Production process development through automation in a metal industry company

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Abstract

The development of a mid-size deep drawing process through automation was the main aim of this study, which was also aligned with the interests of the target company. This aim was pursued by exploring whether the automation in mid-size deep drawing would bring benefits and what those benefits would be. It also included the investigation of the suitable robot and automation level for this process development. In addition, various methods for investment calculations were required to examine the profitability of the investment. Mixed methods research was conducted, during which the production process development was considered and examined from various perspectives, such as cycle time reduction, robot programming and usage, quality and ergonomics. Both quantitative and qualitative data were gathered from different sources, including measurements, data collection from internal reports, interviews and observations in the target company.

The results illustrated that mid-size deep drawing automation would bring various benefits, such as reduced cycle time due to process standardisation, increased machine utilisation and decreased variability. Another benefit would be the improvement of deep-drawn parts' quality with an automated process, as a result of standardisation in metal sheet lubrication and precise placement in the deep drawing machine. Meanwhile, the automation of mid-size deep drawing would improve ergonomics and safety as well as increase the morale and productivity of operators. The results also showed that industrial robots would be suitable in mid-size deep drawing with automation level 4. Furthermore, the results revealed that investment in an industrial robot would pay back in a few years and would be profitable for the company. Overall, it was concluded that the target company should consider utilising industrial robots in the mid-size deep drawing for loading and unloading, i.e., with automation level 4. The time-value of money should also be considered when making investment calculations, based on which Net Present (NPV) method for calculations was suggested.

Keywords/tags (subjects)

Automation, Deep Drawing Process, Ergonomics and Safety, Production Process Development, Robots.

Miscellaneous (Confidential information)

Appendices 1, 2, 3, 4 and 5 include confidential information, which are hidden from the public thesis. The basis for secrecy is section 24(17) of the Act on the Openness of Government Activities (621/1999), a company's business or trade secret. The period of secrecy is five (5) years, the secrecy will end on 18 May 2028.

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Glossary

Term	Definition
Automation	Application of technology and equipment in production processes to minimise or eliminate manual work
Cycle time (*CT*)	Time from the beginning of the part's production until the end, i.e., the time during which the part is WIP.
Deep drawing	A production process of pressing the metal sheet by a punch into a drawing die.
Lean robotics	Method of efficient robotic cell deployment.
Process standardisation	Creating a set of tasks, their guidelines and sequence by eliminating non-value-added tasks.
Robot	Reprogrammable manipulator designed to implement various tasks.
Robotic cell	Workstations including a robot or robots in them.
Throughput (*TH*)	The average output of the machine or workstation, including only non-defective parts, per unit of time.
Utilisation (*u*)	The amount of time when the machine or the workstation is actually in use and not idle.
Work-in-process (*WIP*)	Parts, the production of which started, but they are not ready end items yet.

1 Introduction

Companies in every industry aim to develop their operations and improve their results. The significance of process development is particularly stressed nowadays when continuous improvement is considered a crucial phenomenon. The process development can be conducted in various manners using different strategies and tools. Therefore, the development methods and steps may vary in different industries and companies. When it comes to industries producing and offering ready products, the emphasis is put on reducing all kinds of waste that lead to unnecessary costs, improving productivity, and increasing throughput. Small actions and changes within the daily activities of the company as well as more extensive changes that require investments can both be beneficial for process development. The scale of development actions depends on the actual conditions of company operations and the company's willingness and readiness to make changes and monitor change management.

This study concentrates on production process development in a metal industry company. The chosen method for development is the usage of automation in production processes, and mid-size deep drawing is the production process aimed to be developed. The topic of this study was chosen based on the significance of automation usage in production processes nowadays as well as the target company's needs. Various aspects of production need to be considered before investing and automating the processes. More precisely, it is essential to study and evaluate the effects of automation on production concepts, human labour, their safety and the company financially. This study examines the production phenomena, deep drawing process, safety and ergonomics, automation and robotics and their connection and effects on each other. It is important to note that the study is conducted in a target company operating in the metal industry, and the results related to the benefits of automation in mid-size deep drawing, the suitable automation method and levels are drawn based on the data gathered from this company. At the same time, the results analysed from the collected data align with the literature; hence, they are generally applicable in the industry.

1.1 Background and significance of the research

The production process development can be viewed from different perspectives. When deciding on how to look at development possibilities, the Logistics Trend Radar by DHL was utilised (see Figure 1). In more detail, the trends applicable in the manufacturing sector with a high impact were considered. According to the Logistics Trend Radar provided by DHL (2022), robotics and automation are considered a megatrend of high impact that will be relevant in the industry within the upcoming 5 years. In other words, the logistics industry is evolving towards automated operations in order to minimize throughput time, decrease costs and satisfy rising customer demand. More importantly, the usage of automation and robotics in production processes aligned with the target company's interest. That is, the company's main interest was improving the economic results through process improvement with automation. Therefore, the objective was to study various automation options and how they can be utilised for enhancing different concepts of production processes and choose the most suitable option for this particular company case. Moreover, an insight into how automation and robotics with modern technologies influence different production concepts, such as cycle times, machine utilisation, safety and ergonomics, would be a significant contribution to the industry.

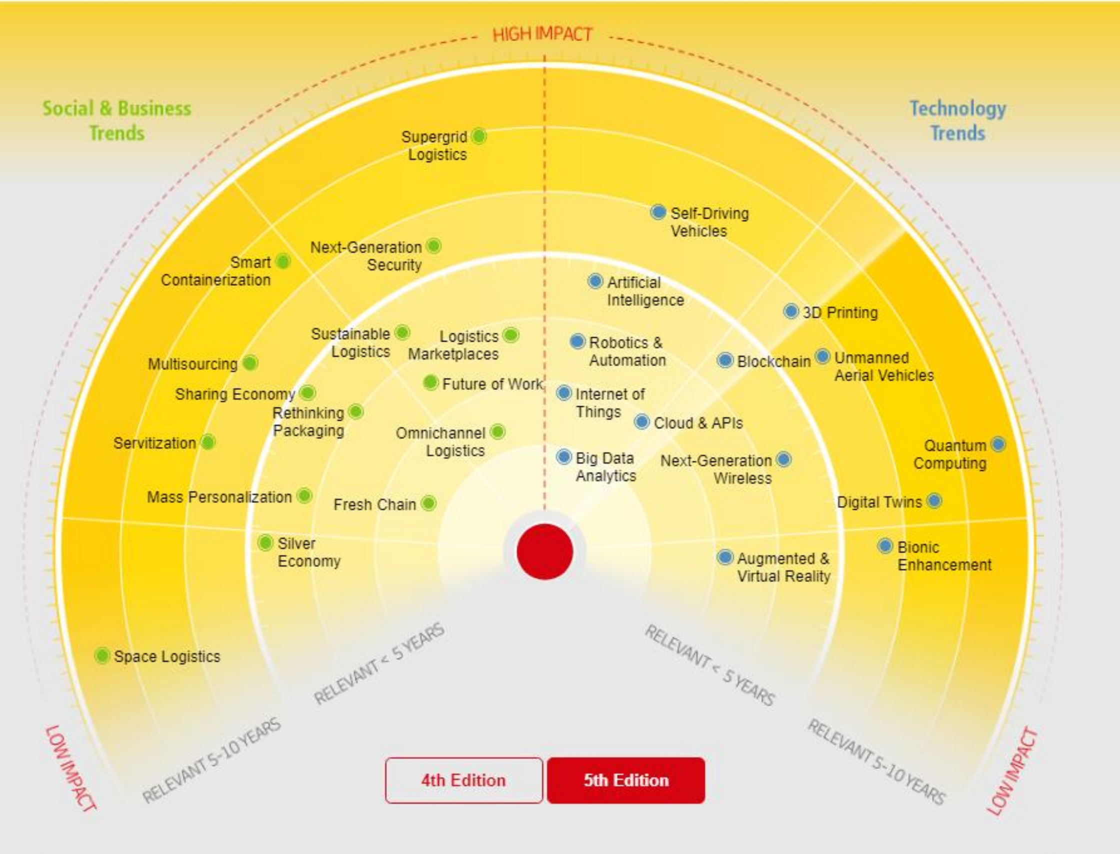

Figure 1. Logistics Trend Radar (adapted from DHL, 2022).

1.2 Research objectives and questions

As already mentioned, the aim of this study is to find out how automation can be used to improve production processes. The objective is to improve the economic results of the company by increasing the utilisation of machines and minimizing the cycle times. Moreover, the safety of the operators and ergonomics are of interest when automating the processes. In this regard, research questions are formulated as follows:

1. Does the automation in mid-size deep drawing processes give benefits? What are those benefits, if any?
2. What kind of robotics can be included and to what degree it is worth automating?
3. Which methods can be used for calculating the payback time for the investments?

In other words, the objective of this study is to find out the benefits of automation in mid-size deep drawing, considering different perspectives. More precisely, the improvement of different attributes such as cycle times, throughput and utilisation, and automation's effects on them need to be studied. The aim is also to study how operator safety can be improved with automation and the alignment of ergonomics with automation. Finally, quality assurance needs to be kept in mind. Thus, it is important to guarantee that process automation would not result in a decline in quality; instead, the quality improvement of the products and production is aimed. By answering these questions and meeting the objectives of the study, it will be possible to not only make development suggestions applicable to the target company but also create a general understanding of automation in this kind of production process and highlight the benefits and possibilities it brings.

1.3 Limitations of the study

Once the research objectives and questions are defined, it is also important to address the limitations of the study. The first limitation refers to the production process, the automation possibilities of which are going to be studied. The deep drawing process, particularly mid-size deep drawing, and its automation are included in the scope of this research, and any other kind of production processes are not addressed in this study. In addition, the study is conducted in a metal industry company; therefore, the results related to deep drawing automation are also relevant to the companies operating in the same industry.

Another limitation concerns the quality of parts, as the quality is not the main focus of this study. However, it is important to discuss quality in a sense that process automation does not negatively affect the end item quality and enables quality improvement through the actions taking place during the production process. The factors, such as machine parameters, that can affect deep-drawn parts' quality but are not taking place during the actual deep drawing process will not be studied. That is, only the factors affecting the quality that take place during the deep drawing process, such as metal sheet lubrication and placement in the deep drawing machine, are included in this study. Moreover, various quality standards are also not included in the scope of this study.

It is also important to note that automation is a relatively broad topic and includes various types. In this regard, studying all the automation possibilities is time-consuming and not realistic. Therefore, the automation of the deep drawing process is limited to the use of robotics. In particular, industrial and collaborative robots are of interest. The reason for this choice is that the target company is more familiar with these robots, and the personnel have more knowledge and experience with the mentioned robots. In addition, this limitation is also consistent with the fact that partners supplying these robots are available in Finland.

1.4 Overview of the thesis

After defining the research objectives, questions and limitations, research approaches and data collection methods are reviewed in chapter 2, enabling to grasp an understanding of different research approaches and how data can be collected for each. This is followed by a literature review covering all the necessary topics needed to gain knowledge on different perspectives of this study. The literature review presented in chapter 3 is divided into four main parts: production phenomena, deep drawing process, safety and ergonomics, and robotics and automation. After the relevant literature is reviewed, the implementation of the study starts in chapter 4. The implementation of the study includes the selection of the research approach and research design, along with the selection of data to be collected and its sources. The implementation of the study also consists of various sections, each taking a different perspective on the study and describing the relevant data collection procedure along with the overall implementation of it. The reliability and ethical considerations are also addressed at this point. Afterwards, the gathered data is analysed, and the results are presented in chapter 5. The results are also divided into sections based on different perspectives on the study and the collected data, and they are summarised and merged at the end of the chapter. The final chapter 7 includes the discussion and conclusions of the study. This chapter contains the answers to research questions, suggestions for implications for the company, and directions for future research.

2 Research approaches and data collection methods

Along with the understanding of production phenomena, deep drawing process, safety and ergonomics, robotics and automation, research needs to be conducted in order to be able to study and answer the research questions. Generating knowledge and developing understanding via research involves collecting data and analysing it to create a picture of the external and internal worlds (Walliman, 2021, p.18). In this regard, it is important to understand different types of research approaches and choose the suitable method for data collection and interpretation.

As Creswell and Creswell (2018, pp.40-42) state, research approaches are plans and processes for conducting research that brings together distinct methods, study designs, and philosophical perspectives. Three main research approaches are defined to be quantitative, qualitative, and mixed methods. It is important to note that qualitative and quantitative approaches are not polar opposites but rather various points on different sides along a continuum. The difference between qualitative and quantitative research is usually described in terms of using words for qualitative research as opposed to using figures for quantitative research. What refers to mixed methods research, it falls somewhere in the centre of this continuum due to its integration of both qualitative and quantitative approaches.

Creswell and Creswell (2018, pp.56-59) also discuss the selection of the research approach, which depends on various factors, including the research problem or research questions, the researcher's individual experiences and the target audience. More precisely, quantitative research is the most suitable approach when a research problem involves testing a theory, identifying elements that affect an outcome and comprehending the best predictors of outcomes. On the other hand, the qualitative research approach is appropriate for examining a phenomenon that has not been extensively explored or involves an understudied sample. Mixed methods research should be chosen when the best knowledge regarding the research problem can be achieved by combining the advantages and data of both quantitative and qualitative research. From the point of the researcher's individual experiences, the qualitative research approach is better suited to individuals who enjoy conducting one-on-one interviews and making observations, whereas the quantitative research approach is for individuals who are skilled in statistics and technical writing. Additionally, individuals, who are qualified for conducting both quantitative and qualitative research as well as have enough resources, may prefer mixed methods research. Last but not least, the favoured research approach of the target audience, such as professionals in the field, a commissioning company or faculty committees, may influence the decision of the researcher regarding the approach selection.

After selecting the most suitable approach, the type of inquiry should also be chosen. The types of inquiry within the three research approaches are known as research designs and they provide clear directions for carrying out the research study (Creswell & Creswell, 2018, p.49). There are different research designs typical to each research approach, which are discussed in the following sections. Moreover, the methods for data collection, analysis, and interpretation are key components of any research approach. It is important to take into consideration all possible data collection methods to use the ones which will be the most effective for investigating the research problem. Data collection methods vary, such as surveys with closed-ended, interviews with open-ended questions, and observations, which are covered in more depth in section 3.4.

2.1 Quantitative research

The approach for evaluating theories and concepts through analysing the connection between variables is known as quantitative research (Creswell & Creswell, 2018, p. 41). According to Walliman (2021, p.156), the primary goals of conducting quantitative research include measuring, developing ideas and concepts, generating forecasts, testing hypotheses, investigating relationships and drawing comparisons. As can be seen from the name, in this kind of research, data is collected in the form of numbers, and their attributes and relationships are investigated using mathematical operations. Quantitative data can be collected through surveys as well as content analyses of various publications and documentation. It is critical to consider the levels of measurement when collecting data, such as nominal, interval, ordinal and ratio as well as the number of cases when determining the type of suitable analysis, which is known as statistics. Statistical techniques are provided by various computer packages, which makes them accessible to researchers without requiring any deep mathematical knowledge.

Within each research approach, it is important to understand the most common research designs in order to have precise directions for carrying out the research with that particular approach. Creswell and Creswell (2018, p. 207) discuss the survey design and experimental design as common research designs when conducting quantitative research. In a study design, a sample of a population is examined, based on which the trends, features and views of that population are analysed quantitively and correlations between its variables are tested. The use of survey design can assist in addressing descriptive questions as well as questions about variables' connections and predictive connections over time. In an experimental design, one or more variables are purposefully modified to assess how the change affects one or more desired outcomes. As all other variables are kept constant during an experiment, the effects of this modification are isolated.

2.2 Qualitative research

Qualitative research is focused mostly on facts conveyed in verbal data instead of relying heavily on numerical data (Walliman, 2021, p.177). Data collection and analysis are crucial components of this research approach. In qualitative research, data is collected through observations, interviews, documents and visual materials; and a technique is designed for recording the collected data. Unlike quantitative research, qualitative research does not require random sampling or a large number of participants to generate data; on the contrary, the goal of qualitative research is to carefully choose the research implementation sites and participants that will best enable the researcher to comprehend the research problem (Creswell & Creswell, 2018, p. 262). After some data is gathered, comprehension of the situation is improved and the need for more data collection is recognized according to analyses of the initial data (Walliman, 2021, p.177). In order to develop a more in-depth comprehension of the research problem, this procedure is repeated.

Referring to the research designs used in qualitative research, Creswell and Creswell (2018, pp.50-51) suggest narrative research, phenomenological research, grounded theory, ethnography and case studies. In narrative research design, the lives of individuals are studied by asking one or more of them to share their life experiences and a narrative chronology is created by retelling these stories, which is typically done as a fusion of viewpoints from the participants' lives and the researcher's life. Furthermore, the experiences that individuals encounter with a phenomenon are described in phenomenological research design, which has solid philosophical foundations. In the case of the next grounded theory design, the broad, abstract theory of a process, activity, or interaction is based on the participants’ opinions. The ethnographic design is used for studying an intact cultural group's common patterns of behaviour, language, and activities are studied over an extended period of time by conducting interviews and making observations. Finally, within the design of a case study, a detailed analysis of a case is conducted, which commonly includes a program, activity, event, process, or one or several participants.

2.3 Mixed methods research

Creswell and Creswell (2018, p. 41) describe mixed methods research as the collection of both quantitative and qualitative data, their fusion, and the application of distinctive designs. The main idea behind this research method is that the combination of quantitative and qualitative data makes it possible to reveal new information and perceptions that would not be possible with only one type of data. Moreover, mixed methods research enables combining the advantages of both quantitative and qualitative data collection, getting beyond their limitations and improving the comprehension of the research problem and research questions. Similarly, Walliman (2021, pp. 200-201) mentions that the purpose of adopting mixed methods is to strengthen a single design's aspects while eliminating its shortcomings along with the aim to analyse and interpret the research problem at various levels.

According to Creswell and Creswell (2018, p. 299-308), it is important to understand the applicable research designs and to choose the suitable one when conducting mixed methods research. The convergent design, the explanatory sequential design, and the exploratory sequential design are the three primary mixed methods designs that are recognized. The convergent design is the most famous one and it has only one phase during which both quantitative and qualitative data are collected and analysed separately, after which their results are compared to determine whether or not they are consistent. The key challenge in this design is combining and analysing these two databases, which can be done by side-by-side comparison, joint display of data through a graph or a table, or by converting qualitative data into quantitative variables and combining the two quantitative databases. The explanatory sequential design includes two-phase data collection when the quantitative data is collected and analysed in the first phase, and the results of the first phase are used to prepare or expand upon the second phase of qualitative data analysis. It is crucial to link the results of quantitative data analysis to qualitative data collection since the primary goal of this design is to use qualitative data in order to explore the initial results of quantitative data analysis in greater detail. The last mixed methods research design is the three-phase exploratory sequential design which starts with qualitative data collection and analysis, followed by the construction of a feature to be evaluated and its testing in the third phase of quantitative data analysis. The difficulty is recognising and developing the quantitative feature in the second phase using the data from the first qualitative phase, which is the integration point in this design. These three main mixed methods designs are summarised in Figure 2.

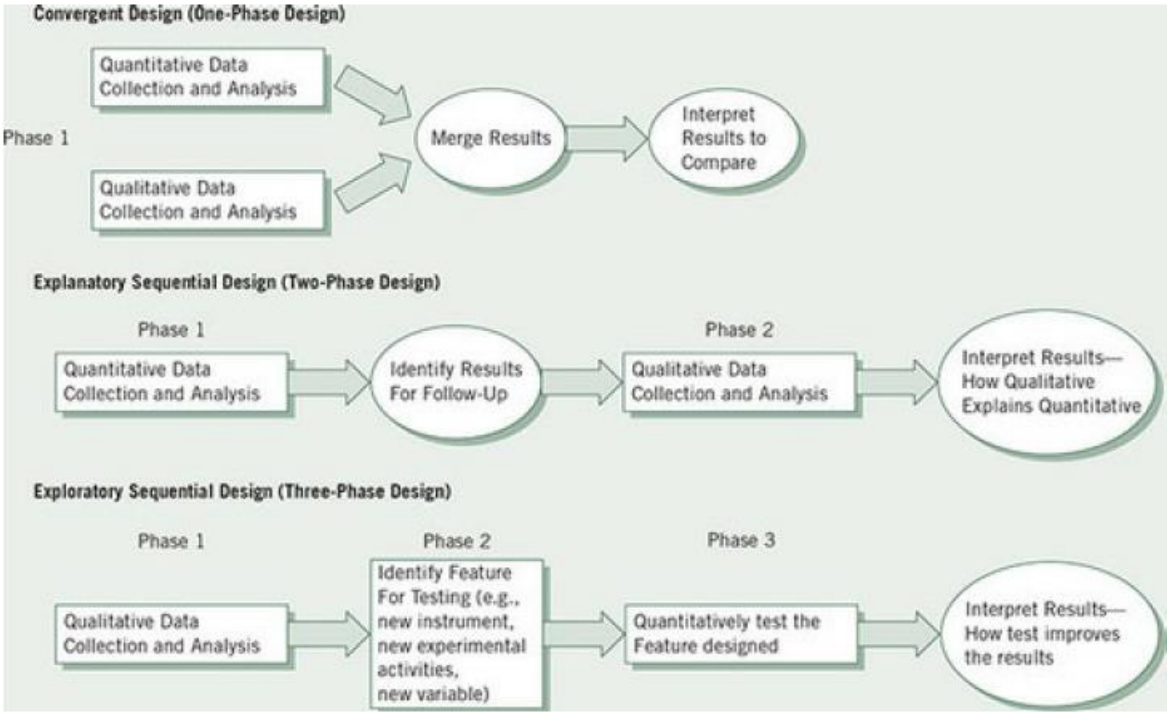

Figure 2. Mixed Methods Designs (adapted from Cresswell and Cresswell, 2018, p. 300).

