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TAMPERE UNIVERSITY OF TECHNOLOGY

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PLANNING OF ROBOT WORK CELL - COMPARISON OF ALTERNATIVE SCENARIOS

Master of Science thesis

Examiner: prof. Minna Lanz
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ABSTRACT

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The purpose of this thesis was to research the possibilities of adding automation on the product finalization stage of the production of plastic products in Finncont Oy. At the beginning of this thesis work practically all of the finalization work was conducted manually with mostly hand held tools. On the same time, the company was starting to feel pressure to automate some of the production processes; partly due to financial concerns and partly due to company image concerns. Some customers had even expressed their wishes for more automation in Finncont's production system.

During the project, product and production system analysis was conducted on the products of Finncont Oy. The analysis included reviewing product data such as drawings, work instructions and production data, mainly production volumes. A time study was performed for 10 most potential products. Concurrently to the product analysis a literature review was conducted on production systems, layouts and production processes. Based on the results of the analyses and the literature review, two product groups were formed and three work cell designs were made. Two for group 1 and one for group 2.

For group 1 a multi-product work cell and a single-product work cell were created. The multi-product work cell can process multiple products with one industrial robot in the centre of the work cell and turn tables around it. The single-product work cell is similar to the multi-product work cell, but has only one turn table, less tools and can process only one type of a product. Both group 1 work cell designs are able to cut, drill and measure. For group 2 a collaborative work cell was designed. In this work cell an industrial robot is used to held and manipulate a product while a human operator does all of the actual processing to the product. The work cell operates with speed and separation monitoring safety method.

The three designs were analysed and compared to each other and it was found out that with different criteria any of the designs can be a good choice. The main criterion for the automation system imposed by Finncont was a payback period of less than 4 years. The multi-product work cell achieved a payback period of 4.75 years or 4.25 years depending on the products. The single product work cell achieved a payback period of 11 years and the collaborative work cells achieved a payback period of 15.5 years with the current production volumes. With higher production volumes the payback period would be shorter. The payback periods are affected by large error margins caused by small number of observations during time study and high degree of variation in working methods among the company's employees.

TIIVISTELMÄ

Anssi Kaakkomäki: Automaattisen robottityösolun suunnittelu – vaihtoehtojen vertailu
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Tämän diplomityön tavoitteena oli tutkia muovituotteiden viimeistelytyövaiheiden automatisointimahdollisuuksia Finncont Oy:n tuotannossa. Diplomityötä aloitettaessa kohdeyrityksen lähes kaikki viimeistelytyövaiheet olivat manuaalisia. Yritykselle oli kuitenkin kasaantunut paineita automatisoida joitakin työvaiheita. Automatisointipaineet johtuivat osin käsityön kalleudesta ja osin firman halusta parantaa imagoaan potentiaalisten asiakkaiden silmissä. Jotkut asiakkaat olivat jopa ilmaisseet toiveensa automaatioasteen lisäyksestä Finncontin tuotannossa.

Diplomityön aikana toteutettiin tuoteanalyysi Finncontin tuotteista, sekä tuotantoanalyysi näiden tuotteiden tuotantojärjestelmästä. Analyysissä tutkittiin tuotedataa, kuten piirustuksia ja työohjeita, minkä lisäksi analysointiin tuotantojärjestelmän tietoja, etenkin tuotantovolyymejä. Kymmenelle lupaavimmalle tuotteelle tehtiin työaikatutkimus. Tuote- ja tuotantoanalyysin kanssa samanaikaisesti tehtiin kirjallisuustutkimus, jolla selvitettiin erilaisia layout-vaihtoehtoja ja tuotantoprosesseja ja niiden automatisointia. Tutkimusten tulosten perusteella tuotteista muodostettiin kaksi tuoteryhmää. Ryhmälle 1 suunniteltiin kaksi tuotantosolu vaihtoehtoa ja ryhmälle 2 yksi tuotantosolu.

Ryhmälle 1 suunnitellut solut ovat monituotesolu, sekä yksituotesolu. Molemmat solut rakentuvat teollisuusrobotin ympärille, joka pitelee työkaluja ja työstää tuotteet. Soluja erottaa kääntöpöytien ja työkalujen lukumäärä, joka on suurempi monituotesolussa, jonka ansiosta se pystyy työstämään useita eri tuotemalleja. Yksituote solu pystyy työstämään vain yhtä tuotemallia. Kumpikin solu pystyy sekä leikkaamaan, poraamaan, että mittaamaan tuotteita. Ryhmälle kaksi suunniteltiin yhteistoimintasolu. Tässä solussa käytetään tavallista teollisuusrobottia pitelemään ja siirtelemään tuotteita niin, että ihmis-operaattorin on mahdollisimman helppo työstää niitä. Solu operoi nopeus- ja etäisyysmonitorointitekniikalla.

Suunniteltuja kolmea solua analysoitiin ja verrattiin keskenään, sekä kohdeyrityksen antamiin reunaehtoihin. Solut ovat niin erilaisia, että reunaehdoista riippuen mikä tahansa niistä voi olla paras. Tärkein kohdeyrityksen antama reunaehto oli neljän vuoden takaisinmaksuaika, jota yksikään solu ei täyttänyt. Monituotesolun takaisinmaksuaika nykyisillä tuotantovolyymeillä on 4,75 - 4,25 vuotta riippuen sillä työstettävistä tuotteista. Yksituotesolun takaisinmaksuajaksi työssä saatiin 11 vuotta ja yhteistoimintasolun takaisinmaksuajaksi 15,5 vuotta nykyisillä tuotantovolyymeillä. Tuotantovolyymejä nostamalla takaisinmaksuajat lyhenisivät. Takaisinmaksuaikoihin vaikuttaa suuret virhemarginaalit, jotka johtuvat vähäisistä tarkkailukerroista työnaikatutkimuksessa, sekä työskentelymetodien vaihtelusta Finncontin työntekijöiden joukossa.

PREFACE

It was really nice working with everyone in Finncont! Thank you Hannu-Ranta-Lassila for providing the thesis position and topic for me and thanks to everybody in Finncont Oy for your support!

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Anssi Kaakkomäki

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

CNC	Computer Numerical control
FMS	Flexible manufacturing system
HAZ	Heat affected zone
HDPE	High density polyethylene
IBC	Intermediate bulk container
LDPE	Low density polyethylene
PE	Polyethylene
PP	Polypropane
ROI	Return of investment
WIP	Work in process

CF_A	average yearly cash flow
CF_t	cash flow per period t
I_T	total cost of the investment
k	accuracy
k_d	discount rate
n	number of observations
n_t	total number of time periods
s	standard deviation
t	time period
x	sample average
z	confidence level

1. INTRODUCTION

Modern production automation can be considered a megatrend that began in 1950's (Y. Nof 2009). Production automation is seen by the industries as method of gaining advantage in competition and lately it has be seen as a way for developed countries to keep their industries. The automation began from automotive and aerospace industries and has been fast to spread in mass production industry. (Y. Nof 2009) However, the introduction of automation to small companies has been slow and the production of low volume products has been found to be especially difficult to automate.

This is also the case for the target company of this thesis, Finncont Oy located in Virrat Finland. The company produces rotationally moulded plastic products. It has both subcontracted and own products in production. The rotationally moulded products often need some finalization work before they are ready for shipping to customers. Currently that finalization work is almost completely manual. The company would like increase the automation level of the finalization stage. One reason is the high cost of manual work and the other is company image. Some customers have even expressed their hopes of higher automation level in Finncont's production system. The purpose of this thesis is to research about the automation possibilities in the finalization stage.

According to Bellgran & Säfsten (2010, p. 185) requirements specification guides the development process and is therefore important. For this thesis there was only one requirement which was given by the management of the target company: a payback period of less than four years. Constraints for the design are:

- Scope of the cell is in product finalization (ie. not in moulding machine tending, packaging or other)
- Not exceeding maximum investment cost
- Economically risky plans should be avoided
- Products chosen for processing in the system should be chosen from the list provided by the company management

While this thesis has been written in linear order, the actual research was somewhat iterative. Therefore some motivations and reasons for decisions done during the making of this thesis may come later in the text than the decisions themselves and not vice versa as would be logical. For example, research about production processes was done partly simultaneously to product analysis and the choice of products for time study and production mixes was affected by this.

The thesis begins with a literature review which builds the theoretical background of the thesis. Theories and industry practises of production system planning, layouts, production automation and production processes are studied among other topics. Theoretical background is followed by company introduction and description of products and the current state of the production process. Description of the product analysis on the fourth chapter comes after those. In the fifth chapter the basic layouts of the work cells are made and different production processes researched. That is followed by descriptions of the final work cell plans in chapter six. The planned work cells are further analysed and compared against each other's in chapter seven. In chapter eight the future possibilities and research topics are discussed which is followed by conclusion and closing thoughts in chapter nine.

In brief the assignment from the target company for this thesis consists of:

- Bring automation to plastic products production
- Choose type of the automation
- Choose the type of the cell
- Choose the process of the cell (where it will be located in value stream and what it will do to the products.)
- Choose the products for the cell
- Create preliminary layout plan for the cell
- Calculate Payback period for the cell

Focus of this thesis is on the general preplanning of the work cells. Hence detailed designs are mainly not considered. I.e. the exact shape and size of the work cell components and their locations are not considered but left out from this work.

The main results of the thesis are planned the three work cell designs. On the comparison chapter it can be seen that all of the designs have their strengths and weaknesses and depending on the criteria any one of them can be a good choice. The main criterion for the target company is a payback period of less than four years. None of the designed work cells reached this limit, but one came close. Nevertheless the thesis still provides valuable information for Finncont on the topics of production automation and work cell design. The future possibilities chapter presents topics for further research that can help lowering payback periods.

This thesis work can be helpful for other readers as well as it gives the reader new ideas and solutions for problems related to planning and designing of robotic work cells. The contribution to scientific community is the comparison of three different types of work cells, traditional single-product, FMS type multi-product and state of the art collaborative work cell, on the same general settings.

2. PRODUCTION SYSTEM PLANNING

In all projects and smaller tasks, it is good to base important decisions on solid theory. For a complex project like this, several theories are required. For this thesis a literature review was conducted on the topics related to production automation. This was used as a basis for the rest of the thesis. First the general outlines of production system design are discussed.

Production system design is a wide area task that depends on many sub tasks (Chryssolouris 2006, p. 329-330). Production system design has several stakeholders and influencing factors as can be seen from Figure 1.

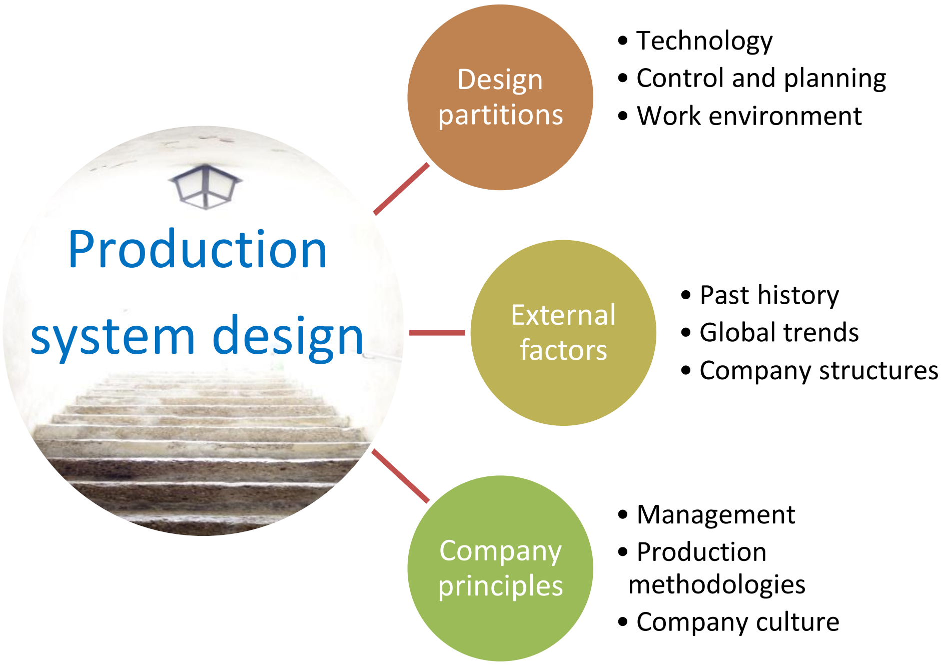

Figure 1. *The aspects influencing production system development. Based on (Bellgran & Säfsten 2010).*

A background study is a necessary pre-requirement for production system design project. It should include existing production system study and study about other possible production systems (Bellgran & Säfsten 2010, p. 172). The existing production system can influence the design of the new system for example by giving ideas, restrictions and a starting place. The influence is great especially when equipment from the old system is be used in the new system. (Bellgran & Säfsten 2010, p.173) In this thesis the background study was conducted. The theory behind it is explained in more detail in chapter 2.1 and the background study is presented in chapters 3 and 4.

The planning phase of production system design project can be divided into three parts. According to (Scallan 2003, p. 37; Bellgran & Säfsten 2010) they are:

1. Conceptual design
2. Evaluation of alternative designs
3. Detailed design of the chosen plan

The scope of this thesis is restricted to the first two parts. Conceptual design is the phase in which alternative conceptual production system designs for are developed. Activities during conceptual design include choosing processes, defining capacity, deciding equipment, planning of layout and defining automation level among other things. (Bellgran & Säfsten 2010, p. 195-214) Theories related to conceptual design are explained in chapters 2.2 to 2.8. The conceptual design done in this thesis is described in chapters 5 and 6.

Conceptual designs should be evaluated and compared against each other. The designing phases and evaluation phases are iterative and the ideas are constantly evaluated. (Bellgran & Säfsten 2010, p.214-221) Requirements specification can be used as evaluation criteria (Bellgran & Säfsten 2010, p.186). In this thesis the conceptual designs were evaluated in chapter 7 and the evaluation is based on the theory in chapter 2.9

Detailed design takes place after one of the created conceptual plans has been chosen. Detailed design includes roughly the same activities as conceptual design, only at a more detailed level. (Bellgran & Säfsten 2010, p. 221-230) Detailed design is out of the scope of this thesis, and the target company is planning to involve system integrator for that part.

2.1 Background study

As said, the Background study is important because, the existing production system can influence the design of the new system for example by giving ideas, restrictions and a starting place. In addition production system design is influenced most by the product and intended production volume (Bellgran & Säfsten 2010, p.85).

In this chapter some background study methods are described. They are product analysis, work measurement and time study. First, product analysis is introduced.

2.1.1 Product analysis

Product analysis denotes the analysis of products for some certain purpose. Product analysis is a general term and the actual analysis can be conducted in many different ways depending on the case. One method suitable for analysing products for production is by listing their attributes based on criteria. The criteria can be freely chosen by the design engineer. Examples of analysis criteria include: size, material, production volume, parts count, manufacturing location, weight etc.

The information of the products can be gathered from multiple sources. Some good sources are product drawings and work instructions. Product analysis is written on chapter 4.

2.1.2 Work measurement

In order to be able to improve their production, companies have to know how the production is being performed currently and how effective it is. Work measurement is a tool created for this task (EK-SAK tuottavuustyöryhmä 2011, p.7). Goal of work measurement is to find out working methods, time usage and ergonomic aspects of the work (EK-SAK tuottavuustyöryhmä 2011, p.6). For being able to give and keep delivery promises for customers, companies have to know how long it takes to complete a specific job and how many workers are needed for it. With work measurement these questions can be answered. Other topics that benefit from work measurement are employee compensation programs and productivity monitoring. (Rowbotham et al. 2007, p.123) In this thesis work measurement is used as means to find out the actual cost of current production.

Work measurement can be conducted in several ways. According to (Aft 2016), there are three methods for conducting work measurement: Time study, work sampling study and physiological measurement study. As its the name suggests, time study involves measuring time taken to perform a specific task. It is applicable for measuring cyclical, well defined jobs. (Rowbotham et al. 2007, p.124; EK-SAK tuottavuustyöryhmä 2011, p.25; Aft 2016) In work sampling study the work task being measured is observed irregularly over a period of time to obtain information on how time is divided on different work tasks. Work sampling study can be done also for irregular and not well defined tasks. (Rowbotham et al. 2007, p.126-128; Aft 2016) The third option presented by Aft is the physiological measurement study. It differs from the other two greatly in that instead of observing how tasks are performed, workers physiological condition is observed. The observed condition can be for instance heart rate or oxygen consumption. Physiological measurement study is useful for measuring physical strain tasks inflict on workers. (Aft 2016)

In product finalization in Finncont Oy, work tasks are mainly cyclical and well defined. For this reason time study was chosen as the method used in this thesis. EK-SAK tuottavuustyöryhmä states that time study measurements can be used for planning investments and layout (EK-SAK tuottavuustyöryhmä 2011, p.8).

2.1.3 Time study

As it was stated before, time study is used for measuring the time taken to complete a specific task or a set of tasks. Standard time is the time consumed by normal worker to complete well defined normal work at normal speed and using normal methods (EK-SAK tuottavuustyöryhmä 2011, p.18). Standard time is the result of time study.

In time study the time taken to complete the task is measured with a stopwatch or a similar device. First part of the study is examining the task and dividing it to sub tasks called elements. An element is a small part of a task and it repeats in every cycle of the task. It needs to have clear starting and ending point in order for it to be reliably measured. (Aft 2016) The actual measuring is conducted by an engineer by observing a worker performing the job and clocking time taken for each individual element. The worker performing the work should be familiar with the work and skilled. However, no one can always work at constant pace and people tend to change their working intensity while being observed. Work intensity rating is used to normalize the working speed to achieve more reliable results. Normal speed is a speed at which the worker can keep up for whole day. The rating is done by the engineer subjectively; hence the engineer needs training and experience to give consistent ratings. (Rowbotham et al. 2007, p.124-126; EK-SAK tuottavuustyöryhmä 2011; Aft 2016)

To get reliable results, it is advisable to measure the tasks several times (Aft 2016). The measurements should also be done with several different persons to average the measured times (Rowbotham et al. 2007, p.124). To obtain a standard time a few calculations are made. First the measurements are averaged and multiplied with the rating for each measurement. Then several allowances are added to get the standard time. The allowances are time the workers use for something else than the task itself during the day. The allowance time can consists for example of personal rest, toilet breaks, search of tools, talks with supervisors, quality related abruptions and time used for cleaning for example.

