%	88.90%	81.54%	80.72%
99%	95%	99%	99%	9.78	23474	16.74	92.18%	88.55%	87.65%	83.27%	82.39%
95%	97%	99%	99%	9.60	23041	24.82	90.32%	88.13%	88.98%	88.99%	80.80%
97%	97%	99%	99%	9.79	23494	6.74	92.22%	88.58%	85.88%	83.22%	82.38%
99%	97%	99%	99%	9.99	23968	17.29	94.12%	88.55%	87.59%	84.95%	84.06%
95%	99%	99%	99%	9.77	23452	38.74	92.18%	88.61%	84.00%	83.14%	82.23%
97%	99%	99%	99%	9.98	23963	22.29	94.12%	88.58%	85.86%	84.95%	84.06%
99%	99%	99%	99%	10.19	24457	22.83	96.06%	88.55%	87.64%	86.69%	85.77%
100%	100%	100%	100%	10.62	25484	0.00	100.00%	88.54%	88.53%	88.53%	88.52%

Table A.2: Simulation results by folding configuration (sorted by machine setting)

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se



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