2.4 Data collection methods

The selection of a suitable research approach alone is not enough, and the data collection methods need to be studied. Different data collection methods can be utilised for each of the research methods. This section discusses various data collection methods, including surveys, interviews, observations, focus groups and case studies.

Survey questionnaire

To begin with, the survey questionnaire as a data collection method consists of questions and responses. A survey questionnaire is a suitable tool for gaining quantitative data but can also be used as a tool for qualitative data collection. As Westat (2002, p. 49) mentions, responses can be either close-ended or open-ended. Close-ended responses are useful when quantitative data is needed, as the respondents need to choose their answers from predetermined options. Open-ended responses, on the other hand, give the respondent the possibility to answer the question in their own narrative. What comes to the advantages, surveys are structured, they are easy for the respondents to understand and use, and they are also cheap and easy to make for the researchers, particularly in cases where a large number of responses is anticipated (Walliman, 2021, pp. 132-133). When selecting a survey to gather data, it's essential to keep in mind that a broad range of subjects may be covered and can be analysed owing to the current software; nevertheless, survey responses may only present the overall picture without any in-depth analysis.

Interviews

Interviews can also be conducted in order to collect qualitative data. The use of interviews as a data collection method is common when the human perspective is believed to be valuable and profound for getting a deeper understanding of the topic and solving the research problem. Walliman (2021, pp. 137-138) distinguishes three types of interviews:

- Structured interview, which includes predefined questions and closed-ended responses;
- Unstructured interview, which is conducted in a flexible way enabling to get into more details when interesting and unexpecting topics come up;
- Semi-structured interview, which commonly starts with predefined questions and then expands to address more issues in a flexible manner.

Westat (2002, p. 52) mentions that interviews enable gathering the most comprehensive details and novel insights on the topic. Moreover, the interviewer has the opportunity to clarify and explain questions, which enhances the possibility of getting helpful responses. Despite the fact that all these factors make interviews appear like a desirable data collection method, there are drawbacks, such as the volume of the gathered information being quite large and challenging to transcribe or reduce.

Observations

Observation is another data collection method used to record data, which may be done visually or by utilising a variety of devices for measurements. Both quantitative and qualitative data can be recorded through observations. As Westat (2002, p. 55) states, observation can be useful for formative evaluation, which gives an initial understanding of the research problems, as well as for the summative evaluation, when evaluating the success of the project. When discussing the need to use observation as a data collection method, the benefits, such as the possibility for the observer to enter into the context and understand it better and to exist in the natural setting, are kept in mind. In addition, the observer has the possibility to gain direct information about the setting and the individuals operating in that setting as well as to foresee unanticipated results. Observations, on the other hand, can be expensive and time-consuming, and there is a risk that the observer may affect the behaviour of the individuals operating in the setting that is being observed.

Focus groups

According to Westat (2002, p. 52), attributes of both participant observation and interviews are incorporated in focus groups. In more detail, an interview of the focus group, which includes a group of people sharing the same characteristics, is conducted. The behaviour and attitudes of focus group participants are also observed since they are just as significant as the responses to the questions. Focus groups are employed when it is necessary to come up with fresh concepts, pinpoint shortcomings and get recommendations from different people with complementary qualifications and experiences. Focus groups can also help in getting opinions on project results and implications.

Case studies

Case studies are also commonly conducted as a data collection method, and they are mostly based on ethnographic observation. More precisely, case studies are descriptive examinations where the examiner is part of the setting, has access to available documents, interacts with the participants, observes the operational processes, and develops an analysis of project findings (Westat, 2002, p. 61). Conducting case studies may enable noticing or explaining factors which would be otherwise invisible through other data collection methods. One of the possible risks connected to case studies is that individual cases can be overgeneralized. Furthermore, case studies, similar to observations, require time and other resources.

3 Literature review

3.1 Typical phenomena in production

Since the study primarily focuses on production processes and their development possibilities, it is important to comprehend common production phenomena. In other words, the key concepts that are intended to be improved, their features and connections with each other, and some steps for improvements need to be understood. Furthermore, lean manufacturing is kept in mind while examining production processes as well as in further steps of implementing the study. To explain briefly, lean manufacturing refers to the philosophy when all forms of waste are aimed to be eliminated and the products are produced only in the needed quantity and time (Goetsch & Davis, 2016, p. 366). Although the lean approach is not the focus of this study, it is aligned with the study objectives as, according to Goetsch and Davis (2016, p. 375), reduced work-in-process, shortened cycle time and waste elimination are among its benefits. Thus, it is valuable to take lean philosophy and its features into account when working on production development in order to “walk with world-class manufacturing” and accomplish the benefits that it brings.

Hopp and Spearman (2008, p. 221) find that “manufacturing management needs a science” in order to have a link between policies and objectives, enabling more profound and predictable improvements. Both in operational management and in production literature, the used terms vary, which creates challenges for industry-wide communication and learning. In this regard, the most important terms and concepts are firstly defined in the following section, as precise terminology is needed not only for “manufacturing science” but also for implementing this study. This makes it feasible to go into more detail on production phenomena and understand how these concepts can be improved through corrective actions.

3.1.1 Key concepts and definitions

Starting with defining the terminology, the term *part* is used in this study to refer to the piece of raw material, component, or assembly that is being worked on at the workstation. In this regard, raw materials are the materials, such as bar stocks or metal sheets, purchased from suppliers;

components are individual pieces, such as gears or bolts, assembled to products; and assemblies are fully assembled products or end items. It is also important to note that one or several machines, which carry out identical tasks, such as the deep-drawing machine, are implied by a workstation. Furthermore, it is crucial to grasp the meaning of the term *work-in-process (WIP)* when discussing the different parts used within the production process. *WIP* refers to the inventory from the start of the product's processing until it becomes an end item; in other words, WIP includes all the products until they reach the finished goods inventory (Hopp & Spearman, 2011, p. 230). It is common for some companies to have high inventory and high WIP volumes in order to keep up with customer demand and continue production even when there are problems in the downstream workstations; however, it just covers the existing problems within production and holds the production back from an efficient operation and continuous improvement. Ideally, WIP as well as the inventories of raw materials, components and end items need to be reduced, which will make it possible to "unmask production system's problems" as a part of lean manufacturing (Goetsch & Davis, 2016, p. 375).

One of the objectives of this study is to increase the utilisation of machines or workstations through automation. According to Hopp and Spearman (2011, p. 231), *utilisation* of the machine is the portion of time when it actually processes or, in other words, it is not idle. When calculating the utilisation, the time spent on processing the parts as well as the time of parts waiting or machine waiting due to setup, machine failure, or other hindrances is also considered. Thus, utilisation can be defined as the relation of the arrival rate to the effective production rate. However, it is possible that either one of the arrival rate and effective production rate is unknown, and the utilisation, in this case, can be simply calculated by dividing the time used on processing the parts by the total available time (Chapman et al., 2017, p. 129).

Production processes' output, often known as throughput or throughput rate, is typically of interest. Hopp and Spearman (2011, p. 229) define a system's *throughput (TH)* as the average output of a machine, workstation, or line per time unit. This output is the average quantity of non-defective parts per time unit and does not include the scraps or defective parts. It is important to remember that throughput is limited by the *capacity* of the machine or workstation. Moreover, the total throughput cannot be more than the capacity of the bottleneck. Here it is important to understand that bottlenecks are those workstations which are overloaded, i.e., the needed capacity exceeds that available capacity (Chapman et al., 2017, p. 156).

Hopp and Spearman (2011, pp. 340-343) also consider the basic steps for increasing the throughput. One of these steps is increasing the effective rate of bottleneck, which can be done by, for example, adding equipment and/or operators, having flexible cross-trained operators and through quality improvements. The bottleneck rate can also be increased by making sure that the production does not stop during the breaks and lunch by covering for operators. Another step for increasing throughput includes buffering bottleneck with either WIP or capacity.

Cycle time, also referred to as flow time or throughout time, is an important concept in production that has various meanings in different literature. It could refer to the amount of time given to each workstation to finish its task. In some other literature, it could mean one machine's processing time. The *cycle time (CT)*, in this case, is the amount of time it takes on average from the moment a task is released to the moment it reaches an inventory point; thus, it can be said that cycle time is the time during which the part is WIP (Hopp & Spearman, 2011, p. 230). Within production processes, short cycle times typically result in lower costs and enable quick adaptation to the shifting demand. Viewing from the perspective of lean management, any additional time which is not directly required for manufacturing the end item is considered a non-value-added task and can be considered as an additional cost (Goetsch & Davis, 2016, p. 376). In this regard, the cycle times are aimed to be minimised in practice.

Hopp and Spearman (2011, pp. 343-346) view cycle time to be the sum of the moving time to the workstation, the queue time before processing, the machine setup time, the processing time, the process batch time of waiting to form a batch or for its turn to machine, the time of waiting to match with the other components before the process can start, minus station overlap time. In this regard, the total throughput time reduction is considered from the perspective of improving the mentioned times. The queue time is usually a result of variability and utilisation; thus, it can be improved by reducing any of these two. The utilisation reduction can be achieved by increasing the effective rate of the bottleneck, which is already discussed. The reduction of variability in arrival times or process times is commonly made through decreasing setup time and repair times, improving quality and quality control with the intent to minimize rework or yield loss as well as reducing the operator variability whenever possible. Next, Hopp and Spearman state that reducing the process batch time will result in a throughput time reduction. Process batch size reduction is commonly the key to this, which can be achieved by setup reduction or batching optimization. The reason for this is that short setup times enable to have small batches without the need to increase utilisation and optimal batch sizes allow to have a better balance of batch time and queue time. Furthermore, the arrival times of parts to the workstation should be synchronized in order to minimize wait-to-match time. Since the station overlap time is deducted from the total throughput time, it should be increased. Having transfer batch sizes smaller than the actual production batch sizes will increase the station overlap times.

What is interesting is that a fundamental relationship between WIP, cycle time and throughput exists. This relationship is known as Little's Law and is defined as follows:

$$WIP = TH \times CT,$$

where WIP is work-in-process, TH is the throughput, and CT is the cycle time (Hopp & Spearman, 2011, p. 239; Silver et al., 2017, p. 695). This relationship can be applied in a single machine, a line or the whole plant and will hold over a long period of time when these three quantities are measured in the same units. Next, it is important to understand how this law can be applied in practice. Chapman et al. (2017, p. 398) state that quality improvements and setup time reductions will assist in WIP level and, thus, also inventory level reductions. According to Little's law, the reduction in inventory levels and WIP will result in decreasing the throughput time, which in its turn will enable the company to respond to the changing demand quicker.

Furthermore, it is important to discuss the relationship of utilisation with the other concepts. As already mentioned, raising the WIP or capacity can result in an increase in bottleneck utilisation, which is closely connected with the increase in throughput (Hopp and Spearman, 2011, p. 340). In addition, Silver et al. (2017, p. 695) discuss the relationship between utilisation and cycle time. Utilisation can be increased by starving the machines less, which can be achieved by increasing the WIP. Following Little's law, an increase in WIP requires an increase in cycle time. Consequently, the increase in utilisation can result in an increase in average cycle time. It can be concluded from all these that utilisations impact on the other concepts should be taken into consideration before taking steps to increase it, and an increase in utilisation should not be done just for the sake of increase. Figure 3 summarizes the important concepts in production and their important features that need to be kept in mind.

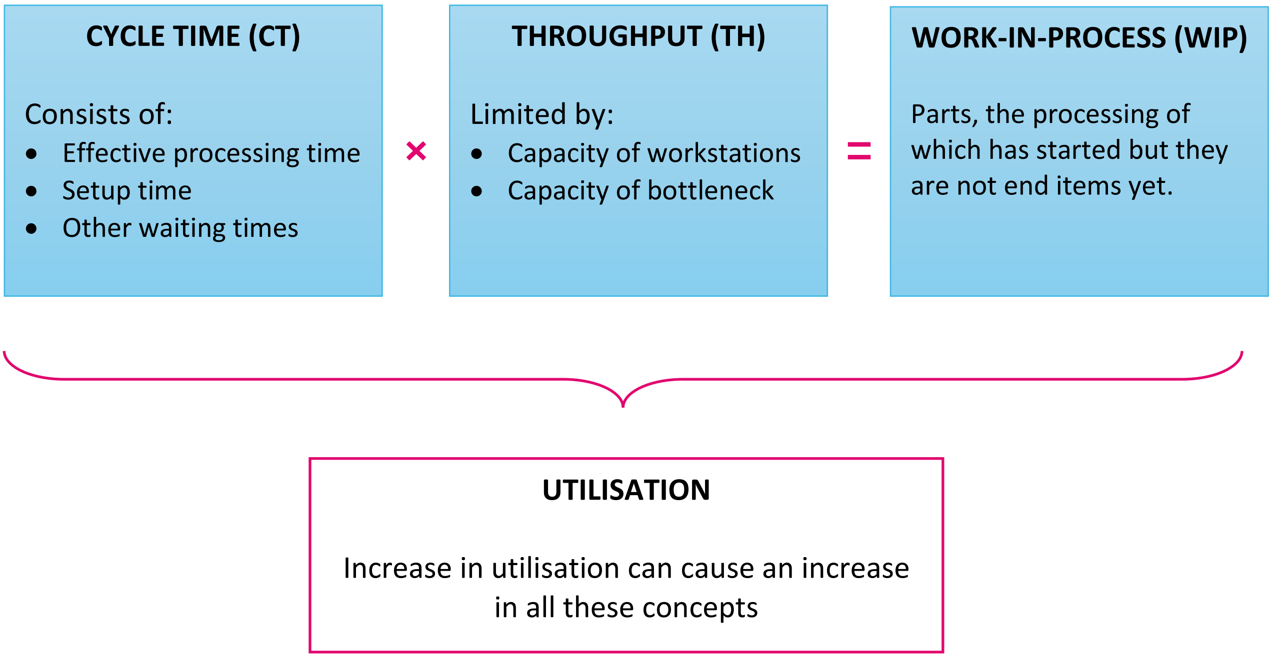

Figure 3. Production phenomena

3.1.2 Production systems

Moving to the production systems, the perceptions of push and pull systems as well as their key distinctions need to be understood. In the traditionally used push system, the dates and quantities are scheduled in advance. MRP (manufacturing resource planning) system is commonly referred to as a push system, which is initiated by the requirement for the end product, or more precisely, the required throughput (Chapman et al., 2017, p. 398). In other words, the information that initiates the schedule and the release of the work comes from outside of the system (Hopp & Spearman, 2011, p. 357). It can be concluded that the push system functions in an uncertain environment, connected to the fact that customer demand is unknown (Chopra and Meindl, 2016, p. 22). Pull system, on the other hand, allows replenishments to be made only based on the system status, depending on whether there is a demand for that particular part. Chopra and Meindl (2016, p. 22) refer to pull systems also as reactive processes, as they react to the customer demand and the customer, in this case, is the next workstation. Thus, the work releases are initiated based on the information inside the system. This information is what allows the pull system to function effectively, and the reason behind this is its connection to the state of work that is currently in process inside the system. What this means is that the amount of WIP is controlled in the pull system, unlike the push system, which controls the throughput. In this regard, Hopp and Spearman (2011, p. 358) define the main distinction between these two systems to be the fact that a limit is established on the WIP in a pull system, which is not the case in the push system. Figure 4 summarises the main idea behind the push and pull systems and shows the distinction between the two systems.

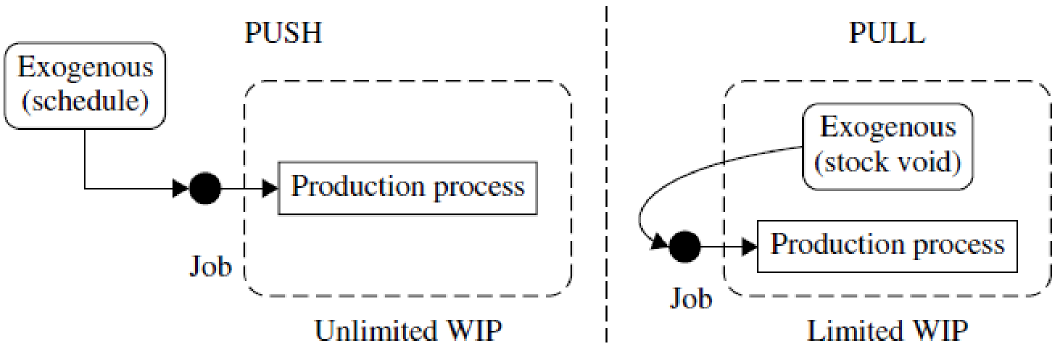

Figure 4. Push and pull systems (adapted from Hopp & Spearman, 2021, p. 357).

The next step is understanding the benefits that the pull system brings and why it was applied in the first place. Setting a limit on the amount of WIP prevents the system from becoming overloaded, as the releases are blocked beforehand. Consequently, the throughput decreases, which would have happened with the push system as well. The reason for this is that the pull system enables implementation of changes in engineering and scheduling priority in the event of machine breakdowns or similar issues as the orders are “only on paper”, whereas changes in scheduling priority need expensive expediting and the engineering changes are nearly impossible with push systems as the orders are already on the plant floor as WIP (Hopp & Spearman, 2011, p. 358). Thus, a reduction of manufacturing costs can be achieved with the WIP limit as a result of expediting and engineering changes that come with the pull system. Moreover, a limit on the WIP level lowers the total WIP level and, therefore, also the average WIP across workstations, which assists in reducing the variability, particularly the cycle time variability (Hopp & Spearman, 2011, p. 361). Due to the

WIP limit and subsequent decrease in total WIP, the need for quality assurance and quality improvements increases. Furthermore, the pull system requires the operators to go from downstream workstations to the upstream workstations in order to collect or so-called “pull” the needed parts, during which quality, which is another benefit of the pull system.

As can be seen from the previous paragraph, the benefits of the pull system mainly depend on the WIP level being limited in the pull system rather than the method of the pull. However, different pull systems need to be considered when making a choice for the company. The Kanban system is one of the well-known pull production systems, which is a two-card system. The basic principle behind this Kanban system is the usage of the production cards authorizing the production of the part which is specified in the card along with the quantity; and the move-cards authorizing the movement of the specified part from one box to the other (Chapman et al., 2017, p. 402; Hopp & Spearman, 2011, p. 168). The production on a certain workstation can start only when the production card is found by the operator and the needed parts are moved to the workstation according to the move-card, thus, controlling also the WIP. The circulation of production cards and move-cards in the Kanban system is illustrated in Figure 5.

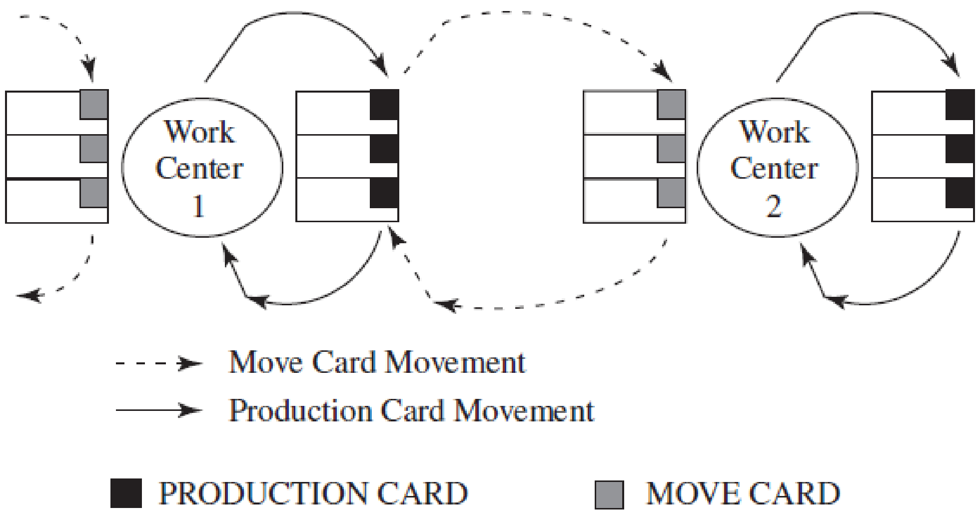

Figure 5. Circulation of Kanban cards (adapted from Chapman et al., 2017, p. 403).

Within the Kanban system, the capacity of the Kanban box is one of the first attributes to be decided. It is common to set the Kanban capacity the same as the capacity of the used box or container.

Based on this capacity, the number of Kanban cards can also be calculated. Chapman et al. (2017, p. 404) suggest the following formula as a simple way of calculating the number of Kanban cards:

$$y = \frac{D}{C},$$

where y is the number of Kanban cards, D is the demand per lead time and C is the capacity of the Kanban box. However, this is not the only way to calculate the number of Kanban cards. Another formula is obtained further developing this relatively simple formula by breaking down the demand per lead time into smaller attributes as well as taking into consideration the safety factor:

$$y = \frac{DT(1+x)}{C},$$

where y is the number of Kanban cards, D is the demand at a given time period expressed by pcs per time unit, T is the lead time for the Kanban box, x is the safety factor in decimals, and C is the capacity of the Kanban box (Sipilä, 2021).