Conducting time study can be costly if very accurate results are wanted (Malakooti 2013, p.974). The amount of observations needed depend on the desired level of confidence and accuracy for the result. The number of observations can be calculated with the formula,

$$n = \frac{s^2 z^2}{k^2 x^{-2}}, \qquad (1)$$

where *n* is the number of observations, *s* is the standard deviation of the sample, *z* is a confidence level variable, *k* is the accuracy and *x* is the average of the sample (Aft 2016). A small sample observation has to be made first to acquire the average and the standard deviation. According to Aft, the calculation is made for each of the elements of the task independently and the highest result is chosen for the final number of observations. The confidence level variable z can be taken from the table in appendix a.(Aft 2016)

However, as it can be seen in chapter 4.2, to get reasonable 90% confidence level with 10% accuracy for one example product as many as 60 observations would have to be made. This was caused by variations in the work tasks that occurred during the sample observation. According to management the workers often differ from the work instructions and hence variations occur. Due to the limited time for the project and production schedules, it was not possible to conduct the required level of observations. This combined with the fact that the author does not have experience on work intensity rating means that the usual way of conducting time study cannot be used in this thesis. Instead a modified version of the study was performed. Only five observations of each task would be performed, no work intensity rating would be made and allowances would not be added to the acquired standard time. To counterbalance this all of the delay time would be added to the standard time which is normally left out.

2.2 Layout

As said above, choosing the layout type is one design phase. Layout characterises the production system and affects rest of the planning. There are roughly four layout categories for discrete part manufacturing: Fixed position layout, functional layout, cell layout and line layout. Each layout type suits different products and production volumes as can be seen from Figure 2. (Scallan 2003, p. 11-12; Spinellis et al. 2009, p. 4; Bellgran & Säfsten 2010, p. 202-204; Hales 2016)

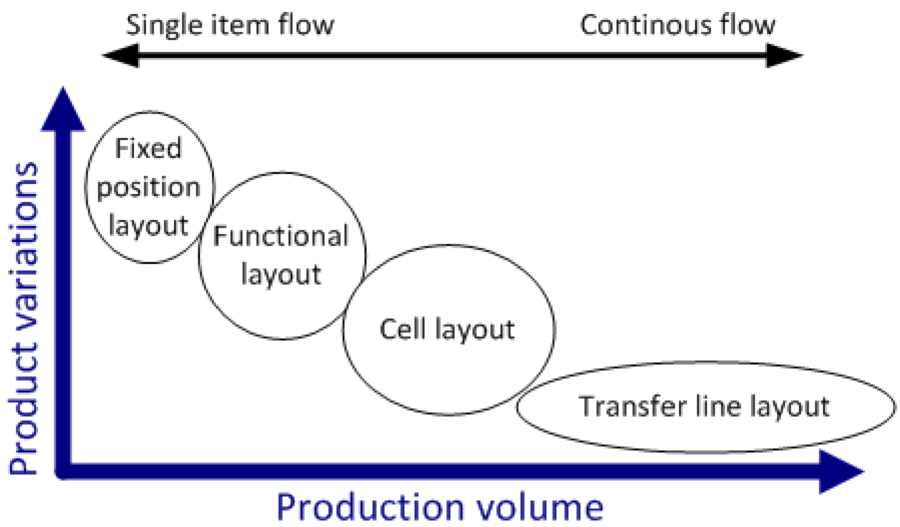

Figure 2. *Layout categories and with respective production volumes and flow types.*

In fixed position layout all production phases are carried out in one place. Work is often mostly manual. The product is stationary and the operators and material move. Fixed position layout is appropriate for the production of large products in low volumes, such as ships. (Scallan 2003, p. 12; Chryssolouris 2006, p. 333; Bellgran & Säfsten 2010)

Functional layout is usually used for producing products with high degree of variation on low to medium volumes. Machines and workstations are organized in groups with similar machines close to each other. The machines can be automatic or manual. Products can be routed in the system in multiple ways. The benefit of functional layout is the high degree of flexibility it offers and potentially high machine utilization level. The bad is the complex management, long lead times and high WIP. (Scallan 2003, p. 12-13; Chryssolouris 2006, p. 333; Bellgran & Säfsten 2010, p. 205-206)

Cell layout is based on the idea of grouping the workstations and machines in groups according to the products they are used to produce. Goal is to gain as good production flow as possible. Cell layout is used with medium production volumes with medium product variation. The whole production cell is considered as one entity from the point of production management which makes it easier to manage than functional layout. Batch production layout is similar to cell layout. Difference between the two is that in batch production layout one worker performs all of the work to the product, whereas in cell layout the work is divided to smaller tasks and one worker only performs one or a few tasks. (Scallan 2003, p. 14; Chryssolouris 2006, p. 333-334; Bellgran & Säfsten 2010, p. 206-207)

Line layout is the traditional mass production layout. In Line layout the product is moved from on specialized station to another on a transfer line. Degree of automation is typically very high. Line layout suits for high volume production of only one or a few similar products. Capital cost is high. (Scallan 2003, p. 13-14; Chryssolouris 2006, p. 334; Bellgran & Säfsten 2010, p. 207-209)

2.3 Production automation

Production automation has been common since the industrial revolution. Basically with automation it is possible to produce more products with less human interaction involved. Traditional production automation involves more or less dedicated automatic machines inter connected by transfer lines. This sort of automation is widely used in car industry. It is efficient and often the best solution when production volumes are high, when there are only a few product variants and when product life-cycles are long. These kinds of automation systems have to be designed exactly for the given situation. Often this results in low variance tolerance and flexibility.

In general the strengths of automation are:

- Humans can be relived from dangerous and repetitive tasks.
- Tasks that require strength or accuracy can be made with machines.
- Increases in production volumes can be achieved.

- Cost per unit can be lowered in some cases.
- Standardisation of work is easier, resulting in higher quality and more consistent production development.(Bellgran & Säfsten 2010, p.211; Lamb 2013)

Automation does also have weaknesses, such as:

- Tasks requiring dexterity are difficult to automate.
- Starting investment is often high and it is not easy to know beforehand the actual cost of the automation system due to complexity of development.
- Automation needs constant maintenance and adds to the costs of running the production. Critical component break down can stop the whole production.(Lamb 2013)

Since the starting investment is quite high, either the payback period is long or production volumes have to be quite high to justify the investment of automation. Many manufacturing businesses however, do not fulfil the requirements (high volumes, few variations, long life-cycles) for transition to automatic production. For example many investment products manufacturers have relatively low production volumes and high product variation. For the majority of 20thcentury such companies couldn't justify the investment to automation, but for the last 50 years flexible manufacturing has been developed for these kinds of companies (Lenz 2016).

2.4 Group technology and cellular manufacturing

Group technology is manufacturing principle which helps to improve productivity of a company. Group technology is based on a rather simple idea that similar products should be processed similarly and possibly with the same machines. (Debnárová et al. 2014, p. 78) Grouping of the products is often done on one of the two grouping options: grouping based on design attributes (such as part geometry, raw material and physical size) or grouping based on manufacturing process (Malakooti 2013, p.652). Advanced coding systems exist to help with the creation of product groups and they are beneficial when there is a large amount of products to be grouped. With only a few products visual inspection and manual grouping is often enough. (Debnárová et al. 2014, p. 79-80)

The improvement of productivity from grouping of products stems from similar tasks being done together, higher resource utilization and easier information management. In manufacturing these turn into faster setup times, less WIP, better quality, fewer tools needed and easier production management. (Curry & Feldman 2009, p. 178; Debnárová et al. 2014, p. 79; Wang 2015, p. 5)

Using group technology to form product groups based on manufacturing process also produces groups of machines based on the products they are used to produce (Malakooti 2013, p.651). Situating the machines within the factory according to these groups effectively leads to a factory layout where machines are grouped into cells based on the products they are used to produce. This kind of layout is called cellular manufacturing.

(Curry & Feldman 2009, p.177; Malakooti 2013, p.651). Group technology can be thought of as a perquisite for cellular manufacturing (Wang 2015, p. 1-7). Some positive arguments for cellular manufacturing include: (Malakooti 2013, p.651)

1. Minimizing manufacturing area
2. Minimizing the need of material handling
3. Decreasing the level of Work in Process (WIP)
4. Shortening lead times
5. Adding flexibility to manufacturing

Manufacturing cells are often compact which may lead to decrease in floor space requirement of the production system. Because material is moved inside the cell directly from one work station to the next, the need for material handling and WIP storages is smaller than in traditional job shops. Additional advantages of the reduced WIP are the shortened lead times. Because cells operate independently from each other, a manufacturing system with many cells is flexible for re-routing and production mix changes (Malakooti 2013; Hales 2016). Flexibility is explained in more detail in the next chapter.

2.5 Flexible manufacturing

Flexible manufacturing system (FMS) is a development in production technology to maintain the high productivity of transfer line based automation while making the production system flexible. An FMS could be considered as high automation cell layout (Bellgran & Säfsten 2010, p. 209). According to Gunasekaran et al (1995), An FMS system consists of one or more flexible machine tools and an automatic transportation system connecting them to each other. Lenz (2016) states, that any manufacturing system capable of manufacturing five or more different products without setup times can be considered an FMS system. There is always a limit to flexibility however; the type of the machine tool varies depending of the type of production done and one machine cannot produce both crank-shafts and silicon wafers for example (Terkaj et al. 2009). GT is applied in FMS. A typical FMS can only process one product group and a change of group may need change of system components. (Spinellis et al. 2009, p. 4-5; Bellgran & Säfsten 2010, p. 209-210)

To understand what FMS means, we have to define the F, “Flexibility”. Basically something can be called flexible, when it is easily able to adapt to new situations. Definition of flexible from Oxford dictionary: “*Able to be easily modified to respond to altered circumstances”* (Oxford Dictionary of English). There are several types of flexibility. There is some consensus that the types of flexibility in manufacturing are (Corrêa 2001, p. 16; Shivanand 2006, p. 22; Spinellis et al. 2009, p. 8):

- Product mix flexibility
- Production volume flexibility
- Product flexibility
- Delivery time flexibility

Product mix flexibility means that the system is capable of processing varying mixtures of products fed to it. Production volume flexibility means that the system can process varying production volumes cost efficiently. Product flexibility means that the system can process several different kinds of products. Delivery time flexibility means that the system can be easily adapted to respond to demand.

High level of flexibility can be reached when the production system consists of flexible machine tools, transportation system and computerised control system (Lenz 2016). An FMS system can consist of several CNC machines, loading/unloading stations and storages. They are all connected to each other via automatic transfer system. Transfer can be done with conveyors or with robots. The transfer system has to also be computer controlled. To make subsystems of an FMS to work together, An FMS has central control system which controls each individual subsystems control system. (Shivanand 2006, p. 22-23) Usually an FMS system is built to tolerate products that have some resemblance to one another.

Flexibility can also be expressed at component level. FMS systems are often built in the way that the products in the system are fixtured on pallets and the pallets are moved on transfer system and to the machines. One kind of flexibility is then pallet flexibility, which means that the pallets in the system are interchangeable e.g. any product specific fixture can be mounted on any pallet. Machine flexibility means that any product can be processed on any machine of the FMS system. In machine tools the flexibility is acquired by computer numerical control (CNC) (Shivanand 2006, p. 22-23). CNC control over the machines enables fast change of programs, thus making them flexible. Complex products might require the processing to be done in steps. Routing flexibility is the possibility to do any of the steps on any of the machines and with any of the pallets.(Lenz 2016)

One advantage of FMS is that FMS systems have defined storage sizes. Some FMS systems have automatic storage, where there is limited space for work in process (WIP). Other systems might have no storage at all and all of the WIP present is currently in production or in movement in transfer system. This ensures that WIP levels in FMS systems can never get out of hand (Lenz 2016). Having an FMS does not mean that whole production is WIP free though. There can be WIP outside of the FMS, waiting entry to the system, or waiting post processing.

Disadvantages of FMS are that FMS systems are relatively expensive; CNC machines can cost millions and automatic transfer lines are expensive as well (Gunasekaran et al. 1995, p. 8; Shivanand 2006, p. 32). It is also said that capacity utilisation in FMS might not be high. Many FMS systems operate at only about 60% of their design capacity. (Lenz 2016) This aspect of FMS should be taken into account before an investment. High flexibility level of the system is also costly especially if it remains unused (Terkaj et al. 2009, p. 2).

Companies involved in non-niche, low volume production, like subcontractors, are more likely to invest in FMS. FMS systems allow them to react to market demand timely and cost effectively. (Terkaj et al. 2009, p. 23)

2.6 Collaborative robotics

Collaborative robotics (Cobots) is a rather new field of robot usage. A collaborative work cell represents modern automation philosophy where human workers and industrial robots work collaboratively. Robots and humans can even work with the same work piece simultaneously. (Bloss 2016; Lawton 2016) The rationalisation behind cobots is the notation that robots are good in some tasks while humans are good in other tasks. Dexterous and non-constant tasks are difficult or uneconomical for robots and repetitive, physically heavy tasks are difficult for humans. By bringing robots and humans together it is possible to achieve a human – robot team that is able to do changing, dexterous, high strength, repetitive tasks (Maurice et al. 2017).

Collaborative robotics is actually a general term for several types of robot uses that include some form of collaboration. ISO standard 10218 allows 4 types of collaboration between humans and robots (ISO 10218-1:2011 2011):

- Safety rated monitored stop
- Hand guiding
- Speed and separation monitoring
- Power and force limiting

The degree of co-operation increases gradually from safety rated monitored stop to power and force limiting. In safety rated monitored stop the robot may work autonomously until a human enters its work space, e.g. through a door. The control system will then stop the robot and monitor its stage until the human leaves the work space. The robot can then automatically resume operation (ISO 10218-1:2011 2011). Safety rated monitored stop is relatively easy to implement even to existing robot systems, since the robot itself does not have to be modified. The robot controller or separate safety controller can be used to ensure the safety of the robot process.

In hand guiding a human operator may guide the robot by holding a guiding device on the robot arm. The robot will only move according to the input from the guiding device and will enter safety rated monitored stop when the operator releases the guiding device. (ISO 10218-1:2011 2011) Hand guiding is mainly used as an alternative teaching method for programming robot. The idea is that instead of having to write G-code or using teach pendant the operator can just guide by hand the robot to the desired position.

In speed and separation monitoring the work space around the robot is constantly monitored and if an object enters the monitored envelope the robot will decrease its speed near the object. If the object reaches a pre-determined separation distance the robot will completely stop its movement until the object has moved away. (ISO 10218-1:2011 2011) Speed and separation monitoring is useful when there is need to use standard, high load industrial robots in situations where some collaboration with human workers is needed. The system can be built with a safety controller and a safety rated scanning system for tracking the work space area. The ISO / TS 15066 allows for both constant and variable safety zones. The zones may be varied according to relative speeds and locations of the robot and human workers. (ISO/TS 15066 Robots and robotic devices — Collaborative robots 2016, p. 11)

Power and force limited robots are designed to be inherently safe. Their maximum power and movement speeds are low so that they cannot harm a human being even if a collision would occur on full speed. Power and force limited robots are also designed with round features and covered joints to prevent injuries. (ISO 10218-1:2011 2011) Because the robot has to be designed safe, an existing industrial robot usually cannot be used in power and force limited mode safely. Power and force limited robots are perhaps the most famous collaborative robots. Some examples of power and force limiting collaborative robots are ABB Yumi, Universal robots line up and Fanuc CR-35iA.

2.7 Safety of a collaborative robot

Safety is important in every industrial robot use scenario. With traditional robots the safety is easy to take care off by building a cage around the robot and ensuring that humans cannot enter the robot work cell while the robot is moving. Ensuring safety with collaborative robots is more difficult however because the human and robot share the same work space occasionally or continuously. In order to ensure the safety of the collaborative work cell a risk assessment has to be performed. Several standards regulate the safety of collaborative robots:

- ISO 12100 (ISO 12100 Safety of machinery — General principles for design — Risk assessment and risk reduction 2010)
- ISO 10218-1 (ISO 10218-1:2011 2011)
- ISO 10218-2 (ISO 10218-2 Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration 2011)
- ISO / TS 15066 (ISO/TS 15066 Robots and robotic devices — Collaborative robots 2016)

These standards should be used as a basis for the risk assessment. It is also important to note that the whole robot process has to be evaluated. Evaluating only the robot by itself is not enough. (Mathieu 2016) The risk assessment has to be application specific: the process, parts, grippers, surroundings etc. have to be taken into account. The risk assessment can be done by the user, integrator or a third party. A risk assessment is required for a CE marking.

2.8 Process planning

The design task continues with process planning which includes choosing the actual manufacturing process, designing production capacity and choosing of the equipment. The choice on the manufacturing process depends especially from on the material of the products and knowledge of the manufacturing processes is needed. Other factors affecting the choice are part size and weight, required processing accuracy, surface finish, production volume and the cost of the process.(Scallan 2003, p. 41-42) In this thesis the process planning is written in to the chapter 5.2.

2.9 Economic analysis of investment

Economic analyses give information on the economic aspects and profitability of an investment. Two types of analyses exist: relative and absolute analyses. Relative analyses can be used to for comparison of several investments and absolute analyses give information on the absolute value of the investment.(Götze et al. 2008; Crundwell 2008)

Some analysis methods account for time value of money and some do not. Present value or time value of money is nowadays important to take into consideration in profitability investment analysis (Crundwell 2008, p. 21). It basically means that one unit of currency is more valuable today than it is tomorrow. Three reasons exist for this: liquidity, inflation and risk. The combined effect of the three almost always causes money to lose its value when time passes and for that reason it should be considered in analysis as well. (Crundwell 2008, p. 125-127) It is calculated with the help of discounted cash flows (Crundwell 2008, p. 124).

Because many analysis methods exist, it is difficult to pick on over another. It has been said that more than one analysis is often needed to cover various aspect of the profitability of an investment (Crundwell 2008, p. 124; Wiggins 2014, p. 68-69). Therefore three different analyses are used in this thesis. Descriptions of the analyses follow.

2.9.1 Payback period

Payback period tells how long it takes for an investment to pay itself back (Baker & English 2011, p. 81; Wiggins 2014, p. 70). It is best used as a limit on how long some specific investments can take for the payback, but it is not very good for giving information on deciding which investment to make among many. That is because it does not convey any information of the value of the investment. (Crundwell 2008, p. 164-167;

Götze et al. 2008, p. 44) Götze et al (2008) even state that payback period should only be used as a supplementary method in investment decisions. Using average values, payback period is calculated with the formula

$$Payback\ period = \frac{I_T}{CF_A}, \quad (2)$$

where I_T is total cost of the investment and CF_A is the average yearly cash flow after the investment (Götze et al. 2008, p. 44).

The advantage of payback period is that it is easy to understand and to calculate. It also gives information of the liquidity of an investment which can be important for companies that have liquidity problems. (Crundwell 2008, p. 166)

Disadvantage is that cash flows beyond the payback period are not estimated (Wiggins 2014, p. 70). Payback period does not account for time value of money which will affect investment profitability especially in long payback periods. (Crundwell 2008, p. 166-167)

2.9.2 Return on investment

Another analysis method is return on invest (ROI). ROI is a ratio analysis that can be used to compare alternative investment possibilities to each other (Crundwell 2008, p. 83-85). ROI can be calculated in several ways (Crundwell 2008, p. 167). One possibility is to calculate it with average cash flows as in

$$ROI = \frac{\mathrm{CF_A}}{I_T}, \quad (3)$$

where ROI is return on investment percentage, I_T is total investment and CF_A is the average yearly cash flow.

ROI is well used in comparing alternative investments to each other’s because it is a relative analysis and the size of the investment does not affect ROI. The method itself does not give indication of what is a good ROI, but some idea could be acquired by comparing it on bank account interest rate. A disadvantage of ROI is that time value of money is not considered in ROI. (Crundwell 2008, p. 168)

2.9.3 Net present value

Third analysis method used in this thesis is Net present value (NPV). It expresses the net value of the investment in present time using discounted cash flows. The cash flows of the investment are all discounted to present value with the use of discounting rate. The idea is to take in to account the time value of money and give more accurate estimate for investment decision. (Baker & English 2011, p. 60-61; Wiggins 2014, p. 70) NPV equation is

$$NPV = \sum_{t=0}^{n_t} \frac{CF_t}{(1+k_d)^t}, \tag{4}$$

where t is time period, n_t is the total number of time periods, CF_t is cash flow per period t and k_d is the discount rate. (Crundwell 2008, p. 168-172)

An advantage of NPV is that it gives absolute values that convey information about how profitable an investment is. It also includes the idea of time value of money and the results are easy to interpret. The disadvantage of NPV is that the discount ratio could be difficult to estimate and it affects the result of the calculation greatly. (Crundwell 2008, p. 170-172) One possibility is to use inflation rate as the discount ratio. Another possibility is to use government bond interest (Baker & English 2011, p. 61).

Common for all of the analyses is that total costs of the investment and yearly cash flows have to be estimated. The investment costs are the sum of all the equipment, integration, and setup and training costs related to the investment. (Crundwell 2008, chapter 4) The yearly cash flow represents the sum of the money spent and received yearly on the project. In manufacturing the yearly cash flow can be calculated as savings per part. That is the future cost subtracted from the past cost of manufacturing a part multiplied by yearly production of the part. The manufacturing costs consist of maintenance, labour cost, down time and fault part cost. (Lenz 2016)

3. THE COMPANY AND CURRENT STATE OF PRODUCTION

The target company of this thesis, Finncont Oy, is the biggest rotational moulder in northern Europe (Finncont Oy , 2016) and the biggest Intermediate bulk container (IBC) manufacturer in Finland. Finncont's own product portfolio contains products such as fuel tanks, IBC's and waste collection products. Furthermore Finncont is also a subcontractor, and manufactures rotationally moulded products for a variety of other companies. The company is located in Virrat Finland and its two factories are located there. One of the factories is specialised in steel IBC's and the other in plastic rotationally moulded products. The company has roughly 150 employees in 2016. (Finncont Oy , 2016)

The company was founded in 1974 in Virrat Finland. First products were steel IBC's mainly for the domestic market. The company grew along the years. Rotational moulding was added to Finncont repertoire when the need arise to produce plastic inner bottles to half steel half plastic IBC's in 20th century. Use of this new manufacturing technology was quickly expanded and soon Finncont began a new business segment as a subcontractor. Finncont also changed its name and owners a few times as well. Current name Finncont Oy has been in use since 2004. These days a large proportion of sales go to export with main markets in Nordic countries, UK, Germany, Belgium and Holland.

In the next chapter, the current production process is described and followed by introduction to some of the products and their processing phases. Since this thesis work is focused in the automation possibilities in the plastic producing factory, only the process in that factory are considered here.

3.1 Current state of production

All of the products studied in this thesis are rotationally moulded from plastic. The basic steps in the production are as follows:

1. Add plastic powder to mould
2. Insert the mould to oven
3. Remove the product from the mould and let it cool down
4. Perform any finalizing work on the product
5. Pack the product ready for shipment.

Common for all of the products is the beginning three steps during which the product is moulded and attains its shape. There's variation mainly to the amount and type of the raw material used, settings of the moulding machine and the instance of the moulding machine. From step four onwards the process steps vary heavily. The now moulded unfinished products all require different amounts of finalizing work before they can be packed and shipped to customers. The usual types of finalizing work are listed below in no particular order.

- Cutting of features only needed during moulding.
- Separating products moulded together from each other.
- Drilling holes and cutting open other shapes.
- Deburring parting lines.
- Performing leak tests.
- Quality inspections.
- Varying assembly tasks.

All of finalizing work is currently done manually and most of it is done by using basic handheld tools such as knives, screwdrivers and handheld millers. For some tasks dedicated machinery is used. For example, for some products the leaking test is done by sealing any openings in the product, pressurizing the product and then submerging it to pool filled with water. The pools have pneumatic cylinders strong enough to submerge even high buoyancy products.

As it was seen in paragraph 2.3, tasks requiring high dexterity are hard to automate. In Finncont’s processes assembly and leak testing were deemed to be high dexterous and for this reason they are largely left out from the scope of this work. Main effort is focused on researching automation potential in the other tasks (Cutting, drilling, deburring and quality inspections). These tasks should benefit from automation.

3.2 Products

In this chapter products that are analysed in this work are introduced. As it was stated earlier, Finncont produces several kinds of products of which only the rotationally moulded plastic products are considered here. The company produces close to a hundred different rotationally moulded products. However, many of these have rather low production volumes, not much finalizing work or short life-cycles. Based on these restrictions Director of operations, Hannu Ranta-Lassila, had already worked out a list of possible products for automation analysis. The list contained 19 products but was later enlarged with five additional products. Both the original 19 and added five products can be seen in Table 1 below.

Table 1. *List of the 24 products considered for automated production.*

1	Product A	Lid for portable fuel tank
2	Product B	Oil tank for forklift
3	Product C	Lid for waste container
4	Product D	Lid for waste container
5	Product E	Lid for waste container
6	Product F	Fuel tank for
7	Product G	Cargo box for
8	Product H	Cargo box lid
9	Product I	Cargo base lid for all terrain vehicle
10	Product J	Composting toilet
11	Product K	Waterless toilet
12	Product L	Composting toilet
13	Product M	Composting toilet
14	Product N	Sand box
15	Product O	Waste water management tank
16	Product P	Light frame for trailer
17	Product Q	Installation panel for
18	Product R	Water pipe intersection
19	Product S	Waste container
20	Product T1	Fuel tank for tractor
21	Product T2	Fuel tank for tractor
22	Product T3	Fuel tank for tractor
23	Product T4	Fuel tank for tractor
24	Product T5	Fuel tank for tractor

The first 19 products in Table 1 are the products originally considered potential for automated production. The last five products emphasized with grey background colour are the products later added to the list. These products are analysed in chapter 4.

4. PRODUCT ANALYSIS

Main research part of this thesis was begun by making product analysis. The goal of the analysis was to identify potential products to build the automation system for and to gather information required for designing the production system. The product analysis is divided into two parts: general analysis and time study. Analysis begins with the general analysis. The reason the general analysis was performed, was to gather some basic information about the products. With the general information, the products for more detailed time study analysis could be chosen. The general analysis was done by reading work instructions, going to see the products in the factory and by unofficial conversations with the employees and management of Finncont Oy. The second part of the analysis, the time study, was performed to find a standard time for the products. The standard time is needed for deciding which products benefit most from automatic production and are what kind of processing the automatic work cell should be capable of. Economic analyses of the work cell designs also require information of the standard time of current production.

As it was stated in chapter 3.2, in total 24 products were considered for automatic production during this project. 19 of these were known to have cutting and drilling as one production process since they were chosen by the management and that was one of the requirements for the selection. The last five of the products were later added to the scope of the project. These five are from the same product family and they are similar to each other in size, geometry and processing steps. They were included to the project because their combined production volume is on the higher side among Finncont's products and since the customer of those products has requested processing improvements to be made. General analysis was only performed for the 19 original products, because the five extra products were added to the project after the analysis had already been completed. Consequently, only time study was performed for the five products added later.

4.1 General analysis

The general analysis is based on mainly the information acquired from work instructions and product drawings. These sources are supplemented by observations of the production and by estimated yearly production volumes. The yearly production volume information was supplied by the director of production.

First 19 products in the Table 1 were analysed. First basic info about the products was gathered into an Excel workbook where it was easy to analyse. The information gathered included names of the products, sizes, tasks needed to be performed on them, list of features to be cut out if any, Tool approach directions, yearly production volumes, length of the cut to be performed if any, sizes and amount of holes to be drilled if any, measurements to be performed is any, tools needed and other notices if applicable. A sample of the information gathering sheet can be seen in appendix b.

The products were then compared in several categories to find out any similarities between them and also dissimilarities. The categories, which can be seen in the list below, were mainly the same as the types of information collected, mentioned in last paragraph.

1. Physical size
2. Work tasks performed
3. Tool approach directions
4. Tools needed

Analysis on category 1, physical size was straightforward. Information of the size available was length, width, height and approximate weight of the parts. From drawings, some knowledge of the geometry of the products was also acquired. Since the geometries were complex on many products, it was decided that the size comparison should be made by comparing the actual maximum length, width and height, rather than volume. Based on the analysis it was thought that the biggest products are so large that the automation system would become unnecessary large and it would be better to exclude them. The size of a EUR-pallet (1200*800 mm) was used as the limit. Figure 3 below presents a chart of the dimensions.

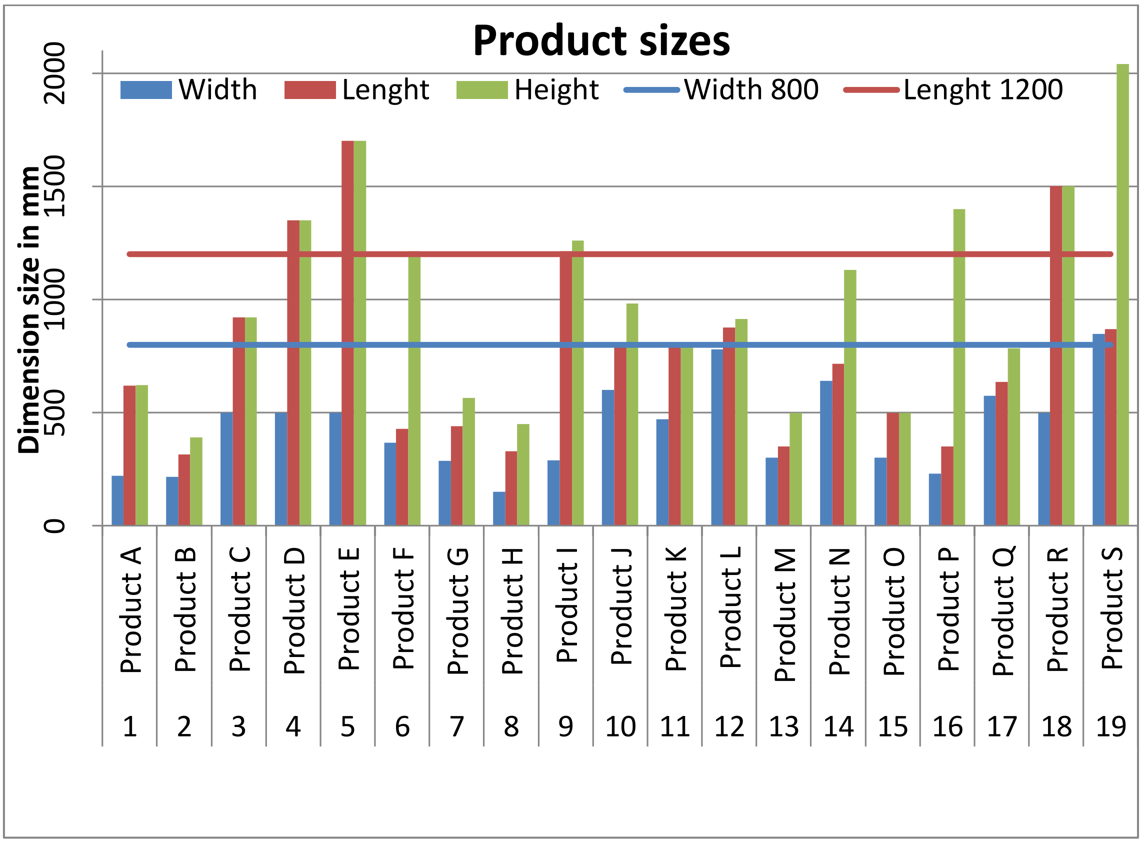

Figure 3. *Product dimensions. For each product the smallest dimension is regarded as width, and the second smallest as length. The width and length of standard EUR-pallet are visualized with lines.*

As can be seen from the Figure 3, there is one product that has a width greater than the width of a EUR-pallet and three products that have length higher than the length of EUR-pallet. The rest of the products fit to the dimensions when height is left unconstrained.

Category 2 analysis was about work tasks performed for each product in finalization. Information on work tasks was acquired from finalization work instructions which shop floor workers use as a guide. All high dexterity tasks were skipped for reasons stated earlier. The rest of the work was divided to tasks roughly by the character of it. Different tasks identified were cutting and drilling, deburring (including deflashing), measuring, marking, chamfering and grinding. Deburring and cutting and drilling were common tasks for all of the products. Other tasks were less common. Task occurrence frequency can be seen in Figure 4.

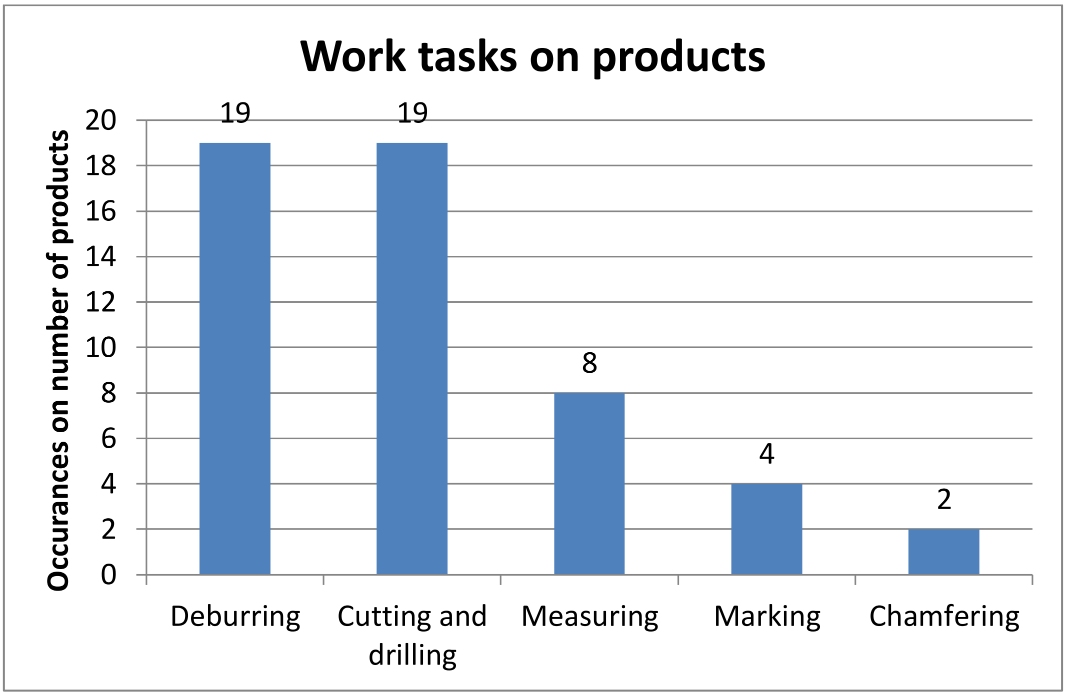

Figure 4. *Occurrences of different work tasks. Tasks are sorted high to low.*

As shown in 23Figure 4, all 19 products have deburring and cutting and drilling tasks. Measuring is also done for almost half of the products. Marking and chamfering are only done for four and two of the products respectively.

Tool approach directions were the third analysis category. Motivation for analysing approach directions is the fact that parts that need processing on many or all of their sides would have to be rotated or turned during the processing in order for the tool to reach obscured areas. For approach direction analysis the products were thought as cubes with 6 sides, where 1 side corresponds to 1 approach direction. Therefore one product can have a maximum of 6 tool approach directions. Information on approach directions was gathered from work instructions. For one product however, there was no information and it was skipped. On Figure 5 a chart is displayed on which approach directions needed per product can be seen.