Although the Kanban system is quite popular, it is not always the most straightforward pull system. In this regard, Hopp and Spearman (2011, p. 363) argue that simply putting a limit on WIP can be enough, and there is no need for further complications. The basic idea is that new replenishments are not allowed when the WIP is more or equal to the constant work in the process CONWIP. That is, a new job enters the line only when a job leaves CONWIP. To put it shortly, CONWIP maintains a line's WIP level at a consistent level by coordinating releases and departures. What is also significant is that CONWIP does not necessarily require the production line to operate within a single loop. According to Hopp and Spearman (2011, pp. 496-497), it is also possible to have several CONWIP loops within the production line, which are separated by WIP buffers. These buffers can cause increases in WIP level and cycle time; however, they might be a necessary trade-off for company-specific needs. Figure 6 demonstrates the card flow for the basic CONWIP system in contrast to the multiloop CONWIP system. It can also be seen from the same Figure 6 that CONWIP becomes identical to Kanban when each of the workstations is treated as a loop.

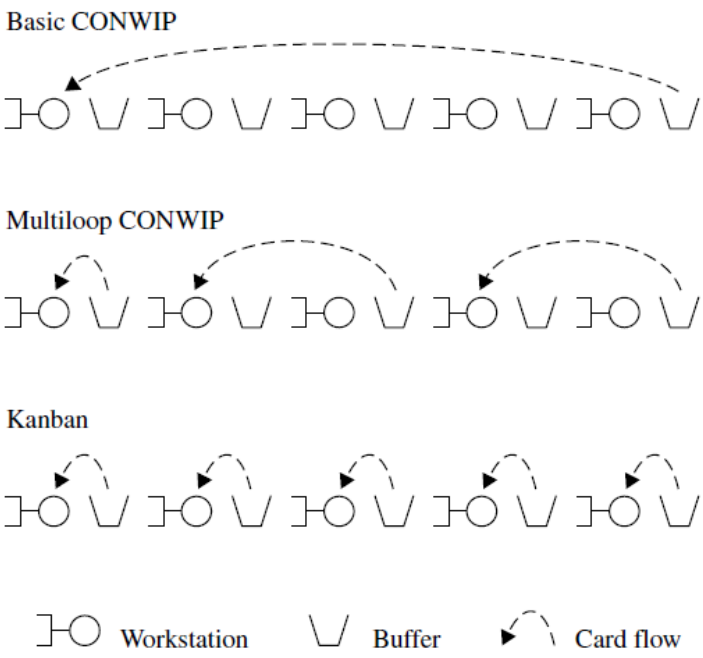

Figure 6. Card flow in CONWIP and Kanban (Hopp & Spearman, 2011, p. 496).

Hopp and Spearman (2011, pp. 380-381) refer to the advantages that CONWIP brings compared to the classic Kanban, as it simplifies the work by requiring only one card count in total rather than individual card counts in every workstation. In this regard, the operator stress is also reduced as the pacing control is more flexible. Using line-specific cards and a release list, CONWIP can adapt to a changing card mix as well. In addition, mix-dependent bottlenecks are commonly an issue, to which CONWIP can also adapt as WIP naturally tends to build up in front of the slowest workstation. Another advantage is when a problem arises at a particular workstation, production will continue up until that workstation and then resume when the issue is resolved with the CONWIP system, whereas in the Kanban system, the downstream workstation that has the issue will not send a replacement signal to the upstream and the upstream workstations will stop operating (Chapman et al., 2017, p. 409). These benefits are relevant to consider when the pull system is already in use, but a more suitable method is required.

On the other hand, it is possible that a complete shift from a push system to a pull system would be necessary. Therefore, the advantages of CONWIP over a push system need to be taken into consideration. The direct observability of WIP is one of the main benefits. Hopp and Spearman (2011, pp. 369-370) also show that CONWIP requires less WIP than a pure push system in order to gain the same throughput. It's significant to note that while a pure push system schedules the job releases and part replenishments, the CONWIP allows for work to be done ahead of schedule when there are favourable conditions. It is also found that a push system is less resistant to errors in its release rate than a CONWIP system is to errors in the WIP level.

3.1.3 Production strategies

When discussing production processes, it is important to address the existing production strategies, what characteristics are typical to them and how they are aligned with the improvement possibilities. The common production methods utilised in the industry include make-to-stock (MTS), make-to-order (MTO), configure-to-order (CTO), assemble-to-order (ATO), and engineer-to-order (ETO), each of which has a different lead time (see Figure 7).

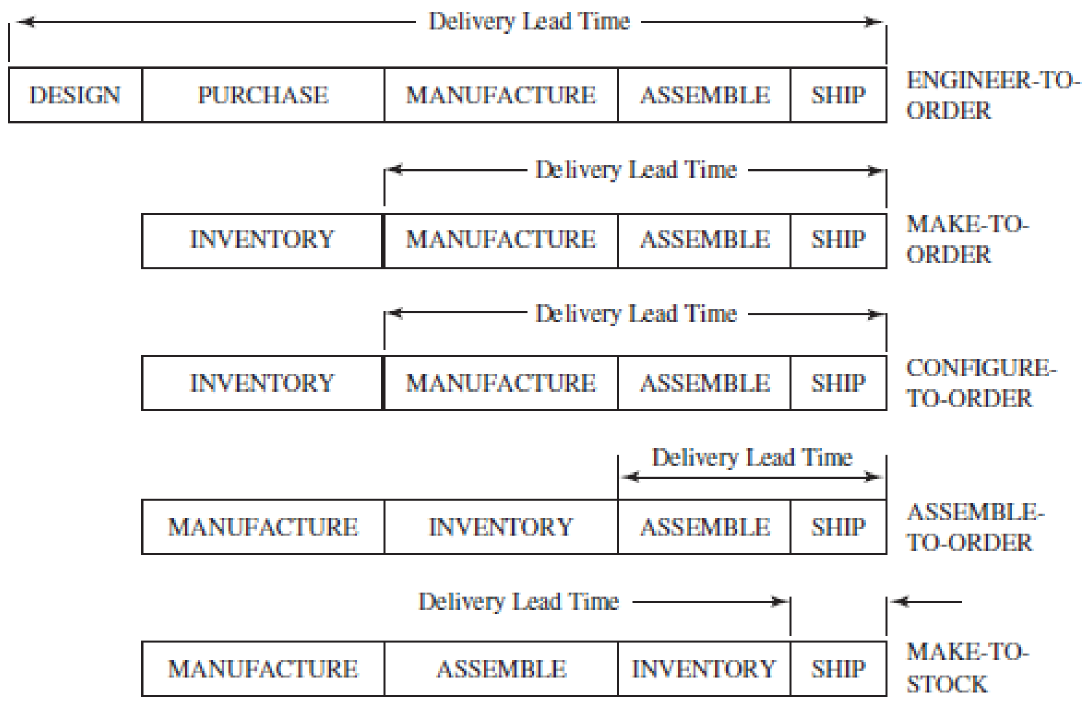

Figure 7. Production strategies and lead times (adapted from Chapman et al., 2017, p. 15).

Make-to-stock (MTS) refers to the production strategy in which the end items are produced and stored in the finished goods inventory, from where they are sold (Chapman et al., 2017, p. 16). In this system, the lead time is very short and the customer input in product design is very little. Companies typically utilise the MTS strategy when the demand is relatively constant and forecasts are available, the demanded lead time is shorter than the cycle time and the end items can be stored for a long time (Chapman et al., 2017, p. 44).

Chapman et al. (2017, p. 15) also define make-to-order (MTO) as another production strategy when production starts after the customer's order is received. Although custom-designed components may also be used, standard parts are typically used to create the end item. It is common for make-to-order systems to have raw materials stored in the inventory. This strategy is convenient to use when the lead time of the order is longer or equal to the cycle time of the end item being produced.

Configure-to-order (CTO) production strategy has a lead time similar to the one in MTO. With this type of strategy, customer involvement starts from the manufacturing stage, when the customer can order a unique configuration with desired features (Chapman et al., 2017, p. 16). Companies that offer end items with unique configurations for each customer and each order use this strategy.

The next production strategy is known as assemble-to-order (ATO), in which the assembly of the end item starts only after the customer order based on their requirements, and the standard components or options are inventoried in advance (Chapman et al., 2017, p. 16). It can be said that only the necessary alternatives for assembly are chosen by the customer in terms of product design. Typically, automobiles or computers are produced using the ATO strategy; that is, the necessary components are already available, and these items are just assembled once the customer places an order.

Finally, it is also possible that end items are highly customized or have a unique engineering design specified by the customer, in the case of which an engineer-to-order (ETO) production strategy is used (Chapman 2017, p. 15). In other words, customer involvement in product design is high. It is also important to note that the needed materials and components are purchased only when needed for production, which results in a relatively long lead time (Chapman 2017, p. 15). In fact, the engineer-to-order production system has the longest lead time among all the production systems discussed in this section.

3.2 Deep drawing process

Along with the knowledge of production phenomena, a general understanding of production processes is also necessary. Mechanical presses are utilised in a large number of production processes, including bending, deep drawing, coining and embossing. Since the deep drawing process is the primary focus of this study, it is covered in more detail here. It is also one of the essential stages in sheet metal forming. Within the deep drawing process, a blank metal sheet is placed on the binder and is drawn into a metal cup in a hollow cavity known as a die, using the normal force of the punch (Dwivedi & Geeta, 2017). The blank metal sheet is placed under the blank holder or so-called pressure pad, which applies the blank holder force and guides the material flow during the drawing process (see Figure 8). Moreover, the deep drawing process is used for forming metal parts of various shapes with the help of a variety of tools designed specifically for deep drawing those shapes.

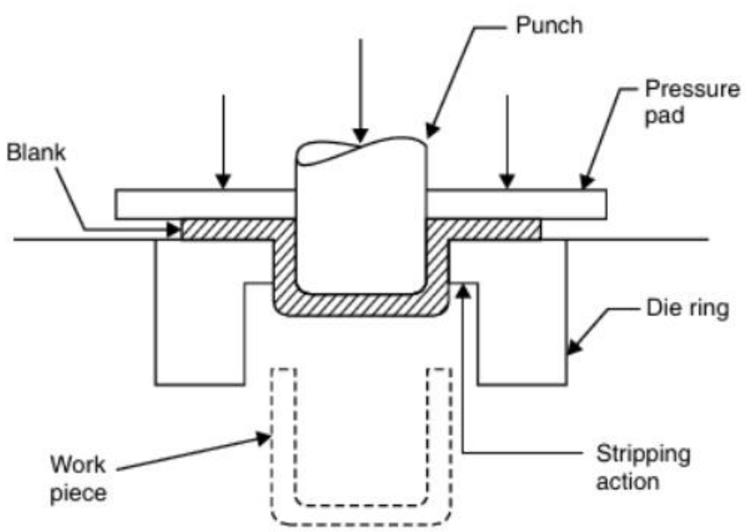

Figure 8. Deep drawing process (adapted from Gupta et al., 2009, p. 69).

Gupta et al. (2009, p. 69) state how the metal sheet is stressed in a convoluted pattern throughout the deep drawing process and how it affects the wall thickness of the deep drawn part. While there is only tension applied to the area between the die wall and punch surface, the area of the blank lower down at the bottom is subject to both tension and bending. As a result of circumferential compressive stress and buckling, the area of the metal blank that forms the flange at the top of the cup thickens. Tensile stresses cause the vertical walls to get thinner; however, all around the bottom corner of the cup is the thinnest area. It is important to note here that the material volume stays the same throughout the deep drawing process; the material just flows over the drawing radius. According to Dwivedi and Geeta (2017), the flow of material starts when the flow stress increases. The yield criterion, a function of the greatest values of the stresses or principal stresses in two perpendicular directions, is used to determine the value of flow stress. It is understandable from here that various tests are done, and simulations are run before the actual deep drawing process. Simulations enable to make a forming limit diagram (FLD), which illustrates the safe regions of the material where deep drawing can be applied. More precisely, forming a limit diagram shows the “rupture zone”, where the drawing process will result in fracture or wrinkling as well as the “safe zone”, where the deep drawing process will be smooth and will not cause any defects to the material (Dwivedi & Geeta, 2017).

Within the sheet metal forming process, it is important to consider the behaviour of friction at the tool-sheet contact, which depends on the contact parameters at the asperity level, including material, the contacting surfaces’ topographies and contact loads (Shisode et al., 2021). In this regard, ensuring proper lubrication is also a crucial step in the deep drawing of metal sheets. A study conducted by Yang (1999) compared the strain distribution under the conditions of full firm lubrication with dry fiction. As a result, it was found that the full film lubrication regime's draw ability is better than the unlubricated condition. Therefore, proper lubrication methods as well as its application need to be considered for deep drawing processes.

3.3 Safety and ergonomics

Ergonomics and safety of operators are significant factors in production processes as well. Liem (2017, p. 2) defines ergonomics as the discipline which examines the interaction of operators, the practical tools they use and their working environment. The purpose is to have a working environment where the processes can be completed in a safe and effective manner. According to International Labour Organisation (ILO), ergonomics aims to maximize operator satisfaction while also increasing productivity by applying biological and engineering sciences to the operator and the working environment (Khanna, 2021, p. 128). When classifying ergonomics based on intervention, the categories of reactive and proactive ergonomics are commonly identified. However, the need for an “optimised balance” between operator safety and satisfaction and productivity leads to the third category of ergonomics, known as prospective ergonomics (Liem, 2017, p. 3). All these categories of ergonomics as well as ergonomic recommendations for operators are studied in more detail in the following subsections.

3.3.1 Categories of ergonomics

To begin with, reactive ergonomics is the first category, includes the correction of existing practical tools or other aspects of the working environment noticed after some problem or injury occurred (White, 2015). it is important to remember that reactive ergonomics lacks flexibility, and it entails significantly high expenses to maintain and upgrade current equipment or implement administrative measures (White, 2015). Despite all the issues and costs that come with the repairs of the used practical tools, equipment or other features in the working environment, the most important problem that arises with the need for reactive ergonomics is the injuries of operators. In this regard, the reactive features for preventing injuries and controlling the tasks from the perspective of satisfaction and injury prevention are the foundation of conventional workplace ergonomics training

However, it is not always needed, and it is not recommended to wait for ergonomics issues to arise and then react to them. On the contrary, possible ergonomics issues should be identified and prevented beforehand so that there are no issues during the production processes and, most importantly, no operator injuries occur. This perspective leads to the next category of proactive ergonomics, also known as proactive ergonomics, which focuses on the practical tools or working environments that do not exist yet. In addition to its preventive feature, cost savings can also be accomplished with proactive ergonomics. More precisely, the direct costs of medical treatment and prescription as well as indirect costs, such as expenses for overtime work and replacement of operators and their training, can be avoided if ergonomics principles are followed and no injuries occur. Proactive ergonomics not only provides the possibility to reduce the risk of injuries but to improve production productivity as well as to accomplish improvements in quality and lean manufacturing (White, 2015). This is done by identifying the possible risk factors in the early design phase of the product or the production process and eliminating them.

The literature review conducted by Wijk and Mathiassen (2011) concentrates on theories of change when designing and implementing proactive ergonomics. The study highlights the importance of personnel training along with the adjustments of workstations or the used practical tools used within proactive ergonomics as it is presented in different literature based on practical observations, studies and research. That is, the improvement in operator skills as well as their working environment will result in positive change in terms of ensuring operator safety and satisfaction. Moreover, the participation of operators has a significant role in ergonomics. The fundamental idea behind this is to involve operators in both identifying the ergonomics issues that already exist and the improvement processes.

Robert and Brangier (2009) suggest the third category for ergonomics, which is prospective ergonomics. Prospective ergonomics aims to predict the requirements and practices of operators in order to design practical tools that address them in the early stages of planning and designing the work tasks and the work environment. In this regard, various factors and data need to be considered and examined and scenario planning needs to be conducted in prospective, which can be achieved by having close contact with operators and collecting data directly from them. Thus, prospective ergonomics is human-centred as it involves the anticipation of operators and their opinions regarding the strengths and shortcomings of practical tools used in their work. This is consistent with the findings of Liem (2017, p. 123), who states that with prospective ergonomics, humans are not only a part of the system but also shape the system.

Liem (2017, pp. 123-126) mentions several characteristics of prospective ergonomics. To begin with, the long-term collaboration advantage is the first emphasis is the focus of perspective ergonomics. That is, social, human, technological and economic factors are taken into account, which leads to so-called “plural outcomes”. It is also essential that perspective ergonomics utilizes hermeneutic, introspective, and participatory ways of reasoning in order to balance the positivistic aspects of strategic design. This means that prospective ergonomics combines both constructivist and positivist viewpoints. Innovation is another characteristic of prospective ergonomics. This is connected to the fact that technology and high-level activities help prospective ergonomics achieve innovative solutions since these designs or solutions are frequently not restricted to certain projects (Robert and Brangier, 2009). However, the innovations that come with perspective ergonomics are not limited to only strategic design; they are rather social innovation-oriented.

It can be said that prospective ergonomics overlap with proactive and reactive ergonomics in some areas (Robert & Brangier, 2009). More precisely, prospective ergonomics contains designing, which is also a characteristic of reactive ergonomics. On the other hand, the correction of existing tools based on operator satisfaction is part of prospective ergonomics, and the correction is part of reactive ergonomics as well. Overall, three categories of ergonomics aim to ensure operator safety and satisfaction. Figure 9 summarises all three ergonomics categories and their overlaps.

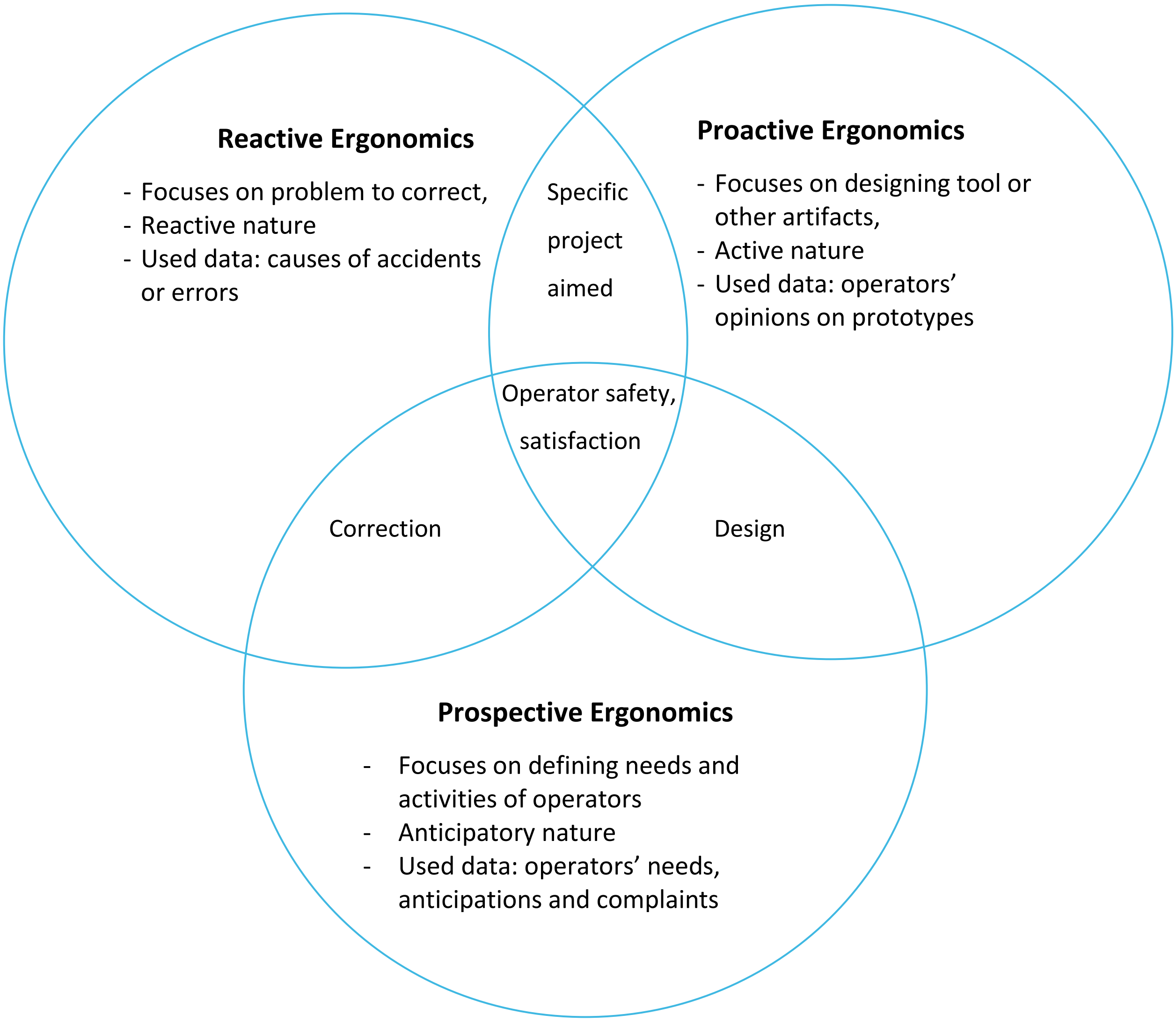

Figure 9. Categories of ergonomics.