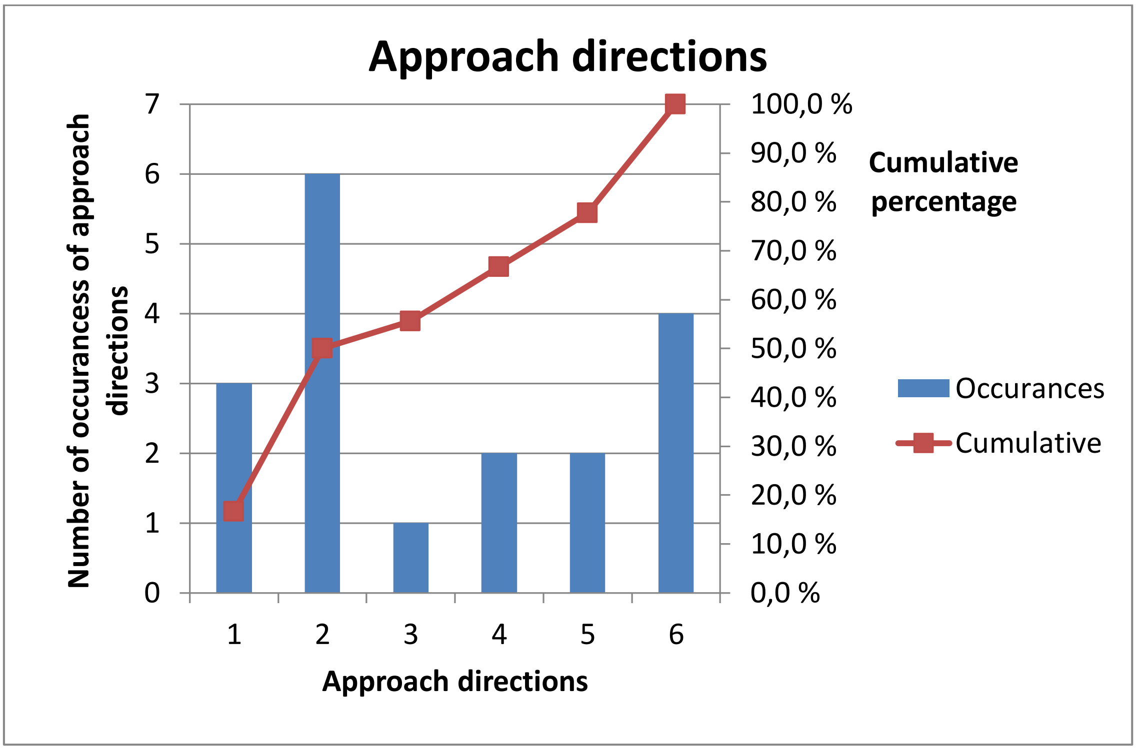

Figure 5. *Approach directions on the products. Columns in the chart display the numerical value of approach directions. Line with markers displays the cumulative percentage of approach directions, with axis on the right. Note, for one product no information of the process tasks was available (Produck K).*

If products are fixtured from all sides it would be almost impossible to do any processing on them. Therefore fixturing should be designed so that it hinders processing of the product as little as possible. Within the 19 products there are four products that need some kind of processing from all six sides and two products that need it from five sides, as we can see from Figure 5. Together they represent about one third of the products total. These products will be hard to fixture. On the other hand, 50% of the products need processing from only one or two approach directions which makes them easy for fixture designing. For one product (Product K) there was no information available of the processing required. It was therefore omitted from the figure above.

Category 4 of the analysis is about tools. Tools needed depend on the work task performed. As we have already identified five different work tasks shown in Figure 4, we base our tool analysis on it. For deburring we need one or more tools depending on the type of burr and surface geometry of the products. Many of the products do have complex geometries so deburring tool needs further research. For now it can be concluded that one or more deburring tools are needed.

Cutting and drilling operations could be done with several different technologies. Possibilities are at least laser cutting, water jet cutting, cutting with knives and cutting with rotational tools. Currently all cutting in Finncont is done with rotational tools, more specifically with pneumatic hand drills/mills. Cutting with rotational tools needs several tools based on the sizes of the holes to be drilled and corner radiuses of the cuts to be made. Finncont has gained empirical knowledge about cutting plastic for years and they were able to confirm that for high speed cutting with rotating tools a tool diameter less than 10mm would easily result in the edges becoming welded back together after the tool has passed on. For this reason it was decided that if cutting would be made with rotating tools the diameter of the tool would be minimum 10mm. Holes on the other hand would preferably be made with right sized drill bits for better quality, although it would be possible to make bigger holes with smaller diameter milling/drilling tools. Information on circular hole sizes was gathered from product drawings and is presented in Table 2.

Table 2. *Circular hole sizes in products, their instances and products in which they occur.*

Size	Instances	Products
3mm	3	9,13 and 16
3,8mm	1	13
4mm	1	7
5mm	3	7, 12 and 14
6mm	2	7 and 13
8mm	1	13
10mm	1	9
12mm	1	2
13mm	1	19
15,5mm	1	10
16mm	1	15
17mm	1	15
21mm	1	15
27,5mm	1	14
44,5mm	1	6
78mm	1	6
80mm	1	10
100mm	1	12
110mm	1	17

As it can be seen from Table 2, the products have a variety of different hole features. In fact, many of the hole sizes occur in only one product. Likewise there is several products that have several unique hole sizes. If cutting and drilling operations are to be made with rotational tools it would be cost effective to decrease the amount of different tools needed. Since smaller hole cannot be made with bigger tool but other way around is possible, it might be best to have several smallest size tools available for the automation system. Some of the bigger holes could then be made with the smaller tool by first drilling a centre hole and then enlarging it with a milling operation. Another option to decrease the amount of tools is to filter out some of the products. For example by eliminating products needing at least two unique sized tools (products 6, 7, 10, 13 and 15) would decrease the amount of tools needed from 19 to 8.

The four types of analyses were combined and some limits were devised to recognize the most potential products. For size, it was decided that the products would have to fit on a standard EURO-pallet. This requirement was based on findings on the process and work cell design that was done simultaneously to the product analysis. Process and work cell design is described in chapter 5. On tool approach directions, products that have processing on all six different sides were left out. This decision is based on the fact that fixturing such products would be difficult. Hole sizes and processing needed was not used as filtering factors at this stage but one product (Product K) was filtered out because no information of processing required was available. A total of eight products were filtered out. The remaining eleven products were chosen for time study. Detailed results of the analysis can be seen in appendix c. Table 3 has a list of products that were chosen for the time study from the original 19 products.

Table 3. *List of the products chosen from the original 19 products with qualitative analysis for time study. The numbering of the products is the same as in Table 1. A total of eleven products were chosen.*

List of the products chosen for time study		
1	Product A	Lid for portable fuel tank
2	Product B	Oil tank for forklift
6	Product F	Fuel tank for
7	Product G	Cargo box for
8	Product H	Cargo box lid
10	Product J	Composting toilet
12	Product L	Composting toilet
14	Product N	Sand box
15	Product O	Waste water management tank
16	Product P	Light frame for trailer
17	Product Q	Installation panel

4.2 Time study

In this thesis time study was used to find out how much work time each of the products needs for completion. This data can be used to sort the products to argument investment for automation, but it can also be used for improving the work methods without investment to automation. This is what MTM is usually used for (EK-SAK tuottavuustyöryhmä 2011).

For most of the products analysed in this thesis, production schedules are either cyclic or otherwise non-continuous. In other words, not all of the products are always in production. During the making of the general analysis, production schedules for all of the products were not yet known. When the analysis was finished it was found out that some of the products chosen for time study would not be in production within the time limit of the project. Therefore those products had to be left out of the time study. Table 4 has a list of the products for time study, where the products that could not be measured are marked with red background colour (grey in black and white prints).

After the general analysis had already been completed, one major customer expressed their hopes of production improvements to the management of Finncont. None of that particular customer's products had been analysed in the general analysis. Thus, it was decided to include their products directly to the time study to see if it would be possible to make improvements to their production processes either with automation or some other means. Because some of the products chosen for time study with general analysis could not be measured, the inclusion of extra products for time study did not cause problems for the schedule of the project. The extra products can be seen in Table 4 with a * sign in front of their index number.

Table 4. *List of the products chosen for time study with a red background colour on those products that could not be measured during the project because of timing.*

The products included in time study

1	Product A	Lid for portable fuel tank
2	Product B	Oil tank for forklift
6	Product F	Fuel tank for
7	Product G	Cargo box for
8	Product H	Cargo box lid
10	Product J	Composting toilet
12	Product L	Composting toilet
14	Product N	Sand box
15	Product O	Waste water management tank
16	Product P	Light frame for trailer
17	Product Q	Installation panel for
*20	Product T1	Fuel tank for tractor
*21	Product T2	Fuel tank for tractor
*22	Product T3	Fuel tank for tractor
*23	Product T4	Fuel tank for tractor
*24	Product T5	Fuel tank for tractor

As it was stated in chapter 2.1.3, the task studied is first separated into elements. To do this the production process of each of the products were first inspected and elements were identified. Because the products and work tasks related to them vary, the elements of the tasks also varied from product to product. Elements for each task are shown in appendix d. After the elements had been identified a sample observation of each task was made to acquire average and standard deviation for the calculation of the number of observations that would have to be made. Measurements were made with a computer program called EasyTime. 20 elements can be defined for one task in EasyTime, which was sufficient for this study.

The first product that was measured was the product with index number 14, Product N. A sample of five cycles was measured and during the measurement it was soon obvious that a normal time study would not work very well since there was considerable variation in the work. Even though the company has made work instructions the product, the worker who was measured did alter from the instructions somewhat. For instance, at one point the product should be placed on work table for cutting and after being cut it should be cleaned from inside with a vacuum cleaner. The worker however did the cutting with the product on floor and cleaned the product by forcefully pulling it up, turning it upside down and shacking heavily. Apparently the worker diverted from the instructions because she found her way of doing the job more suitable for her.

Diversion from the work instructions is problematic because not all of the workers divert from the instructions. Therefore a standard time calculated for the worker measured would not apply to every worker and because of time limitations there was no time to measure more than one worker's performance. The sample measurement for product number 14, Product N can be seen in Table 5 .

Table 5. *Sample measurement results for the product number 14, Product N. All measurements are in seconds.*

	unit1	unit2	unit3	unit4	unit5	lot	whole pallet	Grand Total
Taking of new part								
Deburring of parting lines								
Drilling of water holes								
Opening of axel holes								
Cutting lid off								
Removing sharp edges and cleaning the cutting line								
Packing								
Cutting the extra part off								
Vacuuming								
Delay								
Grand Total								

In Table 5 the left most column has the elements of the task, columns titled unit1 to unit5 have the measured time for the elements for each unit in order, column titled lot has the element times that occurred once for every five products, column titled whole pallet has the element times that occurred once for every 10 products which was a full pallet and last the column titled Grand Total has the total time for each element. The last row has the total time for each unit measured.

Another problem arouse as well. Not all of the cycles and elements recurred identically each cycle. From Table 5 it can be seen that for some of the elements the measured time varies substantially, like for the first element "taking of new part" and the element "packing". During the first element, "taking of new part", the worker walks from the packing area to WIP conveyor, picks up a new unit and carries it to the working area. The units on the WIP conveyor do not move automatically however, and therefore the worker has to walk longer distance each time to pick up a new unit. The first measurement for this element on unit1 is an error, but on the other measurements we can clearly see this trend of lengthening element time. The short five seconds time measured for unit5, results from the worker picking up this particular unit from next to the close end of the conveyor. The unit had been placed there because earlier the conveyor had been full. If we calculate number of observations for each element based on this sample with a 90% confidence and 10% accuracy we end up with following result: 58 cycles would have to be observed. This was a problem because there was no time or chance to measure this many cycles during the project. Full calculation results can be seen in appendix e.

These problems make the calculation of standard time with the usual method meaningless. It was then decided to only measure five cycles of each product and neglect intensity rating and allowances. A standard time acquired like this is not ideal and cannot be used for wage or employee evaluation (EK-SAK tuottavuustyöryhmä 2011, p. 24). For the purposes on this project it is acceptable and can be used for a rough comparison of the element times of the products to each other and for approximate economic analyses.

All the rest of the products were then measured and five or more cycles were observed of each. The results of these measurements are gathered to appendix f. Small reliability analysis made for the measurements by calculating accuracy for the measurements with function (1). For the calculation the actual measured number of cycles was used as n and confidence was chosen as 95%. Resulting accuracy (how much the time measured can differ from real element time) for each element varies between 4 % and 41000 %. For most elements the accuracy is several hundred percent. For example it can be said with a 95 % certainty that the real processing time for an element with an accuracy of 200 % and an average processing time of 15 s is between 0 s and 30s. This means that the accuracy of the measurements is low which is mainly caused by the relatively small number of observations (5 to 9) and a high degree of variance in the work tasks in Finncont Oy. Detailed results of time study reliability analysis can be seen in appendix f.

4.3 Formation of product groups

Although in the beginning all of the products seemed rather different with different kind of production steps, after the analysis and time study it was noticed that there are meaningful similarities in the products. It was decided to form product groups. Like it was said in chapter 2.4, product groups can be formed with the help of group technology and the forming can be based on design attributes or production processes. Because only the products that were chosen for time study were considered for grouping, there were only 16 products to group. Thus visual inspection was sawn to be adequate.

First, similarities were looked within design attributes, namely from size and shape both of which affect fixturing. It was easy to see that the products number 20 to 24 were similar in shape and size and that gave one grouping option. No meaningful similarities were found on the other products. Material, weight or intended use were not thought of being important in finalization work and were therefore not used as grouping points.

Then similarities were looked from production processes. The breakdown of the production processes to elements was useful for this search. The elements of each product were compared to one another and it was found out that the products number 20 to 24 had very similar production processes that only differed a little bit. This was expected because the products are finalized at the same work site. When compared with the rest of the products it was found out that products 20-24 do not include any cutting or drilling operations whereas the other products all have those. The other products were after all chosen for the project based on the fact that they do include cutting or drilling operations. Based on these findings two product groups were formed. Products 1, 2, 6, 7, 8, 10, 12, 14, 15, 16, 17 in group one and products 20-24 in group two. Breakdown of the groups can be seen in Table 6.

Table 6. *Formation of product groups.*

Product groups			
Group	**Index**	**Name**	**Description**
Group 1	1	Product A	Lid for portable fuel tank
	2	Product B	Oil tank for forklift
	6	Product F	Fuel tank for
	7	Product G	Cargo box for
	8	Product H	Cargo box lid
	10	Product J	Composting toilet
	12	Product L	Composting toilet
	14	Product N	Sand box
	15	Product O	Waste water management tank
	16	Product P	Light frame for trailer
	17	Product Q	Installation panel for
Group 2	20	Product T1	Fuel tank for tractor
	21	Product T2	Fuel tank for tractor
	22	Product T3	Fuel tank for tractor
	23	Product T4	Fuel tank for tractor
	24	Product T5	Fuel tank for tractor

The two groups in Table 6 were formed based on production process similarities. In addition the products group 2 share similar size and shape attributes. These similarities can be exploited on the work cell design for planning efficient work cells as stated in chapter 2.4. The theory of group technology proposes to group machines to groups based on the products they are used to produce. It was decided to follow this proposition and plan separate solutions for each product group.

5. WORK CELL PREDESIGN

With product analysis completed, work continued on work cell design. Due to iterative and simultaneous nature of production system design, work on this part had already been started before the product analysis had been completed.

As it was stated earlier, the work cell design was decided to perform separately for both product groups. This decision was made because it was seen that the two groups differ on the processing they need. The study of work cell design was thus conducted bearing in mind the differences of the product groups while choosing layouts and actual processing tasks and equipment.

On this chapter steps on conceptual work cell design are told. The task of work cell design is divided to two parts: first part discussed is the choice on layout. And after that the research and choice on production processes is presented.

5.1 Formation of layout plans

It is important to study the existing production system according to Bellgran & Säfsten (2010, p. 172-173) as was said in chapter 2.1. For the purpose of developing new layout for the production of group 1 products and group 2 products, the old layout is first studied.

Finalizing work is currently completely manual and consists of work phases listed in chapter 3.1. Not all of the products need every kind of processing however, as was found out in chapter 4.1. Currently all of the products in group 1 are finalized in their own dedicated workstations, whereas products of the group 2 are all finalized in the same workstation. There is only one workstation for each product and all of finalizing work is conducted on that work station. Consequently, all of the work stations contain all of the tools and equipment needed for finalizing the products meant to be produced there. Production in the factory as a whole represents both functional layout and batch production layouts. The layout seems like a functional layout because the rotational moulding machines are all located next to the side walls of the factory and thus grouped together. The finalizing work stations are located next to the moulding machines and also grouped together. On the other hand the layout represents batch production layout because the moulding machines produce from one to several products simultaneously each time an arm finishes its cycle. The products are then placed in WIP buffer storage from where the finalizing worker picks them up one by one and begins finalizing work. For most of the products all work tasks are done in nonstop manner by one worker. If only finalizing is considered, the layout is effectively a project oriented layout. The workstation for products of group 2 resembles cell layout in its present form.

Research on different layout types was conducted on chapter 2.2. For a reminder the layout types are project layout, functional layout, batch/cell layout and line layout. As was seen in chapter 2.2, the choice of the layout depends mainly on product variety and production volume. In case of product group 1 the number of products is eleven and their combined yearly production volume was x last year (2015). There are five products in Group 2 with a combined volume of y per year (estimated 2016).

Table 7. *Product groups with yearly production volumes and totals. Note: the production volume for product 20 consists of the actual production volume for product 20 which is and of the volume for a product which production has already ended (T11).*

Product groups and volumes

Group	Index	Name	Volume (pc/y)
Group 1	1	Product A	
	2	Product B	
	6	Product F	
	7	Product G	
	8	Product H	
	10	Product J	
	12	Product L	
	14	Product N	
	15	Product O	
	16	Product P	
	17	Product Q	
Total		11	
Group 2	20	Product T1 + T11	
	21	Product T2	
	22	Product T3	
	23	Product T4	
	24	Product T5	
Total		5	

Because of the product variety and relatively low production volumes, line layout is not a good solution for either of the product groups. Project layout on the other hand is used for stationary, one at a time -production, so it does not suit the production of multiple products very well. Both the functional layout and the cell layout would suit both of the product groups, production volume and variety wise. Functional layout is however considered to be difficult to manage and easily causes high WIP (Bellgran & Säfsten 2010, p. 205-206). Cell layout on the other hand offers less flexibility than functional layout and often needs higher production volume to be profitable. Because the products have already been grouped, the lost flexibility factor should not be an issue. Cell layout is also seen as offering better chance for production automation than functional layout. That is important because the objective of this thesis is to increase the automation level of the production system. Production volume on group 1 should also be high enough for cell layout. Based on this reasoning cell layout was chosen for group 1.

The current workstation for group 2 was seen as a good basis for the future production system. It is currently organized as production cell and it was therefore decided to use cell layout in the future production system as well, even though the production volume of group 2 is lower than that of group 1.