3.3.2 Loads, posture and movement

When it comes to ergonomics, principles and recommendations regarding the load applied on a human body as well as the operator's posture and movements should be carefully examined in order to reduce the risk of injuries and improve work tasks, practical tools or the working environment itself. Khanna (2021, pp. 129-130) distinguishes physical, perceptual and mental loads, which can be static or dynamic. Regarding physical load, the operators will get tired easily and lose productivity if an excessive physical load is acted on them. Therefore, the posture and the movements of operators should be correct for optimizing the load on the operators. According to CRC Press LLC and Dul (2017, pp. 15-23), one of the initial steps is selecting the basic posture that fits best for the job, such as standing, sitting, sit-stand workstations, or workstations with pedestal stools. It is significant to alternate the basic work posture with walking and some other posture from time to time. The work height depends on the task and personal preferences. In this regard, the height of the working table needs to be adjusted for all kinds of postures and for different operators. Additionally, the chair's backrest and seat heights must be adjustable to accommodate different sitting positions. It is also essential to leave sufficient space under the machine or work surface for the legs and feet, as it enables the operator to be close to the workstation without the need to bend and change the leg positions occasionally. In order to avoid bending and twisting the trunk, the excessive reaches also need to be limited by placing the required practical tools or other necessary objects directly in front of the operators.

CRC Press LLC and Dul (2017, pp. 24-28) also address the importance of following the hand and arm postures because the discomfort of the wrist, elbow, and shoulder might result from the improper posture of hands and arms. Moreover, long-term work with lifted and unsupported arms might cause neck and shoulder discomfort. These discomforts can develop and worsen for a variety of reasons, including posture, application of force, and repetitive motion. Hence, proper working height of hands and arms can assist in having correct hand and arm postures and avoiding unnecessary injuries and further complications. In this regard, it is recommended not to operate with hands behind the back or at a height higher than the shoulder. For proper hand and arm posture, tools also need to be managed correctly, including the selection of the correct model and light-weighted hand-held tools.

Furthermore, CRC Press LLC and Dul (2017, pp. 29-36) discuss movement as a part of ergonomics as it can produce a variety of pains or other discomfort owing to mechanical stresses brought on by bodies moving and exerting force. Starting with lifting, it is advised to reduce the tasks that involve shifting loads manually. However, manual lifting is still necessary in many situations, and it needs to satisfy ergonomic principles and requirements. More precisely, the load should not exceed 23 kg, and it should be held with both hands close to the body so that the distance between hands and ankles is approximately 25 cm. The load should have a proper shape and be equipped with handgrips, and lifting accessories should be utilised when possible. Moving on to the topic of carrying loads, CRC Press LLC and Dul recommend avoiding one-handed carrying and employing accessories for transfer whenever possible. Similar to lifting, loads with limited weight should be carried and the load should be held close to the body.

Moving to the perceptual load, Khanna (2021, pp. 129-130) discusses the reduction of aural, visual and tactile load. More precisely, noise can not only distract operators from tasks requiring precision and coordination but also be damaging to human health. Hence, earmuffs should be supplied to the operators, and the aural load, i.e., noise, should be reduced. For reducing the visual load, proper displays should be utilised, and they should be placed near the location of its control device. Controls should be accessible to the operators so that they are able to handle them easily, thus reducing the tactile load. Last but not least, the mental load, which may include memorising facts, should also be reduced.

3.4 Robotics and automation

Having discussed the different aspects of production, the final section of the literature review addresses robotics and automation. Recently, there has been renewed interest in automation and robotics and their application in production processes. The reasons for automation vary depending on the perspective of the company and what benefits are aimed to achieve. More precisely, the increase of labour productivity; mitigation of the labour shortage effects; reduction of labour costs, manufacturing lead time and routine manual tasks; improvement of operator safety and product quality as well as the possibility to carry out processes that cannot be done manually, are hazardous or difficult to humans and avoiding the high cost of not automating are among the reasons for automation (Groover, 2001; Wickens et al., 2004, as cited in Lindström & Winroth, 2010, p. 150).

Once the goals are identified, it is essential to evaluate the current processes and consider what parts of the processes are planned to automate. Automation and robotics have various applications, including machine loading, picking and placing operations, welding, drilling, cutting or other manufacturing tasks, painting, part inspection, assembling, operating in hazardous settings, etc. (Niku, 2020, pp. 17-23). After reviewing the whole process and understanding the tasks that need automation, it is also important to consider the automation possibilities. Robotics is one of the first things that comes to mind when considering automation possibilities, and it is studied in greater detail in the next subsection. Moreover, only the type of automation is not sufficient; the level of automation should be understood as well. Previous studies on levels of automation have highlighted that automation should be considered as a continuum of whole, partial, or no replacement of a process that was performed by operators rather than as simply replacing the operators with a machine or a robot for the entire process (Frohm et al., 2008, p. 6; Kolbeinsson, 2019, p.451).

3.4.1 Robotics

Moving on to consider robotics for automation, it is necessary to clarify what exactly it means. Niku (2020, p. 3) defines robotics as the knowledge base of robot design, application and operation, emphasizing the fact that other devices are also utilised in robotic systems in addition to robots. This definition is aligned with the findings of Bouchard (n.d., p. 17), stating the importance of discussing robotic cells - workstations that incorporate robots - rather than just robots. Nevertheless, a broad overview of robots, their classification, components and other properties is required before determining the most suitable robot for including in a robotic cell.

Robots and their characteristics

According to Niku (2020, p. 2), robots are designed to carry out a variety of tasks based on different programmes controlled by a computer. The computer runs a specific program and directs the controller that regulates the robot's movements. Since different parts of the world have varying definitions of what constitutes a robot, Niku provides a list of the broad categories of devices that fall within the scope of the term “robot”. Fixed-sequence robots - the devices performing predetermined, unchangeable and difficult-to-modify tasks - fall under the first category. Playback robots are among another category, which records the movements of the robot controlled by the operators and repeat the movements by themselves later. The next category includes numerical-control robots: these robots just take the programme of the movements without any need to be taught manually by the operator. Finally, there are intelligent robots that have the intelligence to comprehend the surroundings and carry out tasks effectively even when the environment in which they are to be carried out changes.

Robot components

Robots are made up of several components that are joined together to create a whole, and Niku (2020, pp. 5-7) goes into further depth about these components. To begin with, a manipulator or rover is part of the robot's body that connects its links, joints, and other parts; it is not, however, capable of functioning as a standalone robot. The component that executes the required tasks by handling objects is the end effector. Being attached to the last joint of the manipulator, it is commonly known as a gripper, as it is not designed with the robot but is rather designed specifically for company purposes. Actuators are the parts of the manipulator which move the links and joints based on the signals sent by the controller. Actuators can be pneumatic and hydraulic as well as servomotors and stepper motors. Next, Niku addresses built-in sensors of robots that provide information about each joint or connection to the controller, which manages the robot's configuration. Moreover, robots can also communicate with their surroundings since they have extrasensory equipment like touch sensors and vision systems. As already mentioned, the controller is an important component in a robot since it uses sensory feedback information to regulate the movements of the actuators after acquiring the data from the processor. What refers to the processor, it acts as the “brain” of the robot. In more detail, the processor calculates how much and how quickly each joint must move to attain the specified locations based on the programmes it executes. Lastly, the software plays a vital role in any robot, and it is classified into three groups: operating software controlling the processor, robotic software calculating the movements of the joints, and a collection of application-oriented routines and programmes for using the robot in specified tasks, such as assembly, machine loading, etc.

Figure 10 illustrates the components of robots. As can be seen from the figure, teach pendants are also used, the function of which is to enable control over each manipulator joint or Cartesian degree of freedom. It is worth mentioning that teach pendants are typically handheld boxes. Miller and Miller (2017, p. 123) state that the manipulator is moved to the desired location manually or with the help of commands on the teach pendant, and then the information about that specific point’s location is saved by pressing the correct buttons on the teach pendant. This method is used for creating all the paths and points.

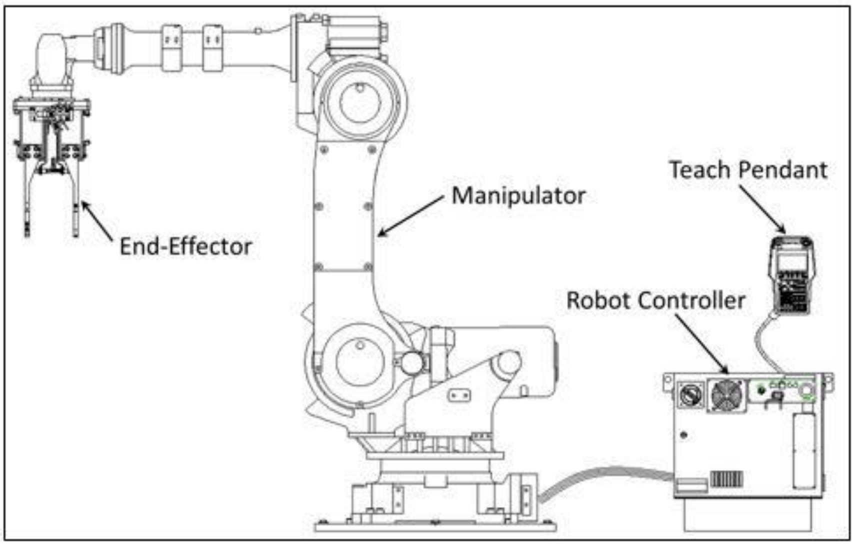

Figure 10. Robot components (adapted from Occupational Safety and Health Administration, n.d.)

Degrees of freedom (DOF)

Turning now to the other properties of robots, it is necessary to determine the number of independent position variables, known as the robot's degrees of freedom (DOF), in order to locate the components of the robot as well as the rigid body it is carrying in space (Craig, 2014, p. 5). In certain situations, complete control of the joint's motions is attainable, while in others, there are some restrictions. Niku (2020, p. 7) specifies that a selected point on the rigid body needs to be identified as well as the orientation of the body needs to be determined, thus, making 6 pieces of information, i.e., 6 DOF, that are needed to properly position and move the object in the space as intended. However, it is common for the robots to have fewer DOF, which places some sort of restrictions on the ranges of motion they can make. Robots with 3 DOF, for example, can only move along those three axes, whereas those with 5 DOF can rotate around three axes but can only move along two of them. Fewer DOF than 6 are very common among industrial robots, which perform successfully when no additional DOF is needed.

Robot coordinate frames

In practice, predefined coordinate frames are used to build robotic configurations. Regarding the robot coordinates, the robot joints need to be comprehended first. Robots have two types of joints: prismatic and revolute, where prismatic joints are linear and do not rotate, while revolute joints are rotary (Niku, 2020, p. 9). The common coordinate frames for serial robots, according to Niku (2020, pp. 9–11), include cartesian, cylindrical, spherical, articulated, and Selective Compliance Assembly Robot Arm (SCARA), which are summarized in Table 1. Figure 11 provides a better understanding by illustrating the robot coordinates.

Table 1. Robot coordinate frames.

Cartesian	3 prismatic joints are used for aligning the end effector. Revolute joints can be used for the end effector's orientation.
Cylindrical	2 prismatic joints and 1 revolute joint are used for part positioning. Revolute joints can be used for orientation.
Spherical	1 prismatic joint and 2 revolute joints are used for part positioning. Revolute joints can be used for orientation.
Articulated	All the joints are revolute.
Selective Compliance Assembly Robot Arm (SCARA)	2 or 3 parallel revolute joints support the robot's movements horizontally. Additional prismatic joints support the robot's vertical movements.

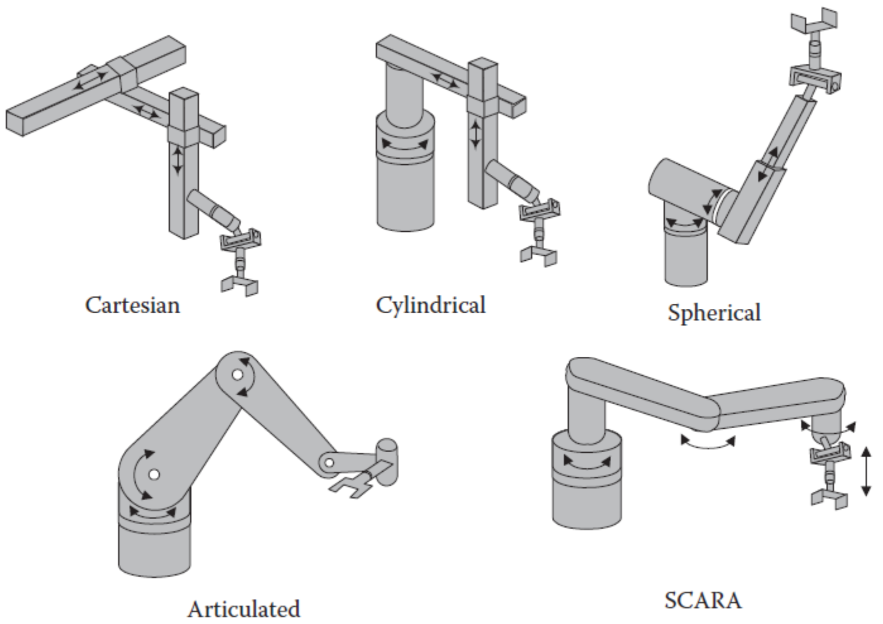

Figure 11. Robot coordinate frames (adapted from Niku, 2020, p. 10).

Industrial robots

An industrial robot is a versatile manipulator that can be autonomously controlled and programmed in three or more axes (Dinwiddie, 2019, p. 22). This can be used in industrial automation applications and is either stationary or mobile. The characteristic of industrial robots is its relatively high payload capacity. However, it should be kept in mind that the maximum payload capacity varies depending on the manufacturer. Additionally, the weight of the gripper attached to the robot is included in the payload capacity in addition to the maximum weight of the part that it can carry (Gurgul, 2018, p. 90).

Gurgul (2018, p. 91) strongly recommends considering industrial robots provided by suppliers, such as ABB Robot Load and KUKA Load, and using data on the weight, centre of gravity, and moments of inertia of the machinery to assess if the load limitations will be surpassed. When it comes to industrial robots, it is important to remember that safety measures need to be considered, as industrial robots cannot sense the obstacles or operators near them. In this regard, safety fences are an important part when installing industrial robots.

Collaborative robots

When discussing the application of automation and robotics in production, collaborative robots or so-called cobots should not be forgotten. As it can be understood from its name, cobots are created to operate safely in collaboration with humans. More precisely, cobots are able to determine the presence of operators thanks to a vision system, cameras or sensors which are mounted on the robot (Niku, 2020, p. 28). However, safety and sharing the workstation with the operator are not the only benefits that cobots bring. Djuric et al. (2016, p. 458) address various advantages that cobots have compared to traditional industrial robots, including the flexibility of being relocated and task changes. It is also easier to educate the operators to use cobots, as cobots are instructed online and can be supported by offline methods. Moreover, cobots are used and can be profitable even with small batch sizes. Despite all these benefits, it is important to remember that cobots are relatively slow and require risk assessment which is not the case for industrial robots. Furthermore, the roles and responsibilities of cobots and operators, as well as their accessibility, the setup time for cobot cells, and the potential for cycle time reduction, should all be taken into account when integrating cobots into production (Grahn & Langbeck, 2014).

3.4.2 Lean robotics

As already mentioned, a particular emphasis needs to be placed on lean philosophy when reviewing production processes and their improvements. The same applies to robotics; it is also important to grasp an understanding of lean robotics. Bouchard (n.d., p. 33) defines lean robotics as the method of efficient robotic cell deployment, which is based on four main principles and consists of three stages. The principles of lean robotics are that people come before robots, the focus should be on the robotic cell's output, the waste needs to be minimised, and the skills of the company and employees need to be built. The stages of robotic cell deployment are designing, integrating and operating, and each stage is covered in greater detail later in this subsection.

Bouchard (n.d., p. 35) discusses how lean robotics is aligned with different features of lean manufacturing. Defining and creating the customer value is one of the first steps in lean manufacturing, which is the same as creating and providing the right part, in the right quality and quantity to the next workstation in lean robotics, as the next workstation is the customer, and the ready part is the value. The value creation chain plays an important part in lean philosophy as well. When the robotic cell is already operating, the set of activities that will add value to the part is of interest. However, the previous stages of design and integration achieve value only when the robotic cell is operating within production. Another important feature of lean manufacturing is the conservation of resources and waste elimination throughout the chain. When it comes to lean robotics, it is important to remember that waste elimination is important to consider not only during the operating phase but during the design and integration phases as well. Finally, continuous improvement is an essential part of lean philosophy. Lean robotics views robots as a tool and encourages the company and employees to build their skills in order to be able to improve robotic cells over time, along with other production line improvements.

Robotic cell deployment

Once the robots are studied, robotic cell deployment may begin. Bouchard (n.d., p. 20) describes the process of robotic cell deployment from the perspective of lean robotics when it has three main stages: designing, integrating and operating. Within lean robotics, the need to identify the customer for a given process as well as the process' value-added and non-value-added tasks and information across the value creation cell in the very beginning is emphasised at the beginning of robotic cell deployment (Bouchard, n.d., p. 69). Figure 12 summarises the whole robotic cell deployment process illustrating the main tasks and the desired output in each stage.

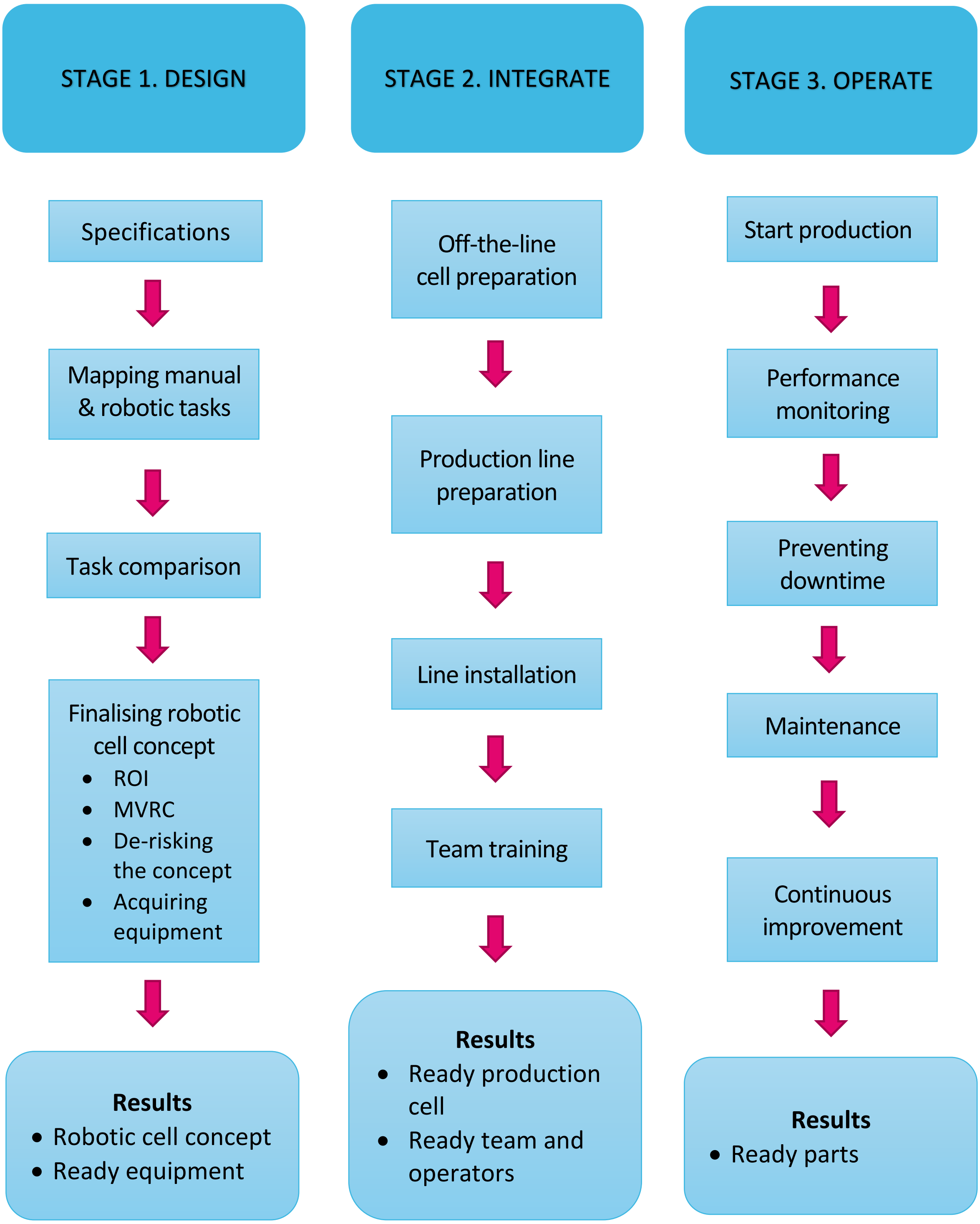

Figure 12. Robotic cell deployment

To begin with the design phase, the project's scope, timetable, team members and their responsibilities are specified, which is followed by mapping the manual and robotic tasks, comparing these 2 and formulation of the final robotic cell concept (Bouchard, n.d., p. 68). In this regard, it is important to understand what needs to be considered when finalising the robotic cell concept. Within the robotic cell concept finalisation, ROI calculations are made, uncertainties are discussed and eliminated for de-risking the concept, the MVRC concept is kept in mind and the needed equipment is acquired (Bouchard, n.d., pp. 126-127). More precisely, Return on Investment (ROI) always needs to be calculated when capital investments are made. There are different methods for ROI calculations, which are discussed later. As already mentioned, the lean philosophy is kept in mind, which is the reason that considering minimum viable robotic cell (MVRC), which corresponds to the robotic cell with exactly the right number of features to consistently provide value for the customer, is taken into consideration during the design phase. (Bouchard, n.d., p. 52). To put it shortly, various aspects are considered in the design stage, which results in the final robotic cell plan, along with ensuring that the equipment for the robotic cell is available and prepared for assembly.

The next stage of integrating starts with the final robotic task map, robotic cell plan and equipment ready to be assembled. According to Bouchard (n.d., pp. 142-159), both off-the-line cell and production line preparations take place during the integration stage. Off-the-line cell preparation requires assembling the cell and programming the task that the robot needs to execute, and tasks for production line preparation come from the comparison of robotic and manual tasks in the design stage. It is worth mentioning that off-the-line cell preparation and production line preparation can be done in parallel. Afterwards, the robotic cell is installed on the production line, and test runs and MVRC acceptance tests are completed. Within the integrating stage, the operators are also trained and prepared to operate, for example. As a result, the robotic cell is installed on the production line ready to operate as well as the operators are ready to work.

Finally, the operation of the robotic cell starts in production. This is the stage that results in ready parts which create value for the customer as well as for the company itself. Within the operation stage, performance is monitored, downtime is prevented, and in case of any problems, those are identified and troubleshooted (Bouchard, n.d., pp. 160-162). When it comes to machinery, it's crucial to remember the maintenance plan and to carry it out as preventive maintenance to avoid severe issues from developing. Continuous improvement needs to be kept in mind as well.

3.4.3 Levels of Automation

Moving to the levels of automation, Rath and Strong (2006) identify 5 levels (see Table 2). As can be seen from the figure, each level is based on a manual or automated completion of different steps in the process. The first automation is introduced in level 2, when the machine cycle is automated first. Once it is automated, the automation of machine unloading can be considered in level 3. "The Divide" can be seen between levels 3 and 4, which relates to the needed technology and costs of automation. Level 4 introduces automation in machine loading as well, and level 5 includes all steps automated. What is worth keeping in mind is that the expenses of automation rise along with the increase in automation level. Rath and Strong also mention guidelines for automation, such as the suggestion of installing one-touch automation when it is feasible and usage of auto-eject in cases when operators will handle the parts using two hands. In addition, sensors should be incorporated in order to signal unusual conditions and stop machines.

Table 2. Levels of automation.

	Load Machine	Machine Cycle	Unload Machine	Transfer Part
1	Manual	Manual	Manual	Manual
2	Manual	Auto	Manual	Manual
3	Manual	Auto	Auto	Manual
"The Divide"				
4	Auto	Auto	Auto	Manual
5	Auto	Auto	Auto	Auto

3.4.4 Robot safety

Gurgul (2018, pp. 188-189) addresses the importance of following safety instructions when programming and working with robots because of the serious accidents occurring annually in robotics. The causes of these accidents are various, being faulty equipment, the lack of knowledge about robot usage and programming or simple human errors. In this regard, it is important to ensure that only personnel who has received appropriate training will be working with robots, it refers to both robot programming and using robots in daily operations. In addition, minimum protective equipment needs to be available for the operators, including safety shows with impact-resistant toe caps, gloves and glasses, clothes with long sleeves and long pants, and earplugs. In addition, proper installation of the robot plays a vital role in safety, as the robot needs to be fastened properly to the floor with sufficient force so that it can function as intended during robot movement and emergency stops and does not pull itself out from the floor.

Another important aspect related to robot safety is the usage of switches available on the teach pendant for emergency stops. Gurgul (2018, pp. 190-191) discusses three emergency stops for spotting the manipulator’s work. When stop category 2 is applied, the robot first begins to slow down before stopping entirely by interrupting the execution of the process while the servomotors are still receiving electricity. The lifespan of the servomotor is not impacted by this emergency stop category. Moving to stop category 1, the power supply to the servomotors is cut off and the manipulator of the robot gradually slows down until it stops totally. The braking is controlled in the aforementioned two categories until the robot comes to a complete stop. Finally, using top category 0 results in uncontrollable braking and instant disconnection of the power supply. The immediate stop of the manipulator is the foremost priority in this emergency stop. As a result, the robot mechanism experiences considerable overloads, which shorten the robot's lifespan.

3.4.5 Robot versus human: process standardisation and quality

As already mentioned, variability is one of the common reasons causing queues and long cycle times, and it is typically desired to be as low as possible. Process standardization is one of the most useful solutions for variability reduction, as it enables the completion of operations in an efficient manner. Mor et al. (2018) describe standardised work as a collection of operational guidelines intended to determine the optimal techniques and steps for each process and worker. In this way, the wastes and non-value-added steps are identified and removed, and the most effective work sequence is determined. Standardized work brings other benefits as well, including documentation of information, easier training of new operators, reduction of injuries, quality improvements, cost reductions, etc. More precisely, a study that was carried out to assess the practical use of multi-criteria standardisation indicates that standardisation in the production line design will lower expenses while retaining the efficiency of machines and training operators effectively (Kurylo et al., 2022). Moreover, several rules are suggested by Spear and Bowen (1999) in order to carry out standardized work. The first step is analysing the work in detail, including the work sequence and production time. The transportation of parts between workstations and within the workstation needs to be studied as well, with the aim of making it simple as possible. What is also significant is that scientific approaches need to be kept in mind when development projects are conducted in order to standardize processes.

Moving to the benefits of robot utilisation, automated production processes will enable achieving standardized work. This results from robots' capacity to repeatedly follow the same path at the same speed. Dinwiddie (2019, p. 239) also draws attention to the robots' accuracy, which ranges from 0.0003 to 0.005 inches, and their capability to consistently arrive at the same precise location with only the tiniest faults. Furthermore, the repetitive movements of the robots and the standardization of the process also contribute to the higher quality of the output. After programming the robot and testing that the desired quality of the part is accomplished, the robot can run with the same programme and produce the parts with the same quality. Operators, on the other hand, are also capable of producing quality components, but there is a higher risk that the human factor will cause some differences in the process and lower the quality (Dinwiddie, 2019, p. 239).

3.4.6 Investment costs

Investment calculations always need to be made when the company invests in any kind of equipment. This way, it is possible to see whether the investment is profitable and should be considered or not. There are various methods for calculating investment costs. Return on investments (ROI) is calculated based on the net project gains and costs of investments (Bouchard, n.d., pp. 127-128; Phillips et al., 2012, p. 210):

$$ROI = \frac{G - I_{cost}}{I_{cost}} \times 100\%,$$

where G is gain from investments and I_{cost} is the cost of investments.

As Phillips et al. (2012, pp. 203-206) state, monitoring all costs are essential even if they are not used in the ROI calculation. The costs do not need to be precise, and they can be estimates; however, they need to be realistic and reasonable. The sources of costs are various, such as project team expenses, supplier expenses, direct and indirect customer expenses as well as expenses for the equipment and services. Phillips et al. list all the costs that need to be considered within ROI, some of these are usually expensed and the others are prorated:

- Initial analyses and assessment (prorated)
- Development of project solution (prorated)
- Acquisition costs (prorated)
- Implementation and application of the project
    - Salaries (expensed)
    - Project material (expensed)
    - Hardware and/or software (prorated)
    - Travel (expensed)
    - Use of facilities (expensed)
    - Capital expenditure (prorated)
- Maintenance (expensed)
- Administrative support and overhead (prorated)
- Evaluation and reporting (expensed).

In addition to ROI calculation, it is also beneficial to use other methods. This is because ROI only provides the amount of money that is gained for every invested euro. If the ROI is 640%, for example, it means that for every invested 1€, the return will be 6,40€. Hence, the Payback Period of the investment is typically of interest as well. According to Phillips et al. (2012, p. 214), the payback period can be calculated as follows:

$$Payback\ period = \frac{Total\ investment}{Annual\ savings}$$

Despite the fact that this method provides information about the period of time after which the investment will pay off, it does not take into account the value of money. Therefore, the method of Net Present Value (NPV) calculation is utilised, which takes the time-value of money into consideration (Bettner, 2015, p. 129). The forecasted cash flows for the upcoming years and the discount rate are needed for calculating NPV, and the Excel formula NPV() can be utilised. If the investment's NPV is positive, then the investment is profitable (Bettner, 2015, p.)

Overall, various calculation methods can be used in order to check the profitability of investments. The ROI, Payback Period and NPV calculations are the most common methods, which provide all the basic information needed before making a decision about investments. Moreover, each company can derive their own calculation formula and template based on the costs associated with the investment and the theory basis.

4 Implementation of the study

After understanding research methods, data collection methods and reviewing relevant literature, the implementation of the study started. One of the essential steps in implementation was understanding the type of research method that would be utilised. Mixed methods research was chosen, as it enables using, analysing and comparing various viewpoints that are derived from both quantitative and qualitative data and gaining a deeper and more thorough understanding of needed adjustments (Cresswell & Cresswell, 2018, pp. 297-298). Moreover, mixed methods research enables interpreting quantitative findings by acquiring and analysing qualitative data and integrating the viewpoints of individuals, which was another reason for choosing this research method. In particular, the convergent design was chosen, as it enables to collect and analyse both quantitative and qualitative data and then merge the results together. The reason for choosing this design was the importance of considering different perspectives in the production development process by combining quantitative and qualitative data sets and finding the best solution taking into account all the factors. More precisely, the effects of automation on reducing the cycle time, increasing the throughput as well as its alignment with improving operator safety and ergonomics and assuring quality needed to be studied. Finally, all these results needed to be combined with financial calculations to estimate the investments' payback time.

After deciding on the research method and design, the steps required to gather data and implement the study of production process development were identified. In the beginning, an observation of the commissioning company's factory was conducted to get familiar with the production and determine the aspects of improvement in the mid-size deep drawing process. Data regarding the deep drawing process cycle times were collected and examined to identify non-value-added time and find solutions for minimising them. Next, cobots were utilised for loading and unloading the deep drawing machine, during which the automated process was observed, data related to the common issues in mid-size deep drawing that need to be addressed with automation as well as the possible issues that can come with automating the deep-drawing process were identified and gathered as well as the cycle times achieved with the automated process were gathered. Moreover, an interview was conducted to collect data on robot usage in production and the factors for making robot programming as efficient and user-friendly as possible. Similarly, another interview was conducted to gather data related to quality issues and their causes to eliminate these issues when automating the process. Furthermore, the ergonomics perspective of production was taken into account, and data was gathered from the operators through a questionnaire. Data related to investments were also collected for making financial calculations. Finally, all the gathered data were analysed and put together in order to illustrate the key takeaways. Table 3 summarises the data gathered and used in this study, each discussed in greater detail in the following sections describing the study implementation.

Table 3. Summary of collected data.

Data	Data type	Source
Cycle times of mid-size deep drawing	Quantitative data	Measurements in the company
Issues in the mid-size deep drawing to solve with automation and issues to consider that might arise with automation	Qualitative data	Observation
Cycles times of mid-size deep drawing automated with cobots	Quantitative data	Measurements in the company
Data related to robot usage and programming in production processes	Qualitative data	Interview

Quality issues and their causes in mid-size deep drawing	Qualitative data	Interview
The proportion of quality issues and their causes in mid-size deep drawing	Quantitative data	Internal reports of the company
Ergonomics	Qualitative data	Observation
Operator perspective on ergonomics and automation	Quantitative and Qualitative data	Questionnaire with close-ended and open-ended questions
Data related to investments	Quantitative data	Calculations

4.1 Cycle time examination

To begin with, it was essential to examine the cycle times of mid-size deep drawing to see possibilities for minimising it. In this regard, data related to cycle times were gathered by making measurements in the company. The cycle times of deep drawing with manual loading and unloading were measured for the two products, and the measurements for each product's cycle time were made 25 times in order to see the variability in manual work. It is also worth mentioning that measurements were made for two products instead of one, so that it would be possible to study, analyse and get a realistic picture of mid-size deep drawing. Moreover, two different operators were carrying out the loading and unloading of these 2 products, which also supported getting a reliable and correct idea of existing variability. It was also significant to remember that cycle time reduction would affect the other concepts of production, for instance, it would enable decreasing WIP or increasing throughput. Consequently, the basic relationship between different concepts was needed to study, starting with the theorem illustrating Little's Law below.

It should be noted that the following notations are used in this section:

WIP	work-in-process
TH	throughput
CT	cycle time
CT_q	mean time spent in the queue
ST	setup time
t_e	mean effective processing time
t_a	mean times between arrivals
c_e	coefficients of variation for effective process time
c_a	coefficients of variation for the time between arrivals
u	utilisation
r_e	rate of effective processing
r_a	rate of arrivals

Theorem 1. *The work-in-process (WIP) is defined using cycle time (CT) and throughput (TH):*

$$WIP = TH \times CT \tag{1}$$

When discussing cycle time and aiming to minimise it, it was essential to remember from the literature review that cycle time consists of the time of the actual processing as well as the waiting times. In this regard, the following lemma was introduced, corresponding to the findings of Hopp and Spearman (2011, p. 284) and Pound et al. (2014, p. 72).

Lemma 1. *Average cycle time consists of the waiting times and the effective processing time for each part and is given by the following formula:*

$$CT = CT_q + t_e \tag{2}$$

This lemma thus provided an understanding of average cycle time, and the need to focus on minimising CT_q was emphasised. Furthermore, it was necessary to remember that a single deep drawing machine was utilised, and the throughput would be the same as the batch size in case no defective parts were deep drawn. The batch size here refers to the number of parts produced in a single run. In this regard, setup time should also be considered when calculating the total cycle time spent on producing one part. However, it should be kept in mind that one setup was done for starting the production of a batch. This would mean that for each ready part, the amount of setup time used would equal setup time divided by throughput. Consequently, the cycle time consisted of the setup time over the throughput, the mean time spent in the queue and the effective processing time for each part. Moreover, the mean time spent in the queue did not include the setup time, as it was added separately:

$$CT = \frac{ST}{TH} + CT_q + t_e \tag{3}$$

This could also be confirmed by using units, as *CT* in the left-hand-side of equation 3 is expressed by [time unit]/[units], and the sum of attributes on the right-hand-side is also expressed by the same unit of [time unit]/[units].

In addition, the variability factor also needed to be considered, as the waiting time could be different for each part. According to Kingman's equation, the mean time spent in queue CT_q for a single machine workstation could be approximated as provided below (Kingman, 1961, as cited in Hopp & Spearman, 2011, p. 288):

$$CT_q = \left(\frac{c_a{}^2 + c_e{}^2}{2}\right) \times \left(\frac{u}{1-u}\right) \times t_e \tag{4}$$

Once the mean time spent in the queue was found using Kingman's equation (4), it was substituted in equation 3. The result was equation 5, providing the cycle time expressed by setup time, throughout, effective processing time, coefficients of variation of time between arrivals and effective processing time, and utilisation. It was later simplified to equation 6, resulting in the following corollary.

$$CT = \frac{ST}{TH} + \left(\frac{c_a{}^2 + c_e{}^2}{2}\right) \times \left(\frac{u}{1-u}\right) \times t_e + t_e \tag{5}$$

Corollary 1. *In order to calculate the total cycle time spent on the production of one part, the setup time, the throughput, the effective processing time as well as relevant attributes of variation and utilisation are needed:*

$$CT = \frac{ST}{TH} + t_e \times \left(\left(\frac{c_a{}^2 + c_e{}^2}{2}\right) \times \left(\frac{u}{1-u}\right) + 1\right) \tag{6}$$

It should be noted that the coefficient of variation could always be calculated by dividing the standard deviation by the mean time. That is, the coefficient of variation c_e between effective process times would be calculated by dividing the mean time of effective processing time t_e by its standard deviation σ_e, as shown in equation 7. In more detail, Excel functions AVERAGE() and STDEV.S() would be used for calculating the mean time of effective processing times t_e and its standard deviation σ_e correspondingly.

$$c_e = \frac{\sigma_e}{t_e} \tag{7}$$

Similarly, the coefficient of variation between arrivals c_a would be calculated by dividing standard deviation σ_a by the mean time between arrivals t_a (see equation 8). It should be kept in mind that the metal sheets arrive at the deep drawing machine in a pallet, meaning that the arrival time for the first sheet is relatively long, while for the others, it is 0 seconds. In this regard, mean time between arrivals t_a would be calculated with the usage of equation 9, that is, by dividing the interarrival time $t_{int.ar.}$, which is the time since the previous arrival, by the quantity q of used metal sheets since the previous arrival (Hopp & Spearman, 2011, p. 281). In other words, the idea of sequential process batch was utilised here, where sequential batch corresponds to batch including the parts which are processed sequentially after each other before the next setup as defined by Hopp and Spearman (2011, p. 319). However, the coefficient of variation c_a between arrivals and standard deviation $\sigma_{a.}$ of arrival times would be challenging to calculate accurately because the deviation of arrival times varies depending on the batch size, interarrival times, the time when the machine is idle and the operators are on break, and it would cause unnecessary complications. In this regard, it was decided to utilise the simplified model of sequential batching determined by Hopp and Spearman (2011, p. 322) and use the squared coefficient of variation c_a^2 between arrivals always equal to 1.

$$c_a = \frac{\sigma_a}{t_a} \tag{8}$$

$$t_a = \frac{t_{int.ar.}}{q} \tag{9}$$

Furthermore, the utilisation u would be calculated as the ratio of the rate of arrivals and the rate of effective processing, as illustrated in equation 10 (Hopp & Spearman, 2011, p. 284). It should be noted that the rate of arrival r_a and rate of effective processing r_e would be calculated as the inverse of arrival time and effective processing time correspondingly (see equations 11 and 12).

$$u = \frac{r_a}{r_e} \tag{10}$$

$$r_a = \frac{1}{t_a} \tag{11}$$

$$r_e = \frac{1}{t_e} \tag{12}$$

Based on these equations, an Excel template was created to calculate the cycle time spent in the queue and the total cycle time. More precisely, these equations were used, and formulas were created in the Excel template, which made the calculations automatically after inputting several pieces of data. Input cells for a sample of 25 effecting processing times were inserted into the template, the measurements of which were done in the company. In addition, input data cells were also added for data regarding the interarrival times and quantity of metal sheets used in between these interarrival times. Overall, all the coefficients of variations, utilisation rate and other necessary concepts were calculated based on several inputs, illustrating all the necessary data and attributes. Finally, equation 6 was substituted in equation 1, resulting in equation 13, which showed the connection of *WIP, TH* and *CT* expressed by the necessary attributes considering the variability as well. All these observations and derivations lead to the following corollary.

Corollary 2. *The work-in-process can be calculated by knowing the throughput, i.e., the batch size for a single machine workstation, the setup time for that batch and the effective processing time per batch as well as the needed attributes for variability factor, such as utilisation and coefficient of variability:*

$$WIP = TH \times \left(\frac{ST}{TH} + t_e \times \left(\left(\frac{{c_a}^2 + {c_e}^2}{2} \right) \times \left(\frac{u}{1-u} \right) + 1 \right) \right) \tag{13}$$

After examining all the attributes and their connection and creating the template, data related to cycle times were gathered. More precisely, effective processing times for two parts were collected and studied. As already mentioned, a sample of 25 effective processing times was chosen to gather and analyse the cycle time values for each part. At this point, it would be necessary to comprehend the significance of a sample. According to Weiss and Weiss (2017, p. 5), a sample is a subset of the population from which data is drawn, whereas the population as a whole refers to all the subjects of statistical research. In this case, the population referred to the cycle times of each part within the process batch, and the collected 25 measurements of the cycle time made a sample of 25. A sample was needed as conducting measurements for the whole batch, which could include more than hundreds of parts, would be time-consuming and unrealistic. It is important to note that the concept of simple random sampling was utilised. In simple random sampling, the likelihood of acquiring any sample of a particular size is equal for all possible samples (Weiss & Weiss, 2017, p. 13). Once the measurements were done, the IBM SPSS Statistics application was used for statistical analysis based on the measured times and the calculated attributes. Moreover, the data was inserted into the relevant input cells of the created Excel template to analyse and identify the actual cycle time considering the variations in arrival and effective processing time.

4.2 Cobot application in the production process

Next, the application of cobots for unloading and loading the mid-size deep drawing machine was examined, for which two types of data were gathered. Quantitative data regarding the cycle times achieved with the automated process was measured. Initially, the cycle time was measured for the basic programme, which included all the steps in the exact order that the robot was waiting for the deep drawing machine to perform its task, and then it continued to move and finish the cycle. Later, the cycle time was also measured for the improved programme, from which non-value-added tasks, such as cobot waiting at a certain waypoint, were removed, and the cycle time was reduced. In addition, the whole process was observed, and qualitative data were gathered regarding the issued in mid-size deep drawing that the cobot application solves and the issues that are noticed with automated process and need to be considered when making a decision regarding automation.

Regarding the implementation of this part of the study, a visit to the cobot supplier's facility took place to receive training related to cobot programming and usage. After this, the cobot was brought into use in the company's factory, and it was programmed with the help of a teach pendant. The cobot was first programmed to successfully carry out all the needed steps for loading the metal sheets and unloading the ready parts from the deep drawing machine. Afterwards, the cobot was continued to be programmed, removing all the unnecessary waiting of the cobot and aiming to achieve minimum cycle time. That is, the main idea when programming the cobot was minimising or entirely eliminating non-value-added steps, which is also aligned with lean robotics. A detailed description of how the cobot was programmed is included in miscellaneous Appendix 3 (the information is confidential about the fact that company employees worked on programming in various ways to gain the most efficient result.) Moreover, the whole process was observed and documented. Notes were taken regarding the issues that were tried to be solved or improved by using cobots for loading and unloading. It was also observed what issues occur when automating the loading and unloading of deep drawing machines to address them and find out how they can be eliminated with this or other kinds of deep drawing process automation. What is also essential is that videos were taken for viewing later to recall the observation, analyse results and make conclusions.