5.2 Process planning

Production processes suitable for product groups 1 and 2 that could be used in automatic work cells were researched next. Because the goal of this project was to add automation to the finalization phase of the production stream in Finncont, only processes related to this part were researched.

In product analysis it was found out that the products require five different kind of processing, when high dexterity tasks are left out. These processes are: deburring, cutting and drilling, measuring, marking and chamfering. Every product does not require every type of processing however. Figure 6 shows how many products of group 1 needs each type of processing.

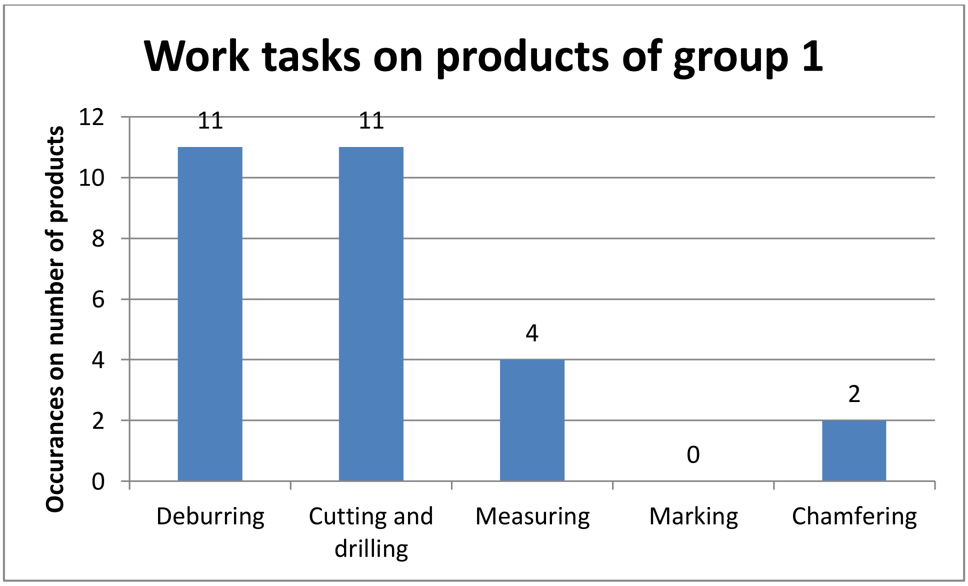

Figure 6. *Finalization work tasks on products of group 1.*

As can be seen from the Figure 6, none of group 1 products requires marking. Thus the work cell for group 1 does not have to be fit with marking equipment. Figure 7 has same information for group 2.

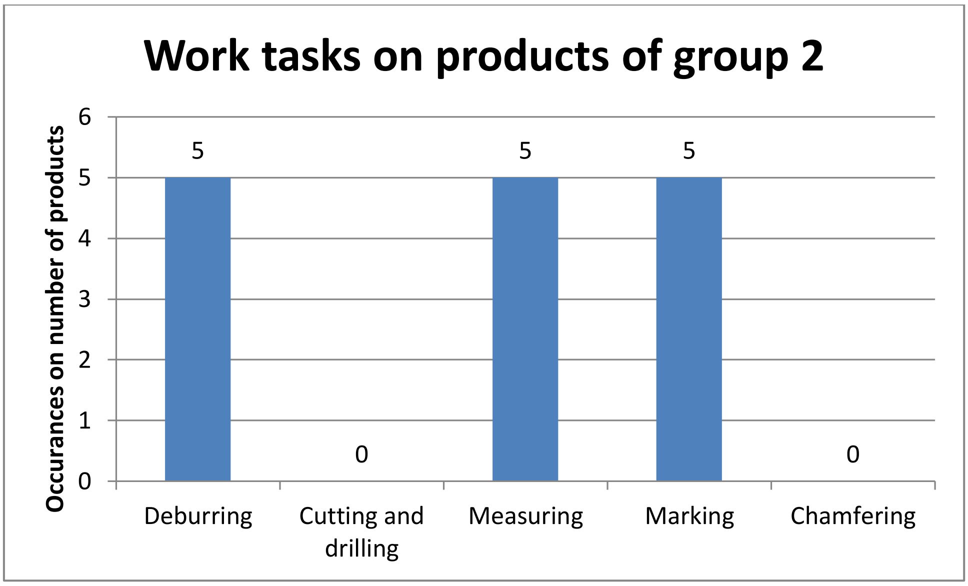

Figure 7. *Finalization work tasks on products of group 2.*

From the Figure 7 it can be easily seen that the products of group 2 all require completely the same work tasks. The processing of group 2 products consists only of deburring, measuring and chamfering tasks. Chamfering and cutting and drilling operations may hence be left out of research of production processes for group 2.

5.2.1 Cutting & drilling

Cutting and drilling methods were researched first. Three main technologies exist for cutting plastic. They are laser, water-jet and mechanical cutting. (Rosato et al. 2004; Ion 2005, chapter 14; Biron 2013, p. 750) All of the technologies have their own processing characteristics that have to be taken into account in production planning.

In laser cutting a laser beam is utilized for cutting purposes. According to (Ion 2005) an air assisted CO2 laser suits the cutting of both PE and PP plastics (Ion 2005, p. 371). The laser is often mounted on an industrial robot. Advantages of laser deburring are the fact that it is a rather fast process (Dahotre & Harimkar 2008, p. 144) and that it does not produce chips (Rosato et al. 2004, p. 568). In addition laser beam is very narrow and can therefore reach areas on difficult locations. The narrowness of the beam also means that it is possible to make very thin cuts. (Dahotre & Harimkar 2008, p. 145) By focusing the laser beam with lenses, holes from 2 to 50mm in diameter can be made without circular movement. (Rosato et al. 2004, p. 568) Because of laser's non-contact nature it does not require the work piece to be rigidly fixtured (Dahotre & Harimkar 2008, p. 144).

Laser cutting has also its downsides. The quality of the cut may deteriorate on thick sections and striations can occur on the cutting edge on thin sections as well (Dahotre & Harimkar 2008, p. 171-175). Often dross forms on the back side of the cut surface (Dahotre & Harimkar 2008, p. 176-179). Laser cutting of polymers creates a fine particle fume that has to be taken in to account in the work station design (Ion 2005, p. 370).

Because laser beam does not stop before hitting obstacle, some damage might occur on the opposite wall of hollow work pieces when the beam cuts through the front wall. This has to be taken into account especially in laser drilling. Drilling hollow products with laser might cause damage to the opposite wall (VanderWert 2006). Laser drilling without damage to the opposite wall is only possible if it can be protected from the laser beam. One option is to place a beam blocker underneath the front wall that is cut to prevent damage to the opposite wall. Another option is to use a detector to detect when the laser has cut through the first wall and then switch off the beam (Ho et al. 2013). (Okasha et al. 2010, p. 199). However, the blocker method cannot be used on the products of either group 1 or group 2 because of their closed form. The detection method on the other hand is rather new technology and adds to the cost of the system. (VanderWert 2006)

Cost aspects might be the biggest obstacle for utilizing laser cutting in low to medium production environment like Finncont has. Laser cutting systems are expensive and have high running costs because of low efficiency (Davim 2008, p. 312). A CO_2 laser has an energy efficiency of 20%. (Black et al. 1996, p. 420-422) According to John Ion, laser cutting system is economical when it is used at least 16 hours per day (Ion 2005, p. 354).

The second option, water-jet cutting, utilizes high pressure jet of water for cutting purposes. The water-jet pressure is typically about 400MPa and the speed of the jet can reach 900m/s. An advantage for water-jet cutting is that it does not create HAZ. Water-jet cutting does not heat the work piece and thus there is no danger of melting (Ion 2005, p. 353). Cutting efficiency can be enhanced by adding abrasive particles to the stream. (Black et al. 1996, p. 426-428) Like laser cutting, water-jet cutting is also a non-contact cutting method that does not need rigid fixturing for the work piece (Dahotre & Harimkar 2008, p. 144). (Davim 2008, p. 304-306)

Water-jet cutting needs dedicated machinery and the work piece has to be fixtured on top of pool. A great disadvantage of water-jet cutting is that because it employs a water stream it does not suit the cutting of hollow products. The reason is that the water used for cutting would be trapped inside the product (Davim 2008, p. 306). Even if some drain holes would be provided there is still a danger of damaging the opposite wall when cutting hollow products just the same as in laser cutting.

Mechanical cutting utilizes a rigid tool for shearing pieces off the surface being cut. Plastic products can be cut with mills, knives and saws. Milling is the most versatile of these methods because milling tools can be used to drill holes and round corners of varying radii.

The machining parameters are important when cutting or drilling plastic mechanically. Because plastics used in the products of group 1 (PE and PP) are good thermal insulators the machined area heats up locally, which can lead to melting and surface defects. (Kaddeche et al. 2012; Biron 2013, p. 750) Some of the heat transmits to the metallic cutting tool reducing its lifetime. According to (Vasile & Pascu 2005, p. 149) some thermoplastics like PP and HDPE are easy to machine, but LDPE is more difficult. Generally a good surface finishing can be achieved on PE with high cutting speeds and low feed rates. Water cooling could be applied for higher feed rates. (Vasile & Pascu 2005)

Experimenting with the processing parameters might be needed in order to find out which settings give the best result. Wrong settings can even damage the work piece. (Ivan et al. 2016) In addition, thermo plastics like polyethylene (PE) tear and melt easily under high stress that might occur during drilling or milling. Milling induces stress to the work piece, so to prevent damage the work piece has to be rigidly fixtured so that it cannot bend while processed. Another important point is to use only sharp tools and minimize contact forces. (Harper 2000; Rosato et al. 2004, p. 565-567)

On the contrary to laser and water-jet cutting, mechanical cutting is suitable for cutting of hollow sections without the need for special protection technology. Mechanical cutting is also the easiest to implement on most production systems for the same reason. The investment cost of mechanical cutting is also quite low compared to both laser and water-jet cutting, but the additional costs like tool wear, need of cleaning of cutting chips and the more rigid fixtures needed add to the cost in time.

5.2.2 Deburring

Deburring (including deflashing) operation was the second operation studied. As a reminder, deburring is the act of removing excess burr formed during machining (Aurich et al. 2009, p. 520). Deflashing is the act of removing flash that materialize during moulding. (Bralla 1999, chapter 50) Here deburring is used to refer to both deflashing and deburring.

Burrs form especially on parting lines and on inserts. Figure 8 has an example of burr formed on mould parting line. This kind of burr has to be removed from the product surface for three reasons. First, it is cosmetically bad and the product looks unfinished if burr has not been removed. Second, the burr might cause the product to not to fit its dimension tolerances because of large burs. Third, sometimes pores develop underneath the burr, like in Figure 9, which is a problem if the part should be air tight. With the burr removed the surface can be inspected for spores.

Figure 8. *Example of burr formed on a parting line between mould segments.*

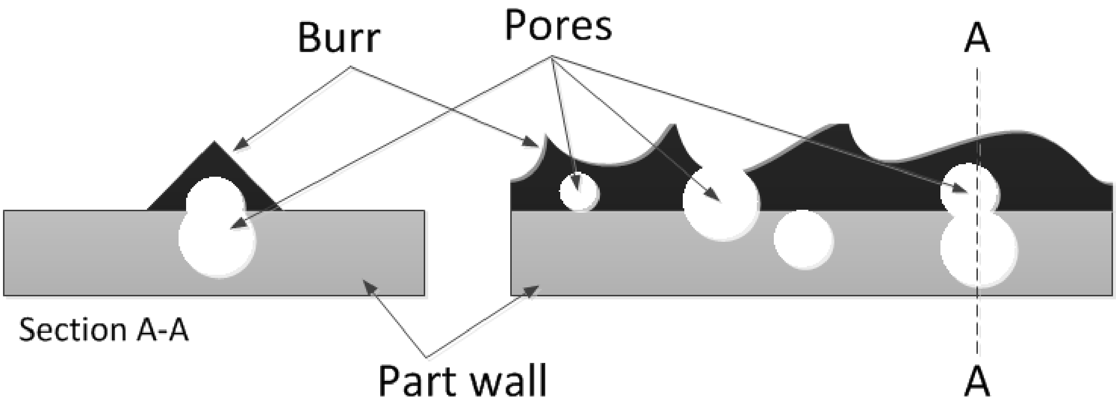

Figure 9. *Pores underneath burr. Some of the pores are visible before deburring but some are revealed only after deburring. Section A-A displays a pore that can potentially result in a leak under physical stress.*

As can be seen from figure 5, the flash on the products is sometimes on hard to reach and curved areas. Especially the parting lines tend to be rather complex and hard to access. Parting lines go around the products and include corners with varying radii and dual curved faces. Other locations include flash on through holes and on top of inserts. The deburring tool would have to be versatile and slim to reach all of the locations. The flash is also non uniform and its length and thickness varies. The flash is stronger on the areas where the used mould is the most worn. Products moulded with good new moulds can have no flash at all, whereas some products moulded with old moulds may have heavy flash thorough.

There is rather small amount of scientific writings about burr removal from large plastic parts. Most of the writings address burr removal in blow and injection moulding where the parts are relatively small and production volumes are high (Lee 2006, p.165-167). For these kind of parts tumbling with or without abrasive material is recommended. Cryogenic tumbling is also possible. (Harper 2000) For the rather large and hollow products that Finncont produces tumbling is not suitable so other methods have to be considered.

For metallic parts many methods for deburring exist. Such as tumbling, water-jet deburring, brush deburring, mechanical deburring, chemical deburring, ultrasonic deburring, electrochemical deburring, robotic deburring, laser deburring and edge rolling (Bralla 1999, chapter 50). Among these methods laser deburring, water-jet deburring and mechanical deburring are also suitable for plastic parts (Rosato et al. 2004, p. 568; Lee 2006, p. 165-167). These three methods can be used in deburring much the same way as they can be used in cutting. Because work piece size does not affect the usability of these methods, all three could be used for deburring of both group 1 and group 2 products.

In both laser and water-jet deburring, the cutting beam is moved parallel with the burred work piece edge. This means that both methods are unsuitable for deflashing of inside corners or other features where there is no free path for the beam before and after the flash or burr. With Finncont’s products this requirement presents a major problem.

In mechanical deburring the burrs and flash are removed mechanically with knives, brushes, mills or by grinding. The process can be automated with CNC machines or industrial robots. With mechanical deburring tools it is possible to reach also areas like inside corners but the tools and the machining parameters affect the resulting surface quality considerably.

All three deburring methods can be used with either dedicated CNC machines or industrial robots like in cutting as well. Both laser and water-jet deburring produce good surface quality and they do not generate small cutting chips like mechanical deburring does. Mechanical deburring tools are cheaper than lasers or water-jet systems, but on the other hand if the work cell is built with laser or water-jet cutting capability, the same system can be used in deburring as well, by only changing the machining settings. In the case of mechanical cutting, dedicated deburring tools would have to be added to a tool changer which increases to the total cost of the system.

One difficult problem for the deburring process is that the moulded products tend to shrink after moulding at varying rates and as a result the exact shape and size is unknown. Three solutions have been developed to counter this problem. According to research by (Burghardt A. et al. 2016, p. 988) if the contact forces are low, for example spring loaded, contact active tools can be used to ensure constant contact with the work piece. With higher contact forces in excess of 10 Nm, robot force control is used. Alternatively pre-processing measurements can be used to generate a modified tool path that follows the part contours as wanted. (Burghardt A. et al. 2016, p. 988) All of the methods are available with mechanical deburring, but because both contact active tools and robot force control rely on contact force feedback to control the deburring process they cannot be used with water-jet or laser based deburring. Those two processing methods can only be used with measurement modified tool path generation.

As a summary, deburring could be done automatically by water-jet cutting, laser cutting or mechanically. They all have their strengths and weaknesses, but laser and water-jet share a particularly problematic weakness which is that they require obstruct free path for the cutting beam or jet. The capital cost factor also favours mechanical deburring which hence seems most suitable for Finncont's products. Automating the deburring process would allow a lot of work to be switched from worker to a machine but it is also risky part of the finalization work to automate due to its complexity.

5.2.3 Measuring

As was said in chapter 4.1, some of the products have some quality inspections involving measurements. There are several methods for measuring: touch measurement, optical measurement with cameras or lasers and several microscopy methods (Leach 2011, p. 1-11). Touch measurement uses a stylus that is moved toward the part measured and location information is read upon contact. Dedicated measurement devices exist for one, two and three dimensional measuring. It is also possible to attach a measurement head to industrial robot's wrist and create a robot measuring platform. The information acquired with touch measurement are contact point coordinates. Feature dimensions can be calculated from point measurements. Hence, if several dimensions have to be measured a considerable amount of time will be consumed. Touch measurement system can be very cheap if an industrial robot is used and only the measurement head has to be bought and robot program programmed.

A degree of more information of the work piece can be collected with optical measurements systems. For a very detailed and thorough measuring, 3D scanning can be used. 3D scanning is done with lasers taking measurements of the whole work piece, one section at a time. Another possibility is to use machine vision. With machine vision it is possible to locate the work piece and determine its outer boundaries. With machine vision and laser scanning some level of surface topology information can also be retrieved. Both machine vision system with a camera and laser scanning systems are more expensive than point measurement system.

Microscopy methods are the most accurate measuring methods and they can give detailed information of the surface topology of the part (Leach 2011). For the current products of Finncont such high detailed information of part surface is not needed.

For the group 1 and group 2 products the measures that have to be performed are mainly dimensions like length, height and diameter of some holes. Surface topology information is not generally needed. However, as was noted in earlier in chapter 5.2.2 pores tend to form underneath the flash line. Currently the worker can inspect the flash line for pores while deburring and separate inspection phase is not needed. In automated work cell this kind of simultaneous quality control might be possible with visual or laser based topology measuring. With touch measurement system it is not possible. Alternatively the quality inspection can be left outside the work cell for a human worker to perform. However, that should be avoided because if the human worker would have to inspect the whole flash line, the overall cycle time of the production process might not be any shorter than it currently is. It is also an industry trend to automate quality control because machines make fewer mistakes than humans and because quality control checks are uninteresting and rather monotonous tasks.

5.2.4 Marking

As was noted in chapter 5.2, none of the products in group 1 need marking. On the other hand all of the products of group 2 have marking performed on them in finalization.

Marking of plastic products can be performed in several methods. The methods can be classified into permanent and non-permanent marking. Permanent marking methods include dot peening, scribing, laser marking and indenting (Ion 2005, chapter 15). Non-permanent marking methods are inkjet printing, offset printing and stickers (Biron 2013, p. 754). The permanent marking methods are almost never able to produce colours, whereas non-permanent methods can. However, by adding special additives to the raw material of the product before moulding, a one colour laser marking is possible (Sabreen 2012).

The permanent marking methods physically alter part surface. Dot peen marking produces small punch dots that form symbols or codes. Scribing produces scratches and the process resembles drawing. In laser marking the marked surface is grooved and annealed so the marked area is of different colour than surroundings. Intending methods include impact and hot stamping. Impact stamping works by hitting a stamp on the surface, thereby producing mark. Hot stamping utilizes a heated stamp that is pressed against part surface to produce the mark.

The non-permanent methods add a layer of other material on the part surface, usually paint. Inkjet printing utilizes a printing head similar to office printers. Ink is sprayed from the printing head to part surface. Offset printing is an old form of printing in which the printed picture is transferred from the printing head to part surface by pressing the printing head to the surface. Offset printing can usually produce only one coloured markings, whereas inkjet printing can do multiple coloured markings. Third option on non-permanent marking is to use stickers.

5.2.5 Chamfering

One product in group 1 has chamfering task. Chamfering means the act of cutting an edge to an angle. Chamfering can be performed with a variety of milling tools like conical, ball end and straight milling tools. Knives, saws and laser can also be used for chamfering by performing cutting act on a desired angle.

Chamfering is basically same process as cutting, but the resulting edge is not perpendicular to neighbouring edges. Hence the cutting method considerations earlier hold true on chamfering as well.

6. DETAILED PLANNING OF WORK CELLS

After process planning had been completed, detailed layout planning commenced. It was decided to make a separate plan for both group 1 products and group 2 products. At first the planning was conducted with a focus on minimum payback period. However, since it was found out that the accuracy of the minimum payback period calculation varies largely on the estimation of saved work time of human workers, an additional plan was devised for group 1 products with a focus on minimal capital cost. The rationale behind this decision was that even if the payback period calculations or work cell design fail, the losses for the company would be lower than in the original plans.

The original, minimum ROI, plan for group 1 is presented first. It is followed by a presentation of the second, minimum investment, plan for group 1. Last the plan for group 2 is presented.

6.1 Group 1, FMS

Earlier it was found out that FMS type of production system will suit the production of group 1 products. The group 1 consists of 11 products that share similar work tasks and noteworthy have significant amount of cutting and drilling tasks.

In the following sub-chapters the products chosen for processing on the cell are described, the detailed layout of the cell is created and production processes chosen. Last the work cell plan is analysed.

6.1.1 Products

The work cell is planned for the products of group 1, the list of which can be seen in Table 8 below. However, only five products were measured in time study and thus reliable payback period estimations for only them can be made, the work cell is planned around those five products. The five measured products are marked with * in front of the index number in Table 8.

Table 8. *Products of group 1 and production volumes. Products with * after index number were measured in time study.*

Group 1 products		
Index	**Name**	**Volume (pc/y)**
1*	Product A	
2*	Product B	
6*	Product F	
7*	Product G	
8	Product H	
10	Product J	
12	Product L	
14*	Product N	
15	Product O	
16	Product P	
17	Product Q	
Total		

As can be seen from the Table 8, the five products chosen for production in the cell have a combined yearly production volume of x. This is roughly 70% of the combined production volume of all group 1 products. With this information the layout can be designed.

6.1.2 Layout design

Layout design is probably the most important phase of the construction of any complicated production system. For this thesis an earlier robot work cell design work done for Finncont during the course Design of Robot System was used as a foundation. On that work the task was to build a reference work cell for processing of plastic products. Hence, the layout conceived during that work was usable for reference for this thesis as well. The reference layout can be seen in Figure 10 .

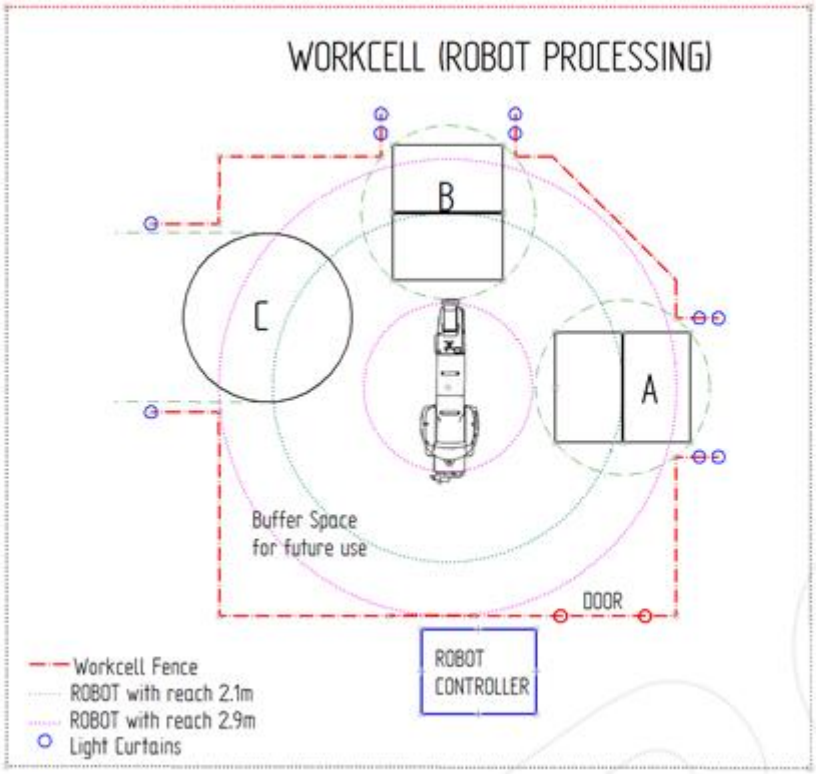

Figure 10. *The reference work cell designed for Finncont during the course Design of robot system.*

This reference design incorporates an industrial robot with a reach between 2.1 and 2.9 meters for optimum processing capability. All tooling would be carried by the robot. The parts would be placed on three turntables marked A to C in the Figure 10. A and B turn 360° degrees and have only two positions, 0° and 180°. They have a protective wall as space divider in the middle of the table which enables the operator of the cell to load and unload parts on the outer side of the table while robot is processing parts on the other side. In the design a pallet is first placed on the table A or B and then a part specific fixture is attached on top of the pallet. The part can then be connected to the fixture. The pallet takes the whole half area of a table and can accommodate parts 1200 mm long and 700 mm wide with height unspecified. In case of small parts several fixtures can be connected to a single pallet to house several parts.

Table C can be turned 360° continuously and acts as an auxiliary axel for the robot controller. It does not have a diving wall and with a diameter of 2 meters it can accommodate very large parts. The table is mounted on rails for part loading and unloading purposes.

This reference layout was seen as a suitable layout for the group 1 products and the final layout is based on it. Final layout can be seen in Figure 11.

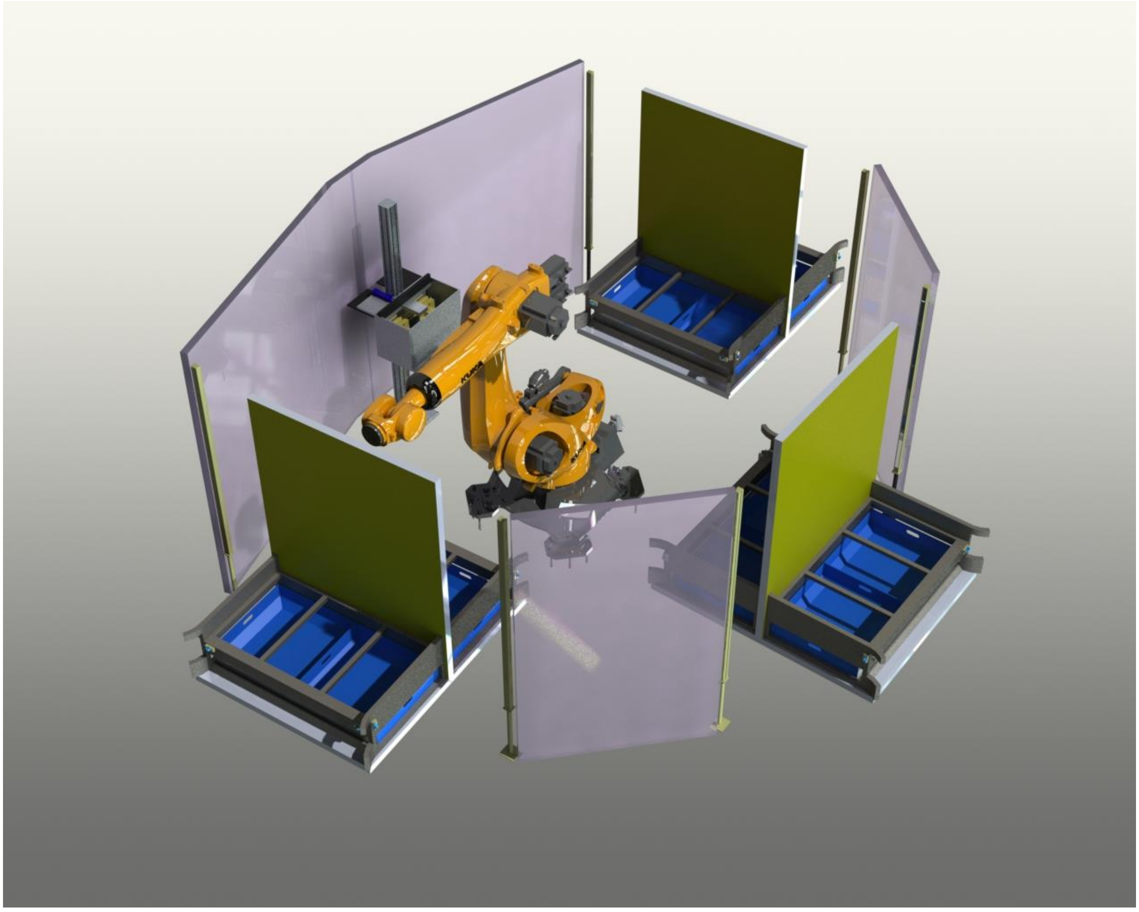

Figure 11. *Figure 1. 3D model of the flexible work cell. Here the cell is built with three turntables.*

The work cell is built around an industrial robot in the centre. The robot is surrounded by turn tables that can be set to two positions. The number of turn tables can be adjusted depending on the need. In front of each turn table there are light curtains and fences are placed in between of the tables.

The tables are similar to the tables A and B in the reference work cell in Figure 10. They measure 1300 x 1630 mm and have a separating wall that cuts the table surface in half. The resulting size is 1300 x 800 mm which is sufficient for standard sized EURO pallet. It was though that the pallets used in the work could be made to match the size of EURO pallet. By also providing fork lift holes pallet manipulation can be made easier compared to a pallet of arbitrary size. The pallets are placed on top of the table which has guiding rails on both sides. Underneath the pallet stand there are two boxes side by side for collection of cutting waste. The boxes are emptied manually. The work cell can be built with either manually or automatically rotated tables. Automatically rotated tables can be powered either pneumatically or electrically. For this thesis automatically rotated tables were chosen.

The processing for this work cell and products was chosen to be mechanical machining with conventional rotating tools. Even though laser cutting would have been advantageous especially because it produces no chips, the investment cost was seen as too high.

The work cell is capable of cutting, drilling, chamfering and measuring. Cutting, drilling and chamfering are done with rotating milling tools of varying size and shape. Laser cutting might be faster and cleaner, but as was shown in chapter 5.2, laser cutting equipment is expensive which is why mechanical tools were chosen for this work cell. The mechanical tools can be powered either pneumatically or electrically. Electric tools are more expensive but offer greater control over the machining process as a result of rpm control. An automatic tool changer is located next to the robot, making it possible to select a suitable tool for each task. The tools needed for processing group 1 are at least one cutting tool, and several drilling tools. The cutting tool should be as large as possible to allow high feed speed and to minimize the danger of the cut edges rebinding right after cutting. Small radius corners on the other hand are not possible with a large tool. Therefore a 10mm cutting mill and a 6mm cutting mill are proposed here. In total the products in group 1 have round holes in 19 different sizes, whereas the five products measured in time study have 15 hole sizes. The number of different sized drills needed depends on the roundness requirements for the holes. The drill for the smallest 3mm hole could be used for drilling the bigger ones as well with reduced quality. For perfectly round holes right sized drills have to be used. In this work cell design it is assumed that only the 3mm drill is needed and the bigger holes are made with it or with the 6mm and 10mm mills. For chamfering a single 45° degree chamfer mill should be sufficient.

Measuring tasks are performed with a measuring laser. A non-contact measuring laser was chosen over a contact measuring tool because non-contact measuring consumes less time than contact measuring. The measuring laser can be fixed to the robot arm, as its small size should not interfere with other operations. In addition to doing the actual measurement tasks the measuring tool will be used for locating the work piece edges and for determining the exact size of the work piece. The robot will first try to locate a predefined point of the work piece according to its programming by approaching the work piece from certain direction. After getting a measurement the robot will continue to a next predefined point and take another measurement. The amount of measurements needed varies from product to product and can be minimized by clever fixture designing that takes into account the processing tasks for each product. When enough measurements have been gathered, the coordinates in the robot program are automatically scaled to match the size of the work piece being processed. Only after scaling, the robot can continue on to perform the actual work tasks. The scaling of the robot program has to be done for each individual work piece. All of the measurements taken from each product can be automatically saved to a higher level system. The robot can also be programmed to reject and inform the operator of products that exceed dimension tolerances.

Deburring capability was left out of this version of the work cell because it was seen as too risky addition. All of the products on group 1 have deburring task, but according to the literature review in chapter 5.2.2, plastic work pieces deburring has to experimented and tested before suitable deburring process can be chosen on. Another problem is the size variation of the work pieces that is especially important to counter in deburring operations where tolerances are very small, and the actual location variances high. The size variations are not uniform in each direction and some of the products have highly complex shapes. Those two facts combined with the information that the flash lines circulate the products on their edges means that a large amount of measurements would have to be taken in order to locate the flash line. A faster method for part measuring would thus be needed, but laser scanning and accurate feature recognizing machine vision systems are expensive. Contact active deburring tools allow a certain amount of uncertainty, but usually only to the direction of the normal of the part surface. However, deburring can be experimented with the work cell by acquiring some contact active tool. If deburring can be made working with even one of the products processed with the work cell, it can reduce the payback period of the whole system and also increase the capacity usage of the work cell.

6.1.3 Processes and functionality of the cell

The work cell will be manned by one person or more persons at a time depending on the load. By judging from the production volumes from Table 8, one operator should be enough. The operators’ working cycles vary depending on the number of operators, products arriving to the input storages and locations and availability of product fixtures. Figure 12 has a drawing of the work cell with input storages, manual working tables, tool racks and packaging areas.

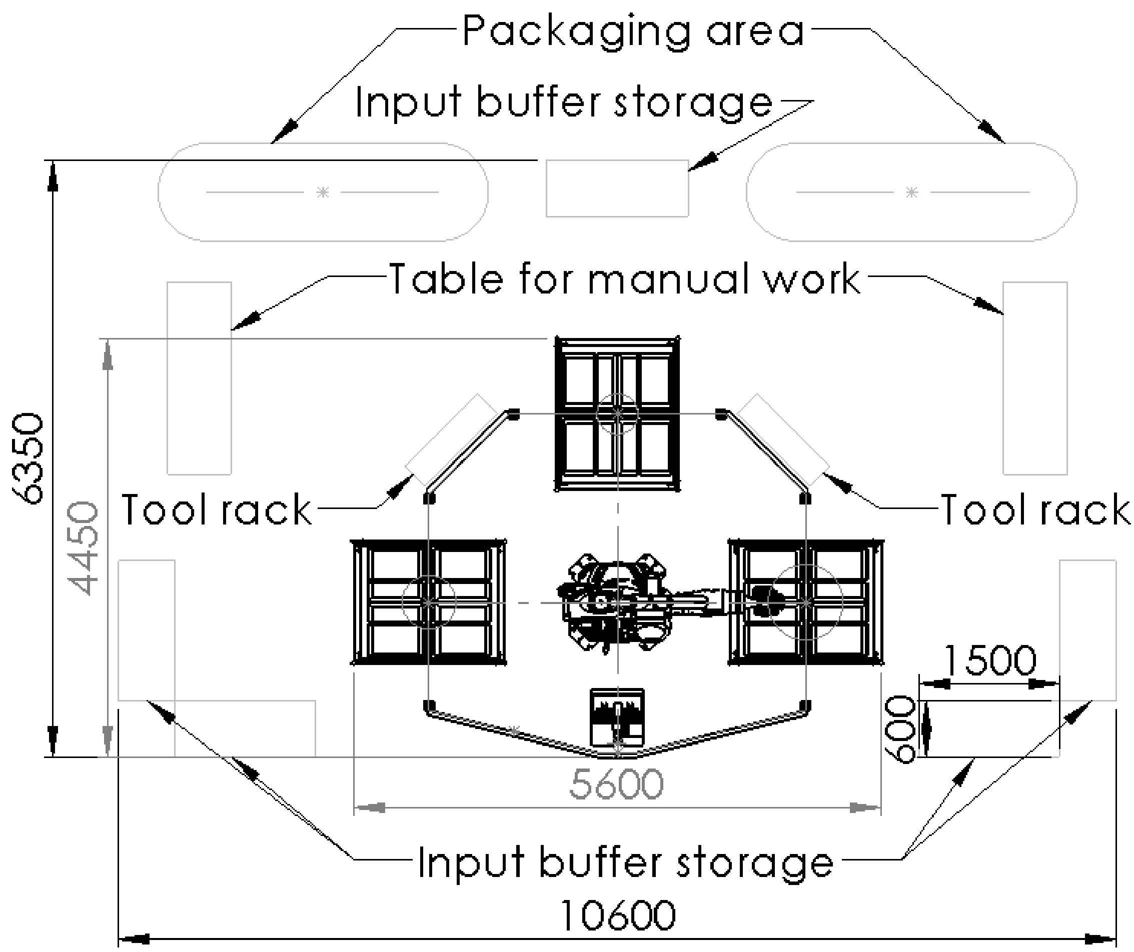

Figure 12. Outline of the work cell for group 1 with dimensions (in mm) and proposed locations for input buffer storages, work tables for manual finishing work, tool racks and packaging areas.