4.3 Robot programming and usage

Observing the cobot application in the deep drawing process, it was noted that simply programming the tasks with robots is not enough, and knowledge and skills are required to programme the efficient execution of the process steps regardless of the type of automation used. In this regard, it was necessary to study how an efficient programme can be made and the most important features to consider. According to Creswell and Creswell (2018, p. 262), purposefully selecting participants is the idea for collecting qualitative data as it can help the best to understand and address the research problem. In this regard, it was decided to interview a company employee from a technical department who not only participated in cobot programming but also had experience working with different kinds of robots and automated machines. The aim was to learn more about executing process steps with the use of robots and their programming as well as to find out what should be the main focus in programming the robots to reduce the cycle time.

Creswell and Creswell (2018, p. 262) also highlight the importance of informing the possible participants about the study being conducted and motivating them to participate, for example, in the interviews. In this case, the employee from a technical department was already aware of the study being conducted thanks to the regular visits for collecting different kinds of data. It was presented to him that practical guidelines about robot programming were aimed to be used as data for the study and he was asked if he was willing to participate in an interview. The employee in the company was happy to participate in an interview and share his experience related to this topic. A time for the interview was agreed and a meeting room was booked in the company. At the beginning of the interview, consent was asked for audio recording the interview, so that transcription could be made and used for analysing the data. It is crucial to state that the audio recording was destroyed after the data was analysed. In addition, notes were also taken during the interview in case the audio recording device failed, as suggested by Creswell and Creswell (2018, p. 266). The interview had a semi-structured form, meaning there were predefined questions, but there were no closed-ended responses, and the interviewee could answer flexibly, which enabled to gain more information about the topic. Moreover, follow-up questions were also asked based on the answers to clarify or get a more detailed perspective on the matter. After the interview was conducted, it was also important to listen to the audio recording and make the transcription of the interview. Appendix 2 includes the transcription of this interview, with predefined questions, answers to these questions as well as follow-up questions and their answers. This transcription was also used for analysing the data collected through the interview. The chosen method for analysis was narrative analysis, the aim of which is to analyse the content, interactions and structure of the interview, and it is a suitable method for analysing semi-structured interviews (Walliman, 2021, p. 192). The main focus when analysing this interview was placed on analysing the content.

4.4 Quality perspective in deep drawing

During the study, the quality perspective in deep drawing was also taken into consideration. At the same time, it should be mentioned that only the aspect of quality that fell within the limitation of the study was examined. That is, the issues in mid-size deep drawing that affect the process and the quality of deep-drawn products were studied. In order to study the quality aspect of deep drawing, two types of data were collected: qualitative data was gathered through an interview with the employee from the quality department working in the company. In addition, quantitative data regarding internal scrap was collected from the company's internal reports and analysed.

As already mentioned in the literature review, process standardization, in turn, is aligned with process development, as it not only reduces cycle time and injuries but also improves quality. Therefore, it was also essential to consider quality, in terms of defects and their causes, when aiming to achieve process development with automation, even though quality was not the main focus of this study. More precisely, it was aimed to gather data related to quality issues in the deep drawing process so that their causes can be considered and eliminated or at least minimised when automating the deep drawing process. In this regard, it was decided to conduct an interview with the employee from the quality department working in the company, as a person who is monitoring the quality within the production and has the most knowledge regarding the defects and their causes taking place in the production. This selection of the interviewee would enable understanding the quality aspect of deep drawing and its connection with process automation in the best way, the importance of which is emphasised by Creswell and Creswell (2018, p. 262).

The implementation of this interview was similar to the one discussed in the previous section. The employee was already informed about the study being conducted in the company and was willing to participate in the interview when asked. Once the suitable interview time was selected, the interview took place in the meeting room in the company, and it again started by asking for consent to record the interview. Once again, the recording was destroyed after making the transcription and analysing the gathered data. A semi-structured interview was conducted, during which predefined questions were asked, followed by discussing other issues raised based on the answers. After the interview was conducted, the transcription of the interview was made to use for analysing the collected data. The transcription of this interview, which includes the predefined questions, answers to these questions and the other issues discussed with follow-up questions, can be found in Appendix 3. The method of narrative analysis was chosen for addressing the data gathered through this interview as well. The objective was to analyse the content of this semi-structured interview (Walliman, 2021, p. 192).

It was also decided to gather quantitative data regarding the defects in deep drawing and their causes. Internal reports were utilised for collecting this data. In particular, the data related to the number of incidents of defective parts in the deep drawing based on their causes was gathered. In addition, information related to the costs of non-quality with relation to its causes was also collected.

4.5 Ergonomics perspective in deep drawing

The study objectives also included the consideration of ergonomics when automating the production processes. Reviewing ergonomics in advance and taking relevant actions before adopting the new automated process was also in line with the idea of preventive and prospective ergonomics. In this regard, qualitative data was gathered to review production automation from the ergonomics perspective. There were two sources of data collection. At first, the data was collected through observations in the company’s factory, paying particular attention to ergonomics and operator safety in mid-size deep drawing. Another source for data collection was a questionnaire from the operators working in the company's production.

In more detail, the production processes and operators’ work during the daily deep drawing process were observed during the company visits to identify possible issues related to ergonomics and operator safety and the actual ergonomics issues. The main focus of the observation was the mid-size deep drawing and the operators working there. In addition, attention was paid to the operators’ posture during the shift and other factors that might cause injuries. Based on these observations, actual and possible issues or their causes were documented by making notes and taking pictures. These different forms of documentation were later analysed, leading to the results.

Furthermore, it was essential to consider the operators' perspective and experience regarding ergonomics in everyday working life. Therefore, an open-ended questionnaire was made for factory operators to find out about their daily work practices and how they think automation can help improve ergonomics and safety. The aim was to find out about operator anticipation related to ergonomics aligned with the concept of preventive and prospective ergonomics and to organise the development in a way that operator safety and ergonomics are taken into account. Regarding the questionnaire, it included questions that required yes or no answers with a follow-up question enabling the participants to clarify their answers as well as open-ended questions. The reason for focusing on questions enabling open-ended answers was that the operators' needs, opinions and ideas would be considered. At the same time, this kind of questionnaire would enable the analysis of relevant data and get a numeric description of attitudes and actual opinions by examining the chosen sample (Creswell and Creswell, 2018, p. 49). The target group of participants for this questionnaire were the operators working in the mid-size deep drawing. As the operators in the mid-size deep drawing made up only 17% of production workers, and the number of answers would not make a large number, the target group was chosen to be the whole population of operators working in mid-size deep drawing. The questionnaire was printed on paper and left on the kitchen table so that the operators could answer it when they had free time to avoid interrupting them during their work. This also enabled to get answers from operators working in the evening and night shifts. The questionnaire included the following questions:

- Can you mention some safety issues that you noticed happen during the deep drawing process or you think it is possible that those problems will happen?
- Did you ever experience back pain because of heavy lifting or other musculoskeletal problems because of repetitive tasks? What were they?
- Do you always raise the pallets to the appropriate height so that you do not need to bend? Why yes or no?
- How can work become safer if no robots are used and the loading and unloading are still done by operators manually?

- What do you think about fully using robots for loading and unloading and replacing operators in this task? Can you mention a few positive and a few negative sides?
- Do you think using robots for loading and unloading in the deep drawing process will reduce unnecessary risks?

After receiving all the answers, a transcription was made from the questionnaire answers. In order to analyse the collected data, the answers for each question were later also grouped together and analysed. The answers to closed-ended questions were analysed based on their frequency as well as viewing the explanation behind those choices. Narrative analysis was done for answers to open-ended questions based on their content.

4.6 Investment calculations

Once the usage of robots and the benefits it brings in the deep drawing process were examined, it was also essential to make investment calculations for finding out whether it is beneficial for the company to invest and what is the payback time of the investment. In this regard, it was important to gather data related to the expenses of initial investment of robotic cell, expenses in case of manual deep drawing process and possible savings in expenses thanks to process automation. The data was collected based on internal reports as well as the knowledge of the personnel from previous investments and quotations they received from suppliers.

In this regard, it was important to understand what kind of costs the investment would bring with it. Based on the literature review as well as after participating in company meetings related to investing in automation, it was identified that the costs of investment include both initial investment expenses as well as expenses that come during the usage of the robot. Initial investments include the costs of the actual robot, grippers, and licenses. In addition, the costs of spare parts, annual maintenance, expenses for educating and training personnel, and quality steps that come during the lifetime of the robot should be considered. It was also important to understand what benefits the investment would bring from the financial point of view. It will reduce the expenses related to sick leaves and internal scrap, it will also make it possible to increase throughput within the same amount of time, thus enabling the labour costs to stay steady with the increasing demand and throughput in the future. Moreover, it was essential to keep in mind the financial benefits coming from the productivity increase, even though it was not possible to calculate. In more detail, the investment will make the work more interesting and appealing for the operators, resulting in an increase in their productivity.

Based on all these considerations, Excel was used for making the financial calculations for ROI, Payback Period and Net-present value using the formulas discussed in subsection 3.4.6. In particular, two different calculations were made: one for investing in industrial robots and the other for investing in collaborative robots. The reason for this was to study and evaluate which robot would be beneficial from the financial point of view for this particular case of deep drawing automation in the target company.

4.7 Ethical considerations

According to Cresswell and Cresswell (2018, p. 145), it is essential to consider the ethical issues prior to conducting the study. One of the most important ethical considerations is to discuss the code of ethics in the company. In this regard, the study started by making the relevant agreements, namely, the thesis agreement and thesis confidentiality agreement with the company and JAMK University of Applied Sciences. A non-disclosure agreement was also made with the company. The anonymity of the company and the people involved in the study was kept while reporting the implementation and results. In particular, the identity of the employees participating in the interview and the operators participating in the questionnaire was kept. Inform consent was also asked for recording the interviews, and the audio recordings were destroyed after the data collection and analysis Walliman (2022, p. 51) identifies two aspects of research ethics: individual values of researcher and the treatment of research participants. All these actions of keeping anonymity and asking for consents supported the assurance of ethical considerations from the perspective of research participants' treatment.

Keeping the institutional data private was also significant from the ethical point of view. More precisely, no data related to company operations is presented in the public version of this thesis. For example, the cycle time examination was done based on real-time data measured in the company; however, these specific times are not presented. Instead, the graphs are created showing the variability and correlations without highlighting the actual data. Moreover, the cycle times are hidden with ## in the public version so that the results could be presented without revealing the actual data of the company. The same refers to the cycle time measurements from the cobot application, where the actual cycle times are hidden with ##, but the percentage showing the cycle time improvement is presented.

After utilising internal company reports for gathering data and making analysis, the results are presented without putting emphasis on the actual numbers found from the reports. This is another ethical consideration for following the confidentiality agreements and not disclosing any private information related to the company. Whenever possible, the results are presented as percentages in order to illustrate the results numerically but not disclose actual numbers of, for example, the operators in the company. According to Walliman (2022, pp. 54-55), scientific objectivity also plays a vital role in research ethics. That is, there should not be biased approach while gathering or analysing the data, and also the selectivity in presenting results should also be eliminated.

4.8 Reliability

Walliman (2022, p. 112) states that the reliability of the study and the sources of collected data should also be discussed. The mixed methods research with the convergent design was applied in this study, thus enabling the collection and analysis of both quantitative and qualitative data and merging the results. That is, the use of both quantitative and qualitative was supported by the data reliability of this study's results, as they were analysed and later combined. Moreover, the automation of mid-size deep drawing was examined from different perspectives, and extensive results from all these viewpoints were also merged, suggesting the final results. What is also important is that various data collection sources were used for collecting the quantitative and qualitative data from all these different perspectives, thus increasing the reliability of this study. The sources of data collection are accurate and objective, as stated by Walliman (2022, p. 113). In addition, each of the sources provides current information relevant to each perspective of study implementation (Walliman, 2022, p. 113).

Cresswell and Cresswell (2018, p. 334) also state that reliability is connected to internal consistency of responses and measurements, stability over time and consistency. In more detail, cycle time examination was done twice for two different samples and the correlations were examined, thus enabling to get a realistic picture of cycle time variation, which depends on the part being deep-drawn and the operator working on that shift. Moreover, taking a relatively more significant sample and making the measurements also increased the reliability, as it enabled to move past the coincidence in measurements and see the actual picture. The cobot's application in automating the mid-size deep drawing allowed to observe and study how the automation in the deep drawing process would work and the aspects characterising the automation of loading and unloading with robots. It could have been better to conduct the same observation with industrial robots; however, it was not available for using in mid-size deep drawing. In any case, the results from the cobot application would also be considered reliable, as they emphasise the aspects of robot programming and usage in any loading and unloading. From the quality perspective, the interview and internal reports provided an understanding of defective parts and the causes of defects that need to be considered within the process automation. The sources of data could be considered reliable as they were driven by the knowledge, experience and data collected in the company. The ergonomics perspective was also considered, for which the data was gathered from the population of the target group, namely the operators working in mid-size deep drawing, ensuring reliability.

5 Results

5.1 Cycle time examination results

As already mentioned, measurements on cycle times were conducted and the measured data were analysed to study and see the effect of manual loading and unloading on the process variability. It is important to note that the aim was to analyse the cycle time variability when the operator was carrying out the process and there were no stops in the process because of pallet changing, the operator taking a break, or some other reasons. In this regard, the cycle times were measured when the operators were continuously loading the metal sheets and unloading the ready parts without any stops in the process. To begin with the first product, a sample of 25 cycle time measurements was chosen, and Table 4 was created with the IBM SPSS Statistics application for illustrating the frequencies of cycle times (please note that the actual numbers of cycle times are not visible for the public version). As demonstrated in the mentioned table, there were 15 different cycle times from 25 measurements due to the human factor. That is, more than half of the sample had different cycle time measurement results, meaning that manual loading and unloading did not enable a steady cycle time of deep drawing.

Table 4. Frequencies of cycle times for product 1.

Cycle time for product 1

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	##	1	4.0	4.0	4.0
	##	1	4.0	4.0	8.0
	##	2	8.0	8.0	16.0
	##	1	4.0	4.0	20.0
	##	1	4.0	4.0	24.0
	##	2	8.0	8.0	32.0
	##	3	12.0	12.0	44.0
	##	3	12.0	12.0	56.0
	##	2	8.0	8.0	64.0
	##	2	8.0	8.0	72.0
	##	2	8.0	8.0	80.0
	##	1	4.0	4.0	84.0
	##	2	8.0	8.0	92.0
	##	1	4.0	4.0	96.0
	##	1	4.0	4.0	100.0
	Total	25	100.0	100.0	

A histogram illustrated in Figure 13 was also made with the help of IBM SPSS Statistics to examine the frequencies better visually. What was noticed is that several cycle times were relatively long or short compared to the mean cycle time. It would even be possible to carry out the process in a cycle time much less than the mean cycle time if the process steps were standardised and conducted in ideal conditions. From here, it was seen that the aim should be not only reducing the maximum cycle time to the mean cycle time but also reducing the mean cycle time to as low as the minimum one. The primary outcome of this examination was that, in the case of ideal circumstances, the cycle time could be reduced if it was not for the human factor. Therefore, it was decided to take a look at the descriptive statistics of the cycle times of this sample, including the maximum and minimum values, the mean value and the standard deviation (see Table 5, the actual numbers are hidden from the public version). In more detail, there was approximately a 30 seconds difference between the maximum and minimum values of cycle time, the reason for which would be the fact that the human operator spent additional time placing the pallets at the correct height in case of the maximum value of cycle time. Additionally, the difference between the minimum cycle time observed and the mean cycle time was over 10 seconds, providing the potential to reduce the cycle time by 10 seconds in case of a steady and standardized process.

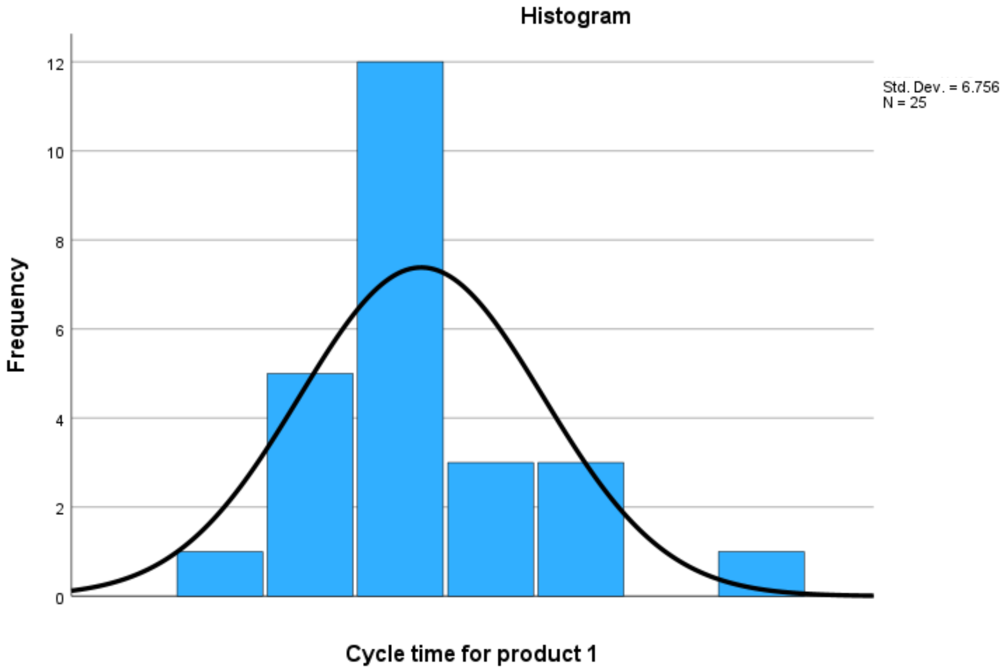

Figure 13. Histogram of cycle times for product 1.

Table 5. Cycle time statistics for product 1.

Descriptive Statistics for product 1

	N	Minimum	Maximum	Mean	Std. Deviation
Cycle times	25	##	##	##	6.756
Valid N (listwise)	25				

The distribution of cycle times was also examined, for which the normal probability plot was made with IBM SPSS Statistics, illustrated in Figure 14. The plot aimed to demonstrate the connection between observed and expected values of cycle times and to examine whether the cycle times are normally distributed. It can be seen that the cycle time distribution was very close to being a normal distribution; however, it was not an ideal normal distribution. This means that there was not only a standard deviation between the cycle times but also some variability in this normal distribution.

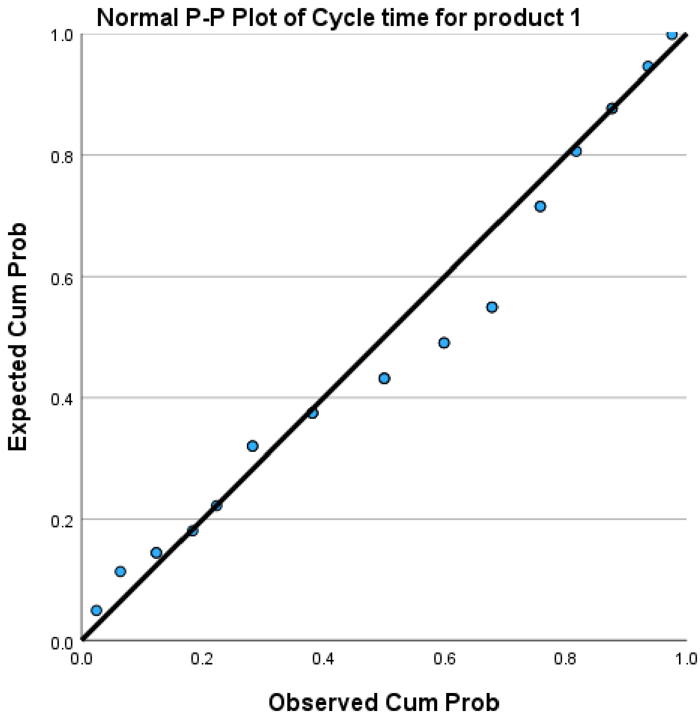

Figure 14. The connection of expected and observed cycle time for product 1.

In addition to examining the variability and distribution of the measured time, it was needed to keep in mind that these measurements of cycle times were made so that the variability of manual work could be examined and the stops were not considered. It could be said that the measurements were effective processing times. However, it was also essential to consider the mean cycle time spent in the queue, the setup time, and its total effect on throughput. In this regard, two corollaries were presented as a result of the cycle time examination in section 4.1. These derived formulas enabled to see the connection of all the essential attributes in one place. Based on these corollaries and the other formulas discussed in the same section, a ready excel template was made (see Appendix 1), in which input data could be inserted and relevant attributes would automatically be calculated. After inputting the data from the sample of 25 effective process times, the Excel template calculated the mean time spent in the queue based on the variability in effective process times and arrival times as well as the total cycle time, including the setup time, effective processing time and mean time spent in queue. The results (see Table 6, the actual numbers are hidden in the public version) indicate that the actual cycle time spent on one part is more than twice as much as the effective processing time. That is, reducing variabilities and, thus, the total cycle time per part would increase the throughput.

Table 6. Cycle time examination for product 1.

variable	time	units
CT_q	##	s
CT	##	s

In addition to observing the first product's cycle time with a sample of 25 measurements, it was also decided to make measurements for the second product and follow its deep drawing process. What was interesting in this sample was that the shift of the operator ended after 22 measurements were made. After this, there was a relatively long stop in this particular deep drawing process when the operator needed to add all the necessary information about the shift's production into the system, and then the next shift's operator would come and continue the process. Thus, there was a significant loss of machine utilisation during the shift change. Moving on to examining the collected 22 cycle time measurements, the frequency table for the cycle times of the second product was again made with the IBM SPSS Statistics application and presented in Table 7 (the actual numbers are hidden in the public version).