Next is a description of one possible working cycle with one operator, steady inflow of every kind of products and one fixture per product per table. The basic working cycle begins with the operator unloading a processed product from a fixture and dropping it to nearby table. The operator then proceeds to pick up a new product from the input buffer storage and loading it to the same fixture on the same table from where the last product was unloaded from. Then the operator chooses the right robot program from control console next to turn table. After that the operator picks up the unloaded product, walks to the manual work table, conducts manual finishing and moves the product to packaging area. The operator will then walk to a turn table that has a robot processed product ready and the cycle starts over. In this cycle computers will control the turntables so the operator does not have to spend time turning them.

6.1.4 Analysis

Three different aspects of the work cell design are analyzed: investment cost, payback period and production capacity. First one will be the investment cost.

The investment cost of a work cell consists on the cost of the components and the cost of buildup, and testing. For this work cell, several Finnish integrators were quoted for a price and based on the lowest offer the cost for the work cell was determined. Table 9 has a breakdown of the total investment cost.

Table 9. *Cost analysis for group 1 work cell with five products. Left column has components, second from left has number of components, third from left has cost per component, fourth has the sum per component and the right column has additional explanation.*

Components	Amount	Cost per piece	Sum
Robot [€]	1 pc		
Fixtures [€]	5 pc		
Rotating tools [€]	5 pc		
Safety [€]	3 pc		
Turn tables	3 pc		
Other Peripherals [€]	3 pc		
Physical Barriers [€]	1 pc		
Robot to Machine Interface [€]	1 pc		
Integration and setup [€]	1 pc		
Integration per product	5 pc		
Integration per additional device	4 pc		
Taxes, Transportation Fees, … [€]	1 pc		
Training [€]	1 pc		
Robot programs	5 pc		
Starting Investment			73 000 €

The cost of 73 000 € includes both components setup. Noteworthy is that the robot chosen for the work cell is a used model which is more than 50% cheaper than a new one would be. This helps bringing the cost of the work cell down. The cost does not include the auxiliary equipment depicted in Figure 12 such as storages, tool racks or manual working tables. These are left out because it is thought that the existing equipment in the factory could be used with only small modifications.

The yearly cash flow generated by the investment can be calculated with the combined information of the general study and time study. The calculations are done with averages of the time study results.

Table 10. *Key figures of current production of the five measured group 1 products.*

Current situation

Aspect \ Product	Product A	Product N	Product G	Product F	Product B
Yearly production					
Manual work per part [min]					
Employee hourly salary & benefits [€/h]					
Scrap Part Cost per year [€]	1000	1000	1000	1000	1000
Jig and Process Enhancement Cost [€]	500	500	500	500	500
Hours per Shift [hours]	8	8	8	8	8
Break time per Shift [min]	55	55	55	55	55
Shifts per day [unit]	2	2	2	2	2
Working days per year [days]	220	220	220	220	220

Table 11. *Key figures of estimated future production of the five measured group 1 products.*

Future situation

Aspect \ Product	Product A	Product N	Product G	Product F	Product B
Yearly production					
Manual work per part [min]					
Employee hourly salary & benefits [€/h]					
Scrap Part Cost per year [€]	600	600	600	600	600
Jig and Process Enhancement Cost [€]	1000	1000	1000	1000	1000
Hours per Shift [hours]	8	8	8	8	8
Break time per Shift [min]	55	55	55	55	55
Shifts per day [unit]	2	2	2	2	2
Working days per year [days]	220	220	220	220	220

From the numbers in tables 10 and 11 savings per product per year and total savings per year can be calculated. By adding up the operating costs of the robot work cell the average yearly cash flow is calculated.

Table 12. *Running costs of a robot work cell.*

Running costs of a robot	
Estimated Yearly Maintenance Cost	1 000 €
Downtime cost	2 000 €

Table 13. *Savings per product, total savings and combined yearly cash flow.*

Product / Aspect	Product A	Product N	Product G	Product F	Product B
Yearly savings per product [€]	535	4447	1925	9953	1607
Yearly savings total [€]	18467				
Yearly average cash flow [€]	15467				

Now payback period can be calculated with the equation (2). With 73 000 € investment and 15 500 € yearly average cash flow the payback period is approximately 4 years and 9 months. That is over the company management induced requirement of maximum four years payback period. To get the payback period under 4 years the work cell plan has to be modified. By leaving out the product number 1, Product A the investment cost can be lowered to 63 800 €. The cheaper investment is due to the work cell having only 2 tables, one less robot program has to be created and fixtures for the Product A can be removed from the calculation. With this modification the payback period is lowered to 4 years and 3 months. The company has a long term goal of increasing revenue by more than 10% every year. Based on that a general 5 % yearly production volume increase can be assumed for group 1 products as well. With that the payback period reaches the required 4 years.

The production capacity and capacity usage of the work cell can be calculated with the values on tables 11 and 12. If an assumption is made that the robot cell is used on three sifts 220 days per year, the total machine time would be 5280 hours per year. According to (Lenz 2016) a practical limit on the usable capacity of an FMS system is 80% of the theoretical capacity. The usable yearly capacity is then 4224 hours. Results of the capacity calculation in Table 14 are based on that assumption.

Table 14. Capacity figures of the group 1 FMS work cell.

Capacity	
Maximum usable (three sifts) [h]	4224
Capacity used (five products) [h]	560
Capacity used (five products) [%]	13,3 %
Capacity used (four products) [h]	540
Capacity used (four products) [%]	12,8 %

As can be seen from the table, producing the proposed five products on the robot work cell will only use about 13 % of its capacity on current production volumes. Dropping one of the products of, Product A, as was done to get payback period under 4 years does not change the situation much; the average capacity used remains at roughly 13%. Overall the proposed work cell has a lot of unused capacity and the production volumes could be eight fold of the current.

The yearly cash flow and payback period calculations above are highly dependent on the amount of manual work time saved per part. The above calculations are done with average values, but as can be seen from the time study reliability analysis on appendix f, the reliability of individual element time measurements is low. In order to roughly estimate the error of processing a whole product, the half of minimum processing time and maximum processing time for each product was calculated from the time study measurements presented on appendix f. The results of the calculation can be seen in Table 15

Table 15. *Reliability analysis showing the effect that the time study error has on the manual work time saved and on yearly savings.*

Reliability analysis

Aspect \ Product	Product A	Product N	Product G	Product F	Product B
Saved manual work time per part with error [min]					
Yearly savings per product with error [€]	535 ± 117	4447 ± 201	1924 ± 122	9953 ± 1586	1606 ± 789

As can be seen from the Table 15, the error on yearly savings caused by the time study unreliability differs by the product ranging from % for Product N to % for Product B. The payback period calculated with minimum yearly savings would be 5 years and 9 months and with maximum yearly savings it would be 4 years. The payback period calculated with averages is 4 years and 9 months.

It could be argued that the minimum yearly savings and longest payback period should be used as the basis on robot work cell investment decision making. This is because by standardising working methods and teaching the workers, the minimum measured processing time could be made a standard. However, the company is aware of this and has been trying to create work instructions and uniform working methods, but in spite of their efforts high variations in working methods and time was observed during time study. Thus it is debatable if the teaching of employees and standardization of working methods is easier or cheaper than investing to a robot work cell.

6.2 Case 2. Minimum investment

Because it was found out that the first work cell plan ended up being more costly than the company would have liked it to be and because the payback period of the work cell is difficult to lower to less than four years, an alternative plan was made. The new plan has an emphasis on minimum cost of the investment while maintaining the flexibility of the work cell and a possibility for future capacity upgrade. The financial risk the investment poses to the company is also smaller with cheaper investment. The easiest way to lower the investment cost is to use less equipment, which in turn is possible by reducing the amount of products to be processed in the work cell.

The new cell is focused around one product. The company representatives chose the product number 14, Product N, as the product for the work cell. The Product N was chosen because it is rather large product that has a lot of cutting and the company hopes to increase its production volumes in the near future. Product N needs deburring and cutting & drilling process tasks. There is no measuring, chamfering or marking tasks which potentially reduces the amount of equipment needed in the work cell. However, measuring tool is needed for work piece size measurement. For cutting, a single 10 mm milling tools should be sufficient. The holes on the product have sizes of 5 mm and 27.5 mm. The 5 mm holes will need a 5 mm drill, but the bigger 27.5 mm holes could be made with the 10 mm mill as well. One good reason for not including the 27.5 mm drill is that the work cell will not contain a tool changer. Instead all tools will be carried by the robot constantly. The fewer tools there is connected to the end effector the less they are in the way during processing. Therefore the work cell is designed to have only 10 mm cutting mill and 5 mm drill.

6.2.1 Layout

The layout was kept similar to the earlier design with only a smaller number of turn tables and other equipment. The resulting size of the work cell is smaller than the first work cell plan because the space for the additional turn tables is freed and fences moved closer to the robot. On both sides if the turn table there are light curtains. A visualization of the work cell can be seen in Figure 13 below.

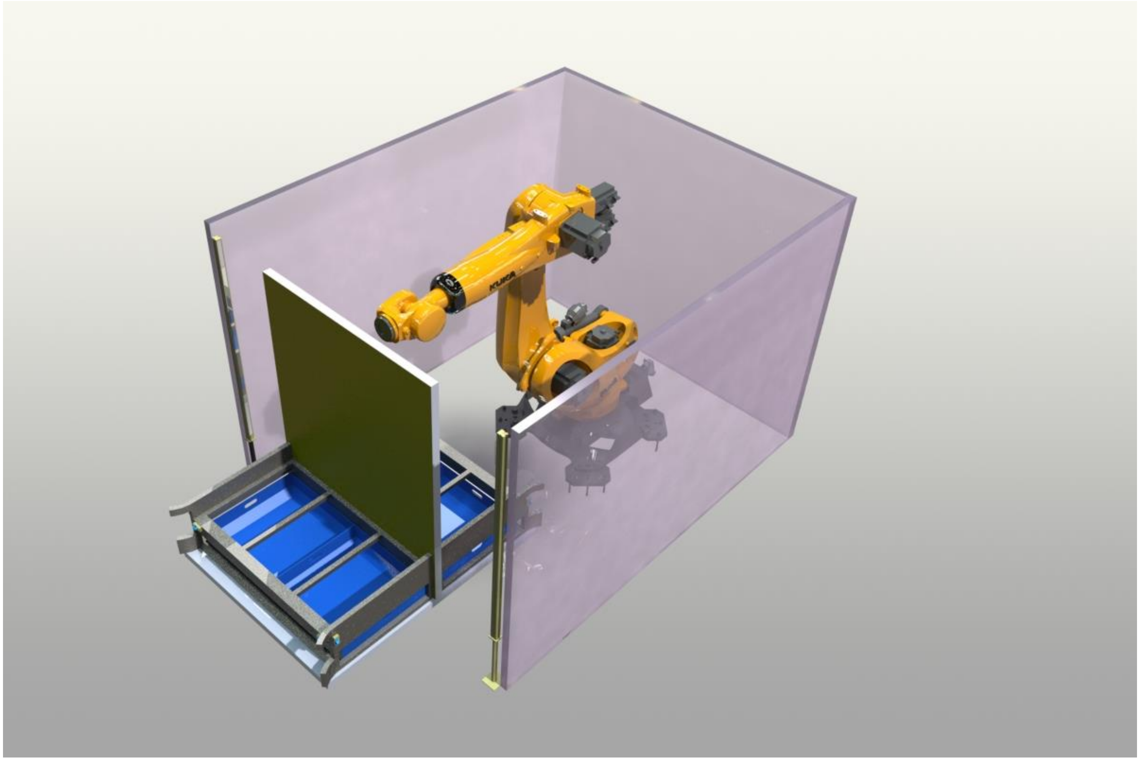

Figure 13. 3D model of the minimum investment work cell. Comparison to the FMS work cell in Figure 11 reveals that this work cell is smaller, has less turn tables and does not contain a tool changer.

The new layout plan consists of only one turn table, has fewer tools and does not contain a tool changer. The table is of same size and shape as in the FMS plan and also in this plan the products are attached to fixtures. With only one product processed with the work cell there is no need for having removable pallets, and instead the fixtures are bolted directly to the tables. If more products are introduced to the cell in the future, pallets can be added. To save costs, the turn table is manually rotated.

Processing is performed with rotating tools like in the earlier plan and the cutting capability is similar to the FMS plan, but chamfering tools are not included. Even though the Product N does not include measuring tasks, the robot programs have to be scaled to match the size variations of the individual products. Therefore, a basic distance measuring laser or contact measuring head is needed. In this design a distance measuring laser is used.

6.2.2 Work cycle

This work cell will be manned by one operator and on the contrary to the FMS plan, there is not much variation in the work content and number of operators. The size of the work cell and the placement of the auxiliary equipment can be seen in Figure 14.

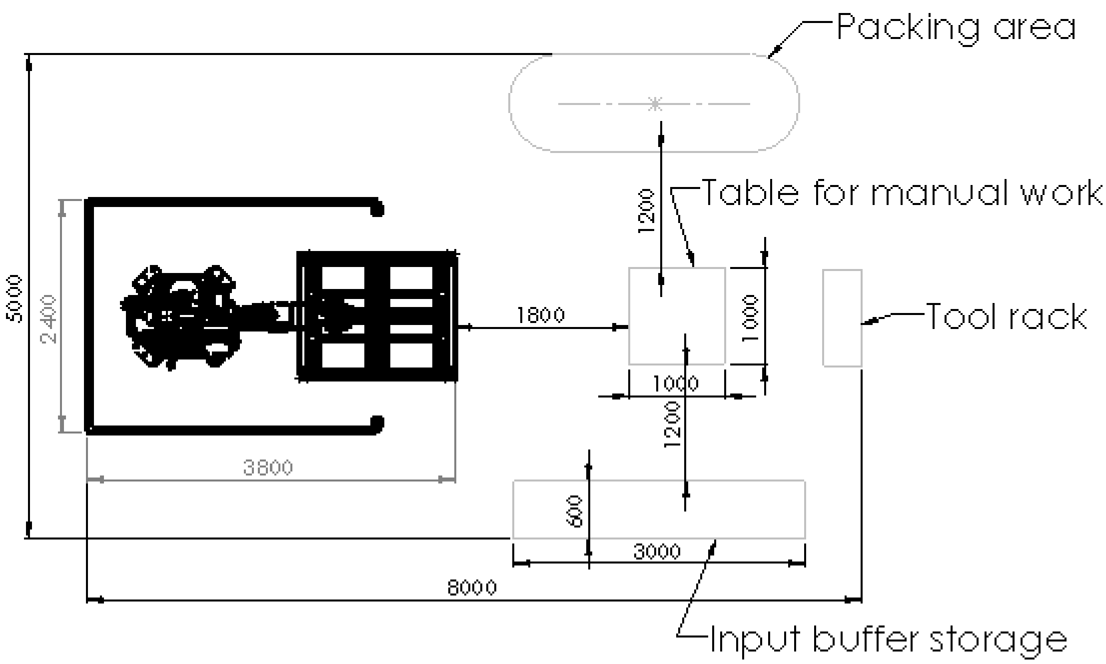

Figure 14. Outline of the basic work cell with main dimensions and locations of auxiliary equipment like storages, tool racks, tables for manual finishing work and packaging area.

The work cycle differs only a little from the FMS work cell work cycle. Here one possible work cycle is described. In the beginning of the cycle the operator stands in front of the turn table, releases its lock and turns it 180° degrees and locks it again. Then the operator starts the robot program by pressing a button and the robot begins to cut the product that entered the work cell. The operator will then unload the product processed earlier, place it to manual work table, takes a new product from the input storage and loads it on the turn table. After that the operator conducts finishing work on the unloaded product and when finished, moves the ready product to the packaging area. After packing the product the operator walks back to the turn table and the cycle repeats.

6.2.3 Analysis

Three different aspects will be analyzed: investment cost, payback period and production capacity. First one will be cost.

The investment cost of a work cell consists of the cost of the components and of the cost of buildup and testing. The cost of this work cell was estimated from the quotes received for the FMS work cell by taking into account the smaller number of equipment needed and lower level of automation. The cost breakdown can be seen in Table 16 below.

Table 16. Cost analysis for single product, minimum investment work cell. Left column has components, second from left has number of components, third from left has cost per component, fourth has the sum per component and right column has additional explanation.

Robot Investment	Amount	Cost per one piece	Sum
Robot [€]	1 pc		
Part Presentation Jig [€]	2 pc		
Robot tools [€]	3 pc		
Safety [€]	1 pc		
Turn tables	1 pc		
Other Peripherals [€]	1 pc		
Physical Barriers [€]	1 pc		
Robot to Machine Interface [€]	1 pc		
Integration and setup [€]	1 pc		
Integration per product	1 pc		
Taxes, Transportation Fees, … [€]	1 pc		
Training [€]	1 pc		
Robot programs	1 pc		
Starting Investment			31 900 €

The total cost for the minimum investment work cell is estimated to be 31 900 €. This cost includes equipment, setup and operator training fees. It is worth to note that the robot chosen for the work cell is an old used model that might not have all of the functions of newer robots. Other equipment is also the cheapest possible. The milling motor is pneumatic, turn table is manually operated and there is no tool changer. All tools are fixed to the robot wrist.

Payback period is calculated next. For payback period calculation some basic information of the products is needed. The information is gathered in Table 17 below.

Table 17. Key figures of current and future production of Product N. The left most column contains the production aspects, second from left contains the figures of the current production and the right column contains the figures of the designed work cell.

Key figures

Aspect \ Case	Current	Future
Yearly production volume		
Manual work per part [min]		
Employee hourly salary & benefits [€/h]		
Scrap Part Cost per year [€]	1000	600
Jig and Process Enhancement Cost [€]	500	1000
Hours per Shift [hours]	8	8
Break time per Shift [min]	55	55
Shifts per day [unit]	2	2
Working days per year [days]	220	220

As can be seen from the table 17, for this analysis the same yearly production volume is used for both the current and the future scenarios. The current and future scenarios differ on the amount of manual work required which is smaller in the future scenario. The scrap part cost is expected to be lower in the future scenario, but the jig and process enhancement costs are expected to rise. Now the yearly cash flow can be calculated. Results of cash flow calculation can be seen in table 18 below.