Table 7. Observation of cycle times for product 2.

Cycle time for product 2, observation

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	##	3	13.6	13.6	13.6
	##	1	4.5	4.5	18.2
	##	3	13.6	13.6	31.8
	##	2	9.1	9.1	40.9
	##	1	4.5	4.5	45.5
	##	1	4.5	4.5	50.0
	##	2	9.1	9.1	59.1
	##	1	4.5	4.5	63.6
	##	3	13.6	13.6	77.3
	##	3	13.6	13.6	90.9
	##	1	4.5	4.5	95.5
	##	1	4.5	4.5	100.0
	Total	22	100.0	100.0	

When looking closely, the relatively higher cycle time would be noticed in the last row. When checking the notes of making the measurements, it was found that this longer cycle time was caused by the operator leaving the workstation. As the aim was to check the variability in the manual work, excluding the waiting time for pallet changes, setups, and any other breaks, this data was rejected, and the final table of relevant cycle times with a sample of 21 measurements was presented in Table 8 (please note that the actual numbers are not visible in the public version).

Table 8. Frequencies of cycle times for product 2.

Cycle time for product 2.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	##	3	14.3	14.3	14.3
	##	1	4.8	4.8	19.0
	##	3	14.3	14.3	33.3
	##	2	9.5	9.5	42.9
	##	1	4.8	4.8	47.6
	##	1	4.8	4.8	52.4
	##	2	9.5	9.5	61.9
	##	1	4.8	4.8	66.7
	##	3	14.3	14.3	81.0
	##	3	14.3	14.3	95.2
	##	1	4.8	4.8	100.0
	Total	21	100.0	100.0	

Similar to the previous sample study, the histogram was made in order to better visualise the cycle times and their frequency within the deep drawing process (see Figure 15). It was seen that there was no single interval where the cycle time was the most frequent; the highest frequencies of the cycle time were observed to be within two different intervals.

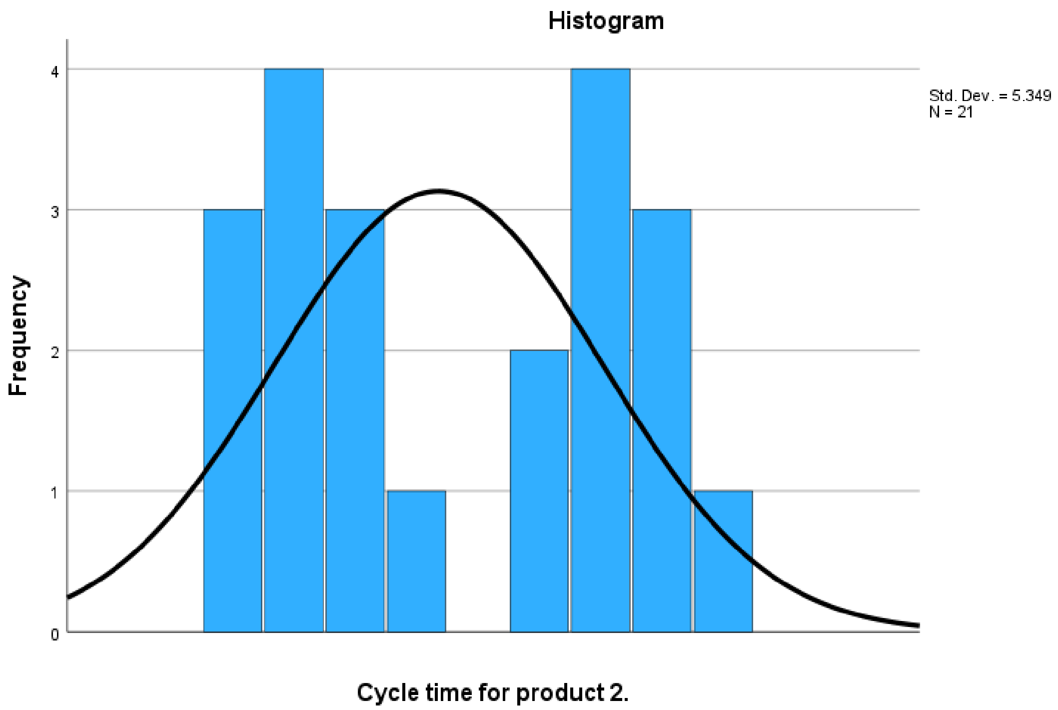

Figure 15. Histogram of cycle times for product 2.

Table 9 for descriptive statistics was made for evaluating the minimum and maximum values and comparing them to the mean value of cycle time. Unlike the first product, the difference between the minimum and the mean values was not that high, and it was a little over 5 seconds. The difference between minimum and maximum values was approximately 15 seconds, which was 2 times less than in the case of product 1. The result from here is that the deep drawing cycle time might vary depending on the part, its lubrication and the operator carrying out the loading and unloading.

Table 9. Cycle time statistics for product 2.

Descriptive Statistics for product 2

	N	Minimum	Maximum	Mean	Std. Deviation
Cycle times	21	##	##	##	5.34923
Valid N (listwise)	21				

Similar to the previous sample, the cycle time of the second product was also examined to see whether it was distributed normally or not (see Figure 16). As can be seen from the normal probability plot, the second product's cycle times distribution could not be described as a normal distribution, meaning that there was even more variability in the case of the second product compared to the first one.

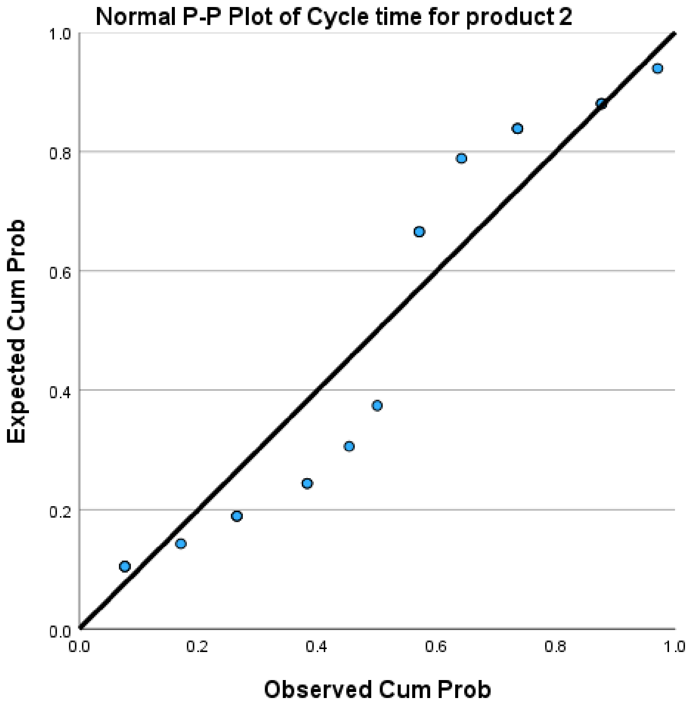

Figure 16. The connection of expected and observed cycle time for product 2.

5.2 Cobot application results

Referring to the results from the cobot application, it was found that cobots can be successfully utilised for loading and unloading the deep drawing machine. It was possible to easily programme the cobot with the help of a teach pendant, perform the needed loading and unloading tasks and later improve the programme to reduce the cycle time. During the limited period of time that the cobots were available for testing and using, the deep drawing process of two products was automated with the cobot, and the cycle time was measured first for the basic programme. This was followed by improving the programme so that there would be no unnecessary waiting at a certain waypoint, and the cobot would grip the next metal sheet and move it to lubrication instead of standing and waiting for the deep drawing machine to complete the drawing of the part. The cycle time with the improved programme was also measured. It was noticed that there were significant improvements in cycle times, and the percentages of cycle time reduction were calculated (see Table 10, please note that the actual numbers are hidden from the public version). It is worth mentioning that the cycle time reduction percentages are different because they were calculated as a percentage of the initial cycle time with the basic programme. Overall, the reduced time might be different for each case, depending on the people programming the cobot and the location of the waypoints used in the programme. The reduction time variation might also depend on the size of the part, the distance of the pallets of raw materials and ready parts and the waypoint from where the cobot starts to move down for gripping action. The programming of the cobot could be continued step by step until achieving the desired, optimal and efficient cycle time. By eliminating the non-value-added steps from the programme, it was possible to achieve from 10 seconds up to 15 seconds of cycle time reduction.

Table 10. Cycle times of deed drawing process automated with cobot.

	Cycle time with basic programme [s]	**Cycle time with improved programme [s]**	**Cycle time reduction percentage**
Product 1	##	##	15 %
Product 2	##	##	27 %

The results from the qualitative data gathered through observation of cobot application should also be discussed. The first observation was that cobots were simple to instal and use. That is, the cobot could easily be installed on a deep drawing machine and there would not be any need to stop the production for a long time. The simple installation of the cobot robotic cell would also enable moving the cobot from one deep drawing machine to another. This was useful as the company producing different parts used different deep drawing tools designed for different deep drawing machines. In other words, the cobot robotic cell could easily be moved and installed to the needed deep drawing machine based on the demand or production volume. Moreover, the programming of cobots was also relatively simple, there were ready programmes which could be used, and the programmes for each part could be saved and used the next time it would be deep drawn. Furthermore, the cobot could work without needing to take a break like operators increasing the machine utilisation.

Continuing with the observation results, it was also noticed that using a lubrication machine with a mangle was not very practical, as it was challenging and time-consuming to programme cobots in a way that the lubrication of metal sheets was achieved successfully every time. The impracticality of mangle lubrication was also based on the observation that lubrication of the metal sheet was not done evenly, which could lead to quality problems with the deep drawing of the part. Therefore, an alternative method for lubrication should be utilised. Furthermore, the cobot detected the operators near it and it slowed down. This could be a helpful feature if an operator needs to come near the deep drawing machine at some moment to check the quality of the deep drawn parts after every 20 parts, for example, and there would be no need to stop the process from doing this.

From the cobot application, an important result related to the automation level was raised as well. As mentioned in the literature review, automation level 3 includes only the automation of the machine cycle and unloading, whereas automation level 4 includes the automation of the machine cycle and both unloading and loading. When utilising a cobot for both loading and unloading, i.e., having automation of level 4, no human labour was needed to monitor the workstation for the whole shift. There might be only needed to carry out a quality check several times during the shift, in which case one operator could be responsible for quality checks for two or more workstations rather than having one operator for each workstation per shift. This would give a possibility to significantly lower labour costs. On the other hand, level 3 automation would require one operator for each workstation per shift who could also take care of quality checks, and the labour costs would be relatively higher. As a result, level 4 automation would be the cost-efficient option and it could work very well, as seen from this cobot application, if the quality checks can be adequately organised to ensure the quality for the customers and not have unnecessary wastes. Regarding the quality of ready parts, it should also be mentioned that the metal sheets were placed in the same position to the deep drawing machine, due to which the parts came out almost identical from the deep drawing process without any defects after the programming and testing of the initial parts' deep drawing was correctly done. Hence, having one operator for checking the quality of deep drawn parts at several workstations and organising this process can be successfully achieved for automating the deep drawing process at level 4, which would result in low labour costs as well as shorter cycle times.

5.3 Interview results related to robot programming and usage

As a result of the interview conducted with the employee from a technical department working in the company, the basic steps of creating the programme for the robot's application in production processes were identified. The main idea was to start programming the raw version, defining the "Move" points, paths and actions. There were also various tips related to robot programmes, which would ease up the programming and making corrections later as well as would reduce the cycle time. However, this would require more knowledge and practical experience from the person making the programmes. One essential tip was the use of Routines and using them in the main programme, which would enable to group the rows in the programme which relate to the same step in the production process and later find them easily and make changes if necessary. The next tip was related to the usage of Zone values in the programme, which enables the robot to shortcut the "Move" points and achieve a shorter cycle time. Moreover, the Speed of the robot would also be increased after creating the basic programme, along with the reduction of unnecessary movements in order to achieve shorter cycle times.

The results also covered the common issues in the usage of automation in production processes. More precisely, the crashes were the main cause of the errors in the case of robots being used for loading and unloading. The reasons for crashes were operator mistakes or broken ejectors. When going deeper into operator mistakes, it was found that they just were not aware or did not pay attention to one small detail, and it caused the crash. In this regard, the importance of educating the operators was highlighted by the employee from a technical department:

> *"The main point is to teach the operators how to use the robots, for example, the difference between some basic steps in using the robots and teach them how to use robots safely."*

From this point, it seems that having a skilled professional who could take care of creating the robot programmes would not be enough and the operators using the robots in their everyday working life should also have relevant knowledge about robot usage. This would not only reduce crashes or other production problems but also improve operators' safety. Safety should also be considered in the everyday usage of robots, no matter the type of robots used in production. In addition, it should also be emphasised that the use of robots and automation is not aimed at reducing human value but at improving and fastening the production process.

When referring to the quality of deep-drawn parts, there would be significantly less or no defective parts based on the accuracy of robots and the standardised placing of metal sheets in the machine if the testing of the initial parts were done properly. Nevertheless, quality checks would be necessary to monitor the parts and ensure the quality also for the customers. It was found that quality could be checked with 3D vision, which is a relatively expensive option, but there would be no need for human labour and, consequently, labour costs. An alternative would be stopping the production process and having operators check the deep-drawn parts' quality. Furthermore, lubrication was also discussed as a part of the deep drawing process that affects the quality of parts’ deep drawing and needs to be considered when automating the process. Based on the interview, the lubrication with the Oil Spray machine proved to be a reliable option in practice, as a proper amount of lubrication is accurately sprayed on the metal sheet.

5.4 Results from the quality perspective

As a result of the interview conducted with the employee from the quality department, various causes of defects in mid-size deep drawing were identified. The causes varied, including the deep drawing tool wear, wrong material type, wrong amount of lubrication, wrong deep drawing parameters, for example, the blank holding force, and the incorrect placement of the metal sheet into the deep drawing machine. However, not all these causes were within the scope of the study as the study is limited to discussing the quality only in terms of the actions conducted during the production process that affect the product quality. Therefore, it was important to identify which quality aspects of the deep drawing process were relevant to the study and needed to be considered when automating the process. That is, the defects caused by the worn tools, deep drawing parameters or wrong material type were not relevant to the study as they could not be influenced by automating the process. The main causes of defects to concentrate on were the correct placement of metal sheets and the correct amount of lubrication. Regarding the defects, there were tears, fractures in the part or other errors in the form of the part. The most common cause of these defects was the wrong amount of lubricant. No specific actions would be needed to eliminate this cause other than just checking and ensuring that the lubrication would be done correctly next time.

It was also found that the defects in a mid-size deep drawing conducted manually were more than the defects in another deep drawing process, the loading of which is automated. This showed how the automation of the processes could affect the quality of deep-drawn products by reducing internal scrap. The reason was that the automated loading was more accurate and the variability of humans placing the metal sheets was eliminated, resulting in a standardized work step and improved quality of products. The main action for addressing this cause of the metal sheet’s incorrect placement in the deep drawing machine would be checking the centre of the metal sheet placement in the deep drawing machine.

In addition, reports related to the internal scrap of the company were also studied. In particular, the statistics associated with the number of incidents based on the primary cause of the defect were reviewed. The incidents were caused by form errors, surface defects, configuration and measurement errors which were the main causes of defective parts. Even though all these defect causes are outside of the scope of this study, it should be kept in mind that customer satisfaction is a priority, and the quality of each part needs to be assured before shipping the ready parts. Thus, implementing quality checks and inspections was needed to consider when automating the processes.

5.5 Ergonomics results

After observing operators' work during the daily deep drawing process, the possible issues related to ergonomics and operator safety process were identified:

- Operators standing during the shift,
- Repetitive tasks,
- Cutting hands due to sharp edges of metal sheets,
- Risk of not putting the pallets at the appropriate height, leading to bending and lifting the parts in the wrong manner.

Most of these identified issues could be considered factors leading to the developing musculoskeletal disorder. Therefore, it was essential to understand how automation of the deep drawing process can reduce these issues. It was also clear that lifting the metal sheets from the pallet to put it on the deep drawing machine and then taking the part from there to put on the pallet were the reasons behind these possible issues. That is, the automation of loading and unloading should be of interest when aiming to reduce such issues related to ergonomics and operator safety.

Significant results related to ergonomics were achieved by analysing the questionnaire as well. To begin with, the existing or possible safety issues in the deep drawing process were put forward by the operators based on their practical experience. After grouping all the answers related to safety issues together and analysing them, the most common issues related to safety and ergonomics were identified to be the following:

- two metal sheets being deep-drawn on top of each other,
- heavy parts causing back pain,
- cut wounds due to the sharp edges of metal sheets,
- metal sheets, parts or the floor being slippery due to all the lubrication used in deep drawing,
- new operators' inexperience and leaving extra items on the floor or tables near the machines.

Within the questionnaire, operators were also asked about their experience of back pain or other musculoskeletal problems connected with their tasks within the deep drawing process. As a result, it was found that the majority of operators continuously or occasionally experienced back pains or strained joints of knees and ankles (see Table 11). Moreover, the questionnaire enabled the operators to clarify or explain their answers, based on which it was found that the lifting of heavy parts and human errors in connection to ergonomic suggestions were the common reasons behind the pains caused during the deep drawing process.

Table 11. Survey results 1.

Experiences of back pain or stressed joints	Frequency % of answers	Clarification/Explanation
yes, sometimes	46,7 %	in case of human errors, in case of heavy parts, human errors of not keeping back in the correct posture
no	53,3 %	thanks to very strong back

In addition, it was also decided to study how the operators follow the ergonomic instructions important for reducing injuries and ensuring their safety. It was discovered that the operators mostly followed the instructions and lifted the pallets to the appropriate height (see Table 12). The questionnaire also revealed the actual reason for not lifting the pallets to the appropriate height, which was the lack of a sufficient number of lifters or forklifts to be used near different workstations in the factory at the same time.

Table 12. Survey results 2.

Pallets being raised to the appropriate height	**Frequency % of answers**	**Clarification/Explanation**
yes	66,7 %	
not always	33,3 %	not enough lifters or forklifts

Before moving on to investigate the operators’ view on robotics, their usage in production and influence on ergonomics and safety, it was decided to study how increasing safety and improving ergonomics could be achieved while still carrying out the loading and unloading during the deep drawing process manually from the perspective of operators. According to the operators' responses to the questionnaire, providing a sufficient number of lifters and forklifts, following the availability and usage of gloves as well as operators’ lifting heavy parts in pairs, might be helpful for assuring safer manual operation. One response also highlighted the importance of teaching the correct lifting methods and other details for supporting ergonomics near deep drawing machines, especially to new operators. At the same time, there were operators who doubted that manual operations could become safer, arguing that manual loading and unloading can still cause pain in the back and joints.

Finally, the questionnaire took a look at the operators’ opinions and perspectives regarding robot utilisation in deep drawing. They were asked to identify the positive and negative aspects of deep drawing process automation. To begin with the positive aspects, the most common response was that automated loading and unloading would spare the operators from conducting the same lifting repetitively and later getting injured. In addition, robots working continuously without needing breaks and working steadily and fast was emphasized as a positive aspect. On the other hand, operators identified several negative aspects of deep drawing process automation as well. The issue of monitoring deep-drawn parts' quality was a widespread answer. What refers to the negative aspect of automation in terms of ergonomics, the responses showed that operators being in the wrong place at the wrong time when a dangerous situation arises during automated loading or unloading could be a significant safety problem. In addition, several responses showed that robot utilisation would decrease the workers’ value and cause unemployment. Despite all the negative aspects brought up by operations, the answers to the concluding question of the survey showed that the majority of the participants found that the robot utilisation in loading and unloading the deep drawing machines will reduce risks and improve safety (see Table 13).

Table 13. Survey results 3.

Robot utilisation reducing risks	Frequency % of answers
yes	86,7 %
no	13,3 %

5.6 Investment calculation results

Finally, the investment calculations were done and the ROI-%, Payback Period and NPV were calculated for both investing in an industrial robot and a collaborative robot. Both of the investments were calculated to be profitable as the NPV was positive. At the same time, it was noticed that the NPV for the industrial robot was higher compared to the NPV for the collaborative robot. In a similar vein, the payback period for the industrial robot was calculated to be several months shorter than for the collaborative robot. The ROI-% percentage was also higher for the industrial robot. All in all, both investments were estimated to be profitable, but investing in the industrial robot is more beneficial from the financial perspective. Table 15 and Table 16 included in Appendix 4 include all the financial results for both calculations; however, the data is not available in the public version as it contains confidential information about the company. In this regard, Figure 17 and Figure 18 illustrate the robotic cell integration analysis for both industrial and collaborative robots correspondingly.

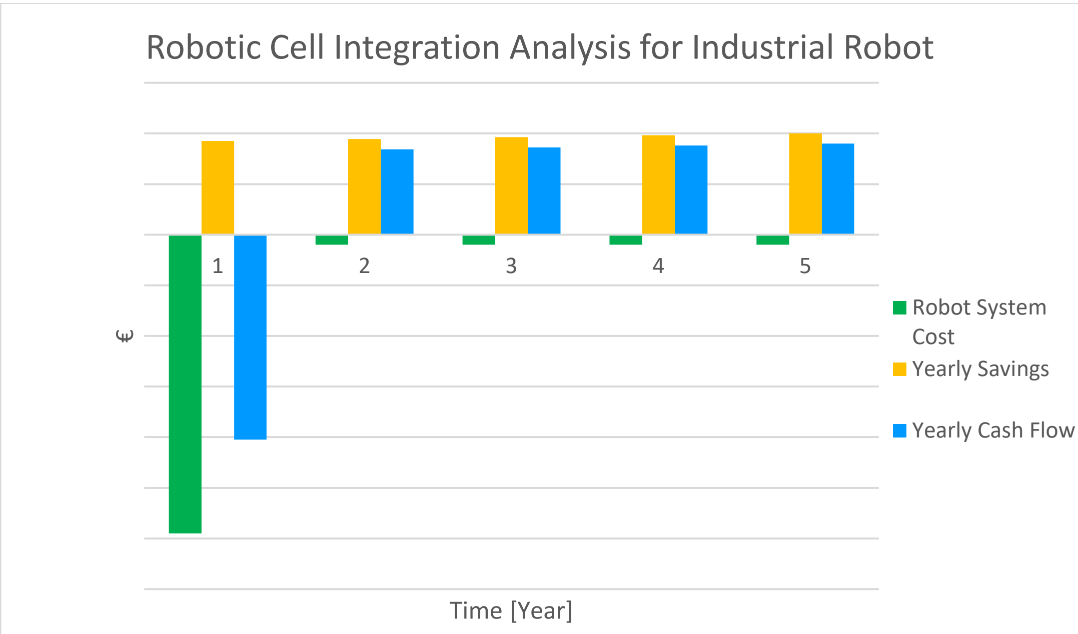

Figure 17. Robotic Cell Integration Analysis for Industrial Robot.

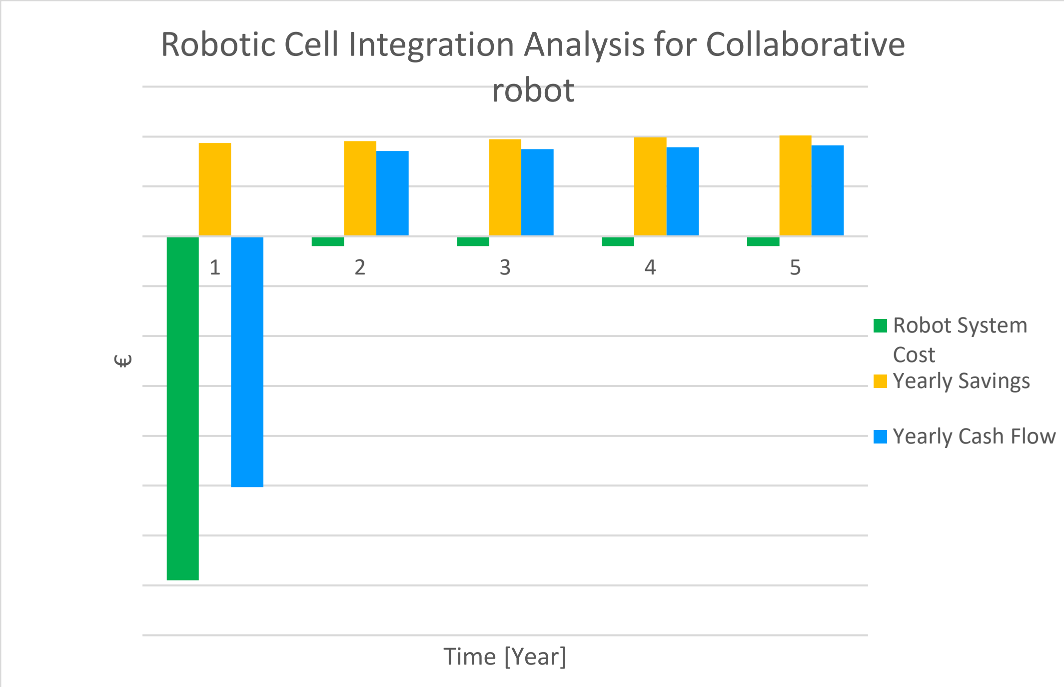

Figure 18. Robotic Cell Integration Analysis for Collaborative Robot.

5.7 Summary of results

After examining the data from various perspectives, it was necessary to summarise the results in one place and merge them to see the study's overall results (see Table 14).

Table 14. Summary of results.

Cycle time examination	There is variability in cycle times due to manual loading and unloading. Cycle time distribution varies; sometimes it is a normal distribution, and sometimes it is not, depending on the parts, lubrication process and operators. There is a high potential of reducing cycle time and thus increasing the throughput by eliminating the human factor. The variability in arrival times and effective processing time causes high mean time spent in the queue, leading to high total cycle time. Breaks, unexpected stops and shift changes cause a reduction in machine utilisation.

Cobot application	There is a potential to achieve a standardised process by automated loading and unloading as well as to achieve constant cycle times. There is a potential to reduce cycle time with programming by having appropriate skills and knowledge. Level 4 automation is suitable for loading and unloading the deep drawing machine. The importance of robot training is highlighted both for programming and daily operations. The usage of oil spray lubrication with robots is practical.
Robot programming	Various tips are provided on robot programming based on experience. The basic programme is created, and then it is improved by eliminating non-value-added steps. The importance of robot training is highlighted once again. The practicality of oil spray lubrication with robots is highlighted again. The accuracy of robots is highlighted.
Quality	Manual lubrication can be uneven, and the placement of metal sheets cannot always be very accurate, causing defects. Defects can be caused by various reasons, even outside the scope of this study, and quality checks need to be conducted to monitor defects caused by any reason.
Ergonomics	Robot utilisation will decrease repetitive tasks. Robot utilisation aligns with prospective ergonomics. The majority of operators believe that robot usage will reduce risks and improve quality. The automation project needs to be conducted in a way that operators see the positive aspects of it, such as steady and fast processes, and do not feel that the value of operators is decreased.
Investment calculations	Both investments in industrial and collaborative robots are beneficial. Investment in an industrial robot has a shorter payback time.

6 Discussion and conclusions

The final chapter addresses the research questions based on the reviewed literature and the results of data collection and analysis. Different perspectives on production mentioned in the implementation part are considered when answering the research questions. Suggestions are made for the target company for developing their mid-size deep drawing process, along with directions for future research that would be useful not only for the target company but also for the industry in general. Finally, a reflection on the conducted research is made.

6.1 Answers to research questions

The main objective of this study was to examine the automation of production processes by reviewing relevant literature and analysing the gathered data from several perspectives essential for production process development. Based on the literature review, data collection and analyses and results, the research questions are answered below:

1. *Does the automation in mid-size deep drawing processes give benefits? What are those benefits, if any?*

The automation of the mid-size deep drawing process brings various benefits from different production perspectives. To begin with, automation enables to reduce the cycle time and increase the throughput during the same amount of time spent. In more detail, the results show that process automation will enable achieving a constant and reduced cycle time. This is connected with the fact that cycle time reduction is typically achieved by reducing one or several of its component times, as stated by Hopp and Spearman (2011, pp. 343-346). At the same time, the cycle time examination shows that a relatively high mean time spent in the queue exists. In this regard, the reduction of mean time spent in the queue can be achieved by decreasing variability and increasing utilisation, as discussed in subsection 3.1.1. Based on the study results, the reduction of mean time spent in the queue is also feasible by automating and standardising the process and thus reducing the variability. In addition, the unnecessary loss of machine utilisation caused by operators taking breaks or changing shifts will decrease with process automation. What is also important is that process automation enables to reduce not only the mean time spent in the queue but also the effective processing time, which will also result in reduced total cycle time. It is found that after standardising the process steps with automation, it is also possible to work on robot programming as much as the majority of non-value-added steps are eliminated and the desired effective processing time is achieved.

Automation in mid-size deep drawing enables improvements from the quality perspective as well. The human factor may often cause uneven lubrication and incorrect placement of metal sheets in the deep drawing machine, which results in defective parts. The defective parts themselves can be considered an unnecessary waste and an additional expense for the company, and it is also against the idea of lean manufacturing. Therefore, these process steps can be automated to reduce the human factor in quality defects and the additional expenses caused by them. In particular, oil spray lubrication is found useful for utilising with the robots, which solves the issue of uneven lubrication. In addition, the robot precisely moves in the same path with the same speed reaching exactly the needed points with a very small error, if any, thus solving the issue of inaccurate metal sheet placement. This way, process standardisation can be achieved along with the benefits it brings, discussed in subsection 3.4.5. That is, process standardisation is another benefit of mid-size deep drawing automation. This is particularly important as there will not be tears, fractures or other defects as a result of the deep drawing process. In other words, the use of automation can help standardise this step of the deep drawing process and reduce defects in the deep drawing process resulting from manual work.

From the data gathered for analysing the quality perspective, it is also seen that quality problems in deep drawn parts occur from other issues such as tool wear or measurement errors. Even though these causes of quality issues do not fall under the scope of this study, it is important to remember that customer satisfaction is a priority, and the quality of every part needs to be assured before shipment. That is, quality checks and inspections need to be conducted whether the process is automated or not. Quality checks can be conducted by operators, who will be in charge of carrying out a quality inspection in more than one workstation. The quality checks can be conducted at the same time when the robot is stopped to change the pallets.

The questionnaire's results illustrate that the majority of operators believe that the utilisation of robots in the mid-size deep drawing will reduce risks, thus leading to safety improvements. It was highlighted that manual loading and unloading could cause some pains in the back or stressed joints in case of operators having back issues or human errors in lifting the metal sheets and parts not correctly. The operators also highlighted the steady and standardised way of robots working as a positive aspect. In addition, the robots conducting the loading and unloading steadily without needing any breaks, along with sparing operators from conducting the same task repetitively every day was also emphasised by the operators as a benefit. The main concern of robot utilisation was the quality check and inspections as well as the concern of decreasing the operator value due to automation. What is also important to mention as a result is that many operators noted their lack of knowledge or experience when it comes to robots, that's why there were not able to assess the effects of robot utilisation in mid-size deep drawing.

2. What kind of robotics can be included and to what degree it is worth automating?

The importance of proper lubrication of metal sheets before the deep drawing process is highlighted with the results from both cobot application and interviews with employees from technical and quality departments, which also corresponds to the literature review in section 3.2. The results illustrate that proper and even lubrication can be achieved by replacing mangle lubrication with oil stray lubrication. The importance of the standardisation of the lubrication process is also highlighted by this, resulting in the need to automate the loading of the deep drawing process. This means that level 4 automation needs to be aimed. Level 4 of automation, according to the literature review found in subsection 3.4.3, includes automated machine cycle as well as automation of both loading and unloading. The observations from the cobot application show that by connecting the deep drawing machine to the robots, it is easy to automate the machine cycle at the same time with loading and unloading based on the inputs and outputs from the robot.

When reviewing the next automation level 5, which is the automation of the final stage of transferring a part to the next production phase, it is related more to the development of the material flow in the factory rather than the development of the deep drawing process. Thus, level 4 automation is the maximum level that should be aimed at. On the other hand, automation level 3 includes only automated machine cycle and unloading. This requires manual loading of metal sheets in the deep drawing machine and does not correspond to the need for having an automated and standardised lubrication method. Manual loading also removes the standardisation of metal sheet placement in the deep drawing machine, which has a potential to reduce the internal scrap and costs related to it. Automated loading would support the reduction of variability caused by the human factor, which will not be the case with manual loading in level 3 automation. In addition, manual loading will require one operator per shift for each machine, meaning that the labour costs would remain the same in addition to investments and would increase along with the increase of throughput in the upcoming years.

Taking into account all the above-mentioned factors, level 4 automation is found to be reasonable when using robotics in the mid-size deep drawing process. The total cycle will be automated and standardised, leading to variability reduction, improved quality due to even lubrication and precise placement of metal sheets and the reduction of costs coming from internal scrap. One operator will be needed to monitor the process of several machines and conduct quality checks. Quality checks and inspections can also be organised efficiently. For example, the process will be stopped for changing the pallets, and the inspection can be conducted at the same time.

What refers to the type of robot, both industrial and collaborative robots have benefits and can successfully be utilised. The decision is based on the advantages that the target company wants to gain. If the company needs to easily move the robot from one workstation to another and use less space without the need to put up fences, then the collaborative robot would be the choice. If the mentioned benefits are not a priority, industrial robots are suggested as they have a strong structure and have the capacity to handle relatively heavier parts. The industrial robot is also suggested based on the fact that the target company and personnel are familiar with it and its programming. Moreover, the initial investment in an industrial robot is relatively less.

3. Which methods can be used for calculating the payback time for the investments?

There are various methods for making investment calculations and checking the profitability of the investment before making a decision. Two values are particularly important and typical to calculate when making decisions regarding investments. The payback period of the investment is commonly of interest to the company, as it is needed to know how long it will take for the investment to pay off. It is also essential to calculate ROI in order to see how much of the investments have been saved thanks to the invested automation. These methods are also useful for comparing investment possibilities and choosing the most profitable one for the company. However, these two methods do not consider the time-value of money; therefore, the NPV of investments should also be calculated along with the mentioned two methods. NPV considers the initial investment, the forecasted over the cash flow as well as the discount rate. NPV is useful not only for checking the profitability of the investment but also for comparing and choosing the most profitable option from the financial point of view.

What is also important for making the investment calculations is considering all the expenses that come with investment as well as the expenses that are possible to reduce. When calculating the initial investment, it is important to consider the expenses of necessary equipment, such as grippers, fences, sensors, lubrication machine, etc. The cost savings in machine downtime, sick leave and scrap thanks to the automated processes should be included in annual cost reductions. At the same time, the investment in mid-size deep drawing automation will increase productivity, improving the overall processes, the direct cost savings of which are challenging to estimate, but the benefits should be considered.

6.2 Suggestions for implications

It is suggested for the target company to automate the mid-size deep drawing process as it brings various benefits from the perspective of cycle time reduction and throughput increase, quality and ergonomics. Industrial robots can be used for automating processes as their benefits correspond to the company's needs, there is an experience in personnel working with this type of robots and the investment payback time is relatively shorter compared to the other method. The programming of the robot needs to be done by an employee with skills and experience with robot programming so that all the possibilities for cycle time reduction and non-value-added steps are eliminated. There should be clear markings on the floor for the pallet placements so that the robot programming is made for picking the metal sheet and placing the ready part on the marked area with the shortest and most optimal path. It is also suggested to make an instruction with the essential tips for the robot programming so that it can be educated to other employees as well. What refers to educating the personnel, it is also essential to educate the operators in production about the basic robot programming and usage. A programme or a ready information package can be created to teach the new operators about robot usage as well as safety instructions for operating when robots are utilised. What refers to the investment calculations, it is suggested to have a regular system for calculating the ROI and Payback Period, which also includes the calculations of Net Present Value and considers the time-value of money.

6.3 Directions for future research

Directions for future research are also suggested in this section. The exploration of these topics will not only be beneficial for the target company in improving its operations, but it will also provide some valuable knowledge for the industry. The following directions are suggested for future research:

- Examine the cycle time variation within morning, afternoon and night shifts. Are there any differences and what are the possible reasons for them?
- Examine other types of automation that can be utilised for the loading and unloading of the deep drawing process. What are their advantages over industrial and collaborative robots?
- Examine the benefits and drawbacks of aiming for level 5 automation. How it affects the total throughput of the factory.
- Examine how the automation of mid-size deep drawing can support switching to a make-to-stock production strategy or *a pull* production system.
- Examine how the automation of deep drawing loading and unloading supports complying with quality standards.

6.4 Reflection on the research

I have developed an interest in the topics of production and automation during my studies at JAMK University of Applied Sciences. Current trends and the requirements of the target company were blended with my interest in this topic. My enthusiasm and motivation have made the implementation of this study more exciting and enjoyable. During the whole process, I have developed both my theoretical and practical knowledge by studying various literature and collecting and analysing data. I have also gained experience in implementing a large-scale practical project individually. While implementing this study, I have kept in mind that the collected data need to be reliable, and the analysis needs to be realistic so that the results are applicable to the target company. I have considered various perspectives of production and aimed to combine and use the data based on the practical skills and knowledge of the company personnel with the theory I have studied. It was also important to follow ethical considerations and not disclose any institutional information. In this regard, I have created two versions of this document and have hidden all the necessary information from the public version. I have also asked the company representatives what information they do not wish to include in the public version.

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Thank you everyone!

Lilit Sahradyan

Appendices

Appendix 1. Cycle time template*

Input data and formulas

Number of measurements	t_e	Units
1	##	s
2	##	s
3	##	s
4	##	s
5	##	s
6	##	s
7	##	s
8	##	s
9	##	s
10	##	s
11	##	s
12	##	s
13	##	s
14	##	s
15	##	s
16	##	s
17	##	s
18	##	s
19	##	s
20	##	s
21	##	s
22	##	s
23	##	s
24	##	s
25	##	s

Used formulas

$$t_a = \frac{t_{int.ar.}}{q} \quad (1)$$

$$c_e = \frac{\sigma_e}{t_e} \quad (2)$$

$$r_a = \frac{1}{t_a} \quad (3)$$

$$r_e = \frac{1}{t_e} \quad (4)$$

$$u = \frac{r_a}{r_e} \quad (5)$$

$$CT_q = \left(\frac{c_a^2 + c_e^2}{2}\right) \times \left(\frac{u}{1-u}\right) \times t_e \quad (6)$$

$$CT = \frac{ST}{TH} + t_e \times \left(\left(\frac{c_a^2 + c_e^2}{2}\right) \times \left(\frac{u}{1-u}\right) + 1\right) \quad (7)$$

Cell formats

input
calculations
result/output

q	##	pcs
$t_{int.ar}$	##	s

TH	##	pcs
ST	##	s

Calculations and results

		units	
t_a	##	s	(1)
c_a^2	##		

		units	
CT_q	##	s	(6)
CT	##	s	(7)

t_e	##	s	(2)
σ_e	##	s	Excel formula AVERAGE()
c_e	##		Excel formula STED.S()
c_e^2	##		

r_a	##	part/s	(3)
r_e	##	part/s	(4)
u	##		(5)

* Please note that the actual data in Appendix 1 is not available in the public version.

Appendix 2. Transcription of interview with an employee from technical department*

Question 1: Can you describe shortly what steps you take when programming some robots? What is the first thing you concentrate on?

Answer: This information is not available in public version.

Follow-up question: Can you explain what do you mean by Routine?

Answer: This information is not available in public version.

Question 2: When you have the basic programme that works, what do you concentrate on to reduce the time?

Answer: This information is not available in public version.

Follow-up question: Can you also explain what are these Zone values and how do they help to shorten the cycle time?

Answer: This information is not available in public version.

Question 3: What are the most common problems that you acquainted with? What were the most common errors?

Answer: This information is not available in public version.

Follow-up question: If we concentrate on these robots that are picking and placing parts, what kind of operator mistakes are common that cause crashes?

Answer: This information is not available in public version.

Follow-up question: Once we are talking about problems, can you also address the safety aspect of different kinds of robots that you noticed in practice, for example, industrial robots and cobots?

Answer:

This information is not available in public version.

Question 4: From your experience, what have you noticed about the product quality when robots are used compared to when it is done manually?

Answer:

This information is not available in public version.

Follow-up question: Can you elaborate more on this other solution for quality checks?

Answer:

This information is not available in public version.

Question 5: From the cobot application, what were you changing to reduce the time?

Answer:

This information is not available in public version.

Question 6: From the cobot application, we had some problems with the lubrication, do you have any ideas or suggestions on how can the lubrication be done in a different way?

Answer:

This information is not available in public version.

Follow-up question: Is there something else that you would like to point out when it comes to using robots in production processes or their programming?

Answer: This information is not available in public version.

* Please note that the answers to interview questions in Appendix 2 are not available in the public version.

Appendix 3. Transcription of interview with an employee from quality department*

Question 1: Are the defects more in mid-size or big deep drawing? (This may help to understand whether automation helps to reduce defects, as big-size deep drawing is automated and mid-size deep drawing is not)

Answer: This information is not available in public version.

Question 2: What kind of defects are seen after mid-size deep drawing?

Answer:

This information is not available in public version.

Question 3: What are identified to be the common causes of defects after mid-size deep drawing?

Answer:

This information is not available in public version.

Question 4: What has been done or suggested to reduce these kinds of defects?

Answer:

This information is not available in public version.

Follow-up question: What other actions are there for different causes?

Answer:

This information is not available in public version.

Answer:

This information is not available in public version.

Question 5: Have the defects decreased after the corrections?

Answer: This information is not available in public version.

* Please note that the answers to interview questions in Appendix 3 are not available in the public version.

Appendix 4. Programming of cobots for loading and unloading*

This information is not available in public version.

This information is not available in public version.

* Please note that the information about robot programming presented in Appendix 4 is not available in the public version.

Appendix 5. Investment calculations*

Table 15. Investment calculations for industrial robots.

ROI-%:	##	(Return on Investment)
Payback Period [Years]:	##	(Payback time of Investment)
Payback Period [Months]:	##	(Payback time of Investment)
Robot Cell Hourly Rate [€/hr]:	##	(Total robotic cell cost / total robot working time)
Total Savings [€]:	##	(Cumulative savings after 5 years)
NPV [€]:	##	(Positive NPV)

Table 16. Investment calculations for collaborative robots.

ROI-%:	##	(Return on Investment)
Payback Period [Years]:	##	(Payback time of Investment)
Payback Period [Months]:	##	(Payback time of Investment)
Robot Cell Hourly Rate [€/hr]:	##	(Total robotic cell cost / total robot working time)
Total Savings [€]:	##	(Cumulative savings after 5 years)
NPV [€]:	##	(Positive NPV)

* Please note that the actual data of Appendix 5 is not available in the public version.