Table 18. *Values for payback period calculation for the minimum investment work cell.*

Aspect \ Product	Product N
Yearly savings per product [€]	4447
Estimated Yearly Maintenance Cost	1 000 €
Downtime cost	500
Yearly average cash flow [€]	2 947 €

With an investment of 31 900 € and yearly average cash flow of 2 900 € the payback period for this work cell is a long 11 years. It is so long actually, that Product N might even face the end of production earlier before the work cell has paid itself back. However, if the production volume of the target product increases like Finncont has planned the payback period shortens radically. By doubling the production volume of the Product N the payback period goes down to 4 years and 3 months. With a production volume of units per year, the payback period would be just about 4 years.

Capacity can be calculated the same way as for the FMS work cell. By assuming the same setting as earlier, (220 days per year, three sifts) the values on the table 19 can be calculated.

Table 19. *Calculated capacity for the minimum investment work cell. The used capacity is calculated with current yearly production volume. The maximum capacity calculation assumes production in three shifts.*

Capacity

Maximum usable (three sifts) [h]	4224
Capacity used [h]	134
Capacity used [%]	3,2 %
Maximum capacity (year) [pcs]	
Maximum capacity (day) [pcs]	

As can be seen from the table 19, only 3.2 % of the capacity of the work cell is used with x pcs yearly production volume on three shifts. The work cell would be capable of producing almost x pcs yearly on three shifts. The work cell has a lot of unused capacity which partly explains the long payback period of 11 years calculated earlier.

As is the case with the FMS work cell, the yearly cash flow and payback period calculations for the minimum investment work cell are also dependent on the amount of manual work time saved per part. The above calculations are done with average values, but as can be seen from the time study reliability analysis on appendix f, the reliability of individual element time measurements is low. In order to roughly estimate the error of processing a whole product, the half of minimum processing time and maximum processing time for Product N was calculated from the time study measurements presented on appendix f. The results of the calculation can be seen in table 20.

Table 20. *Reliability analysis showing the effect that the time study error has on the manual work time saved and on yearly savings.*

Reliability analysis

Aspect \ Product	Product N
Manual work time saved per part with error [min]	
Yearly savings per product with error [€]	4447 ± 201

As can be seen from the table 15, the error on yearly savings caused by the time study unreliability is 4.5% for Product N. The payback period calculated with minimum yearly savings would be 11 years and 7 months and with maximum yearly savings it would be 10 years and 1 month. The payback period calculated with averages is 11 years.

It could be argued that the minimum yearly savings and longest payback period should be used as the basis on robot work cell investment decision making. This is because by standardising working methods and teaching the workers, the minimum measured processing time could be made a standard. However, the company is aware of this and has been trying to create work instructions and uniform working methods, but in spite of their efforts high variations in working methods and time was observed during time study. Thus it is debatable if the teaching of employees and standardization of working methods is easier or cheaper than investing to a robot work cell.

6.3 Case 3. Collaborative work cell

As it was seen in chapter 5.2, the products in the group 2 have only three work tasks performed on them: deburring, measuring and marking. Because deburring was considered too risky task to base the work cell on and measuring and marking tasks are light and fast tasks, normal or traditional work cell design was deemed unsuitable. Therefore research was conducted on alternative automation possibilities.

Because of the dexterity and variety of task elements performed for the group 2 products and the low yearly volume, adding automatic processing machinery was deemed un-economical. During the time study it was observed that the workers used a significant amount of time and effort to move the products around the work area. The products were lifted from gravity conveyor to work table and from the table to leak test pool, from the pool back to the table and finally from the table to EUR pallet for packing. The lifting is done with an overhanging chain hoist that is operated from hanging controller. The lifting takes considerable amount of time and is completely non-productive. On the work table workers often have to turn and move work pieces in order to reach all sides.

Manual handling of the products is tiresome for the workers as they weight from 20 kg to 40 kg as can be seen from Table 21 below.

Table 21. *Weights of the group 2 products currently in production. Name of the Product is on the left column and weight on the right column. Weights are in kilos (kg).*

Name	Weight (kg)	Combination	Combination weight
Product T3	28	1	36
Product T3 addon	8	1, 2	
Product T4	33	2	41
Product T5	33,5	3	42,8
Product T5 addon	9,3	3	
Product T2	22	4	26,8
Product T2 addon	4,8	4	
Product T1	19		

For the reasons above it was thought that using a robot for product manipulation would be beneficial. The robot would pick up a product from the feeding conveyor and present it to the operator who will do all of the actual processing tasks for the product. On this way of working the flexibility and dexterity of human operator and the strength of an industrial robot could be combined.

6.3.1 Layout

As it was stated in chapter 2.6, there are 4 operation modes for collaboration: Safety rated monitored stop, hand guiding, speed and separation monitoring and power and force limiting. Hand guiding is mainly used for teaching the robot and not for normal operation although it could be used as assistive technology. In safety rated monitored stop the work space can be shared, but the robot cannot move if human is present. Power and force limiting robots on the other hand do not offer high enough payloads for manipulation of group 2 products. The only solution left is speed and separation monitoring which allows the use of standard industrial robots and occasional sharing of work space. Speed and separation monitoring was thus chosen as the operation mode and the layout of the work cell, that can be seen in Figure 15, is designed accordingly.

Figure 15. *A rendered image of the proposed layout for the collaborative work cell.*

As can be seen from the figure above, the robot is in the centre of the work cell and other equipment is placed around it. The robot should have load capacity of over 100 kg, preferably 150 kg. This is to ensure that the robot has the strength to hold and manipulate the products even if the centre of the gravity of the product is far from the end of the robot arm. The robot reach has to be at least 2.2 m, but no more than 2.5 m. The other equipment in the work cell has not been changed from the existing ones. The two gravity conveyors, tool rack, leak test pool and EUR pallets for packing are all currently in use. Only the chair for the worker and the fence behind the leak test pool are new additions. The sensors, end effector, safety controller and robot controller are not shown in the Figure 15.

The end effector could be either finger gripper type or vacuum gripper type. The back side of the products could be used as the gripping area because, all of the products have rather even and straight back side that does not have many features needing finalization. The gripper has to be able to hold two products at the same time so that the robot can switch the product from the leak test pool to a new one easily. The size of the work cell can be seen in Figure 16 below.

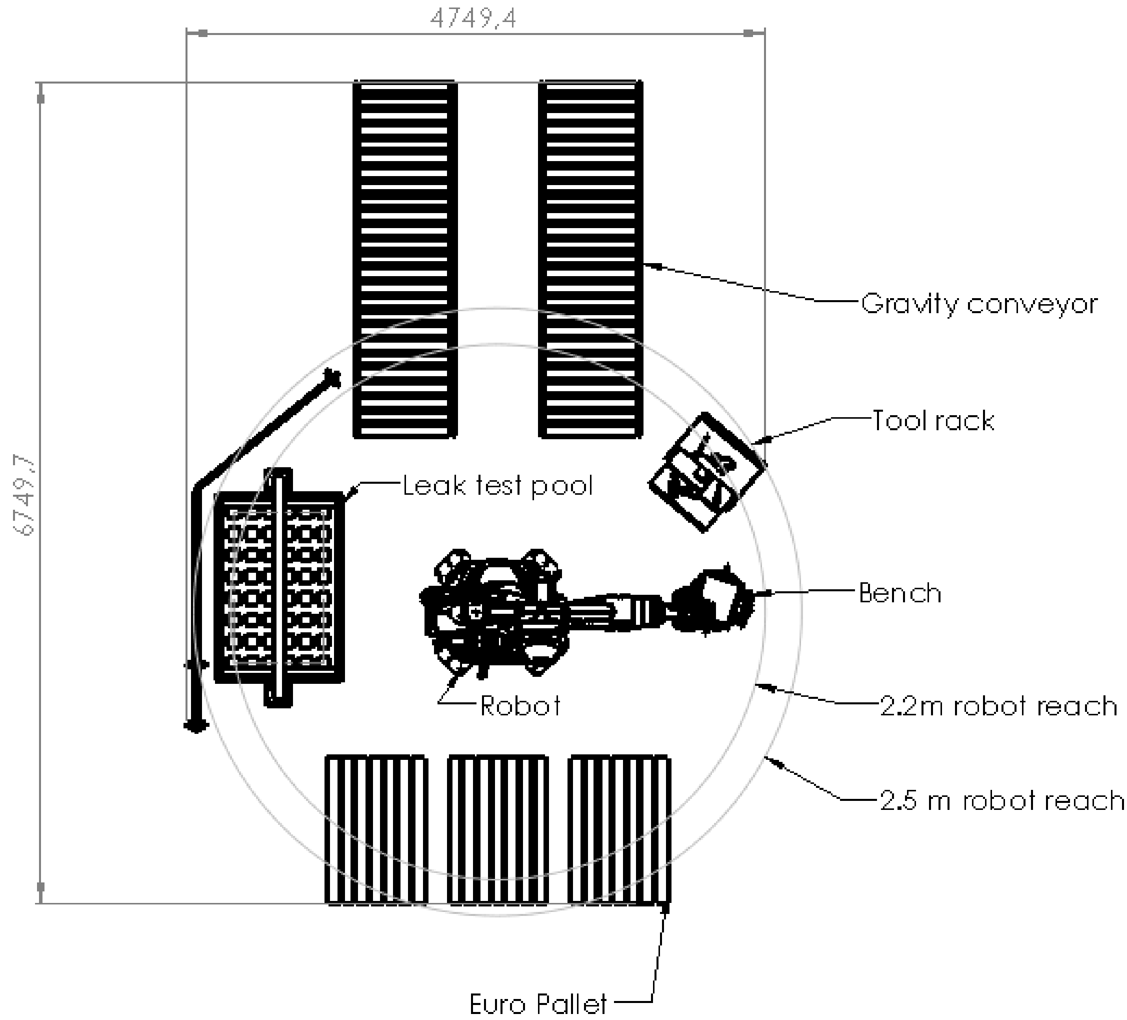

Figure 16. Outline and size of the work cell design for group 2 products. The physical size of the work cell is bigger than the size of the minimum investment work cell for group 1 but smaller than the minimum payback time work cell for group 1.

As can be seen from the Figure 16, the work cell does not contain any light curtains or other traditional safety measures for the robot. Only the leak test pool is protected with a small fence from the back side. Instead the work cell is made safe with safety controller laser scanners and cameras that monitor the area around the work cell. The monitored area is not depicted in the figure. More description of the safety features of the work cell is written in chapter 6.3.3.

6.3.2 Work cycle

The work cell will be manned by one operator per shift. For most of the time two products will be present in the work cell: one in the leak test pool and one in robot end effector. During one work cycle a single product will be finished.

The work cycle begins with the operator signaling the robot to pick up a new product from one of the conveyors. The robot will locate the part, pick it up and present it for the operator, sitting in the work chair, who then proceeds with finalization. During the finalization the worker may push a button signaling the robot to rotate the product according to preprogrammed instructions to better reach around it. After preparation for leak testing is done, the operator inspects the previous product currently in the leak test pool and if he or she finds no leak, operates the pool to lift up the product and unchains it. Then the operator signals the robot to pick up the unchained product to the other side of its gripper and releasing the prepared product on to the pool. The operator then chains the product to the pool and lowers it under water. Next the operator walks back to the work chair and signals the robot to present the leak tested product for removal of leak testing gear and for last finalization tasks. When finalization is ready the operator signals the robot to move the product on to the packing area and to release it on one of the EUR pallets. The operator will then pack the product on the pallet after which the cycle begins anew.

6.3.3 Safety

In order to ensure safety in the above mentioned layout and work cycle, speed and separation monitoring is used. The safety aspects of this kind of operation are instructed with a few ISO standards as was noted in chapter 2.7.In case of constant separation distance, it is possible to set up multiple safety zones, each with different maximum allowed speed for the robot. That is because the standards state that the robot may not approach nearer to human than predefined separation distance that is depended on the movement speed of the robot and the human and of the reaction time of the whole system. The minimum separation distance can be calculated for each case with equations that can be found on ISO / TS 15066 (ISO/TS 15066 Robots and robotic devices — Collaborative robots 2016). If only one zone is used the robot will stop when separation distance becomes lower than allowed. With two or more zones the maximum allowed speed for the robot is lowered in steps when individual zones separation distances are crossed until the last zone when the robot is stopped. For the constant separation distance worst case scenarios have to be used in separation distance equations. (ISO/TS 15066 Robots and robotic devices — Collaborative robots 2016)

Another possibility is to use dynamic safety zones where the separation distances are continuously changing. Dynamic operation can be achieved by constantly monitoring the speeds and locations of all robots and humans in the working area and vicinity. (ISO/TS 15066 Robots and robotic devices — Collaborative robots 2016) Dynamic safety zones have the advantage that they allow the robot to move faster in areas where there are no humans present. Unfortunately the sensors and control systems currently available are struggling to achieve satisfactory performance on this (Anandan 2013).

Research groups have demonstrated some working configurations like Fraunhofer institute's "SAPARO" (Fraunhofer Institute).

Because of the unfinished status of the dynamic safety zone technology, constant safety zones were chosen for this work cell. It was seen that two or more safety zones will be needed in order to allow collaborative working. One of the important considerations is that to realize the above mentioned work cycle where the operator periodically signals the robot to move to next point on its program, the worker would actually have to leave the vicinity of the robot. If the worker stays in the stop zone the robot will not move. For smooth operation the separation distance of the stop zone would have to be as small as possible so that the operator does not have to move far. By adding more zones with lower maximum speeds for the robot it is possible to lower the separation distance of each underlying safety zone.

The robot system has to be equipped with two redundant safety systems so that a failure in one of the safety systems can be noticed and the robot can be brought to stop. (ISO 10218-1:2011 2011) One possibility is to use a combination of laser scanners and cameras.

The standards state that the safety has to be ensured with a risk assessment as was noted in chapter 2.7. The risk assessment has to take into account all possible normal usage scenarios and in addition also miss use scenarios. The risk assessment has to cover the whole operation of the work cell, but small, equipment specific, details do not have to be covered. For those the equipment manufacturers' documentation can be referred to as was stated in chapter 2.7.

6.3.4 Analysis

As with other two cases, three different aspects will be analyzed: investment cost, payback period and production capacity. First one will be cost.

Equipment costs on the collaborative work cell are relatively low because there is no turn tables or tool changers in the design. On the other hand, the safety features and testing fees are costlier than for the other two designs, but because they are mostly services the actual costs depends highly on the integrator offering the service and on the coverage of the service. The novelty technology needed for the collaboration also means that estimating the investment cost of the work cell is difficult. For this thesis the costs in Table 22 below are based on the knowledge gained by the author with unofficial discussions with robot integrators and researchers.

Table 22. *Investment cost breakdown for collaborative robot work cell.*

Robot Investment	Cost
Robot [€]	
Gripper [€]	
Part Presentation Fixture [€]	
Safety Monitoring System [€]	
Physical Barriers [€]	
Integration [€]	
Training [€]	
Taxes, Transportation Fees [€]	
Robot program	
Starting Investment	75 500 €

As can be seen from the table, the total cost of the work cell is expected to be 75 500€. The robot chosen for the calculation is a used model with a price of 40 000€ including a safety controller for the robot. If a new robot is chosen, the cost can be expected to be at least double. The part presentation fixture refers to the fixtures, or more accurately feeders, on the gravity conveyors that present the work pieces in correct orientation for the robot. The safety system cost includes all of the monitoring devices and emergency stop buttons. The following figures in Table 23 are used in the calculation of yearly cash flow.

Table 23. *Production figures of current situation and proposed future situation.*

Key figures

Case / **Aspect**	Current	Future
Yearly production volume		
Manual work per part [min]		
Employee hourly salary & benefits [€/h]		
Scrap Part Cost per year [€]	1000	600
Jig and Process Enhancement Cost [€]	500	1000
Hours per Shift [hours]	8	8
Break time per Shift [min]	25	25
Shifts per day [unit]	2	2
Working days per year [days]	220	220

As can be seen from the table above, roughly x minutes of work time can be saved with the proposed new system. This figure is a weighted average, based on data gathered from time study and independent production volumes of each product in group 2. The cost of scrap parts is estimated to drop by 40 %. Savings from less sick leaves due to less physically demanding work are not estimated because of a lack of data. With this information the yearly cash flow can be calculated. Result of the calculation is show in Table 24.

Table 24. *Yearly cash flow for the collaborative work cell.*

Product / Aspect	Product T1-5
Yearly savings [€]	5865
Estimated Yearly Maintenance Cost [€]	1 000 €
Downtime cost [€]	1 000 €
Yearly average cash flow [€]	3 865 €

Now that the yearly cash flow has been acquired, the payback period can be calculated with the equation (2). With a yearly cash flow of approximately 3900 € the payback period will be a long 15 years and 6 months. It is possible that the work cell will never be able to pay itself back because of end of production of the products of group 2 or failure of some of the equipment of the work cell. For a less than 4 years payback period the production volume would have to triple from the current.

Capacity is calculated for the work cell with similar assumptions as with the other two work cells. Maximum capacities are calculated with an assumption of three shift production on 220 days per year, 25 min break time per shift and 80 % utilization of the theoretical maximum capacity. Used capacity is calculated with a production volume of x pcs per year and y minute capacity used per product

Table 25. *Capacity calculation for the collaborative work cell.*

Capacity	
Maximum usable (three sifts) [h]	4004
Capacity used [h]	1664
Capacity used [%]	41,5 %
Maximum capacity (year) [pcs]	
Maximum capacity (day) [pcs]	

As can be seen from the table above, maximum production capacity of the work cell would be about x pcs yearly. The currently used capacity is about y pcs or 41.5 %, i.e.

the work cell has a sufficient amount of unused capacity. As was noted earlier, the yearly production volume would have to reach x pcs in order for the payback period to stay within the four years target. For such a high production figure to be possible the production days would have to be increased from 220 to 280 by introducing Saturday work and dividing holidays so that not every operator is on holiday at the same time.

Like with the other two work cells, the yearly cash flow and payback period calculations are dependent on the amount of manual work time saved per part. The above calculations are done with average values, but as can be seen from the time study reliability analysis on appendix f, the reliability of individual element time measurements is low. In order to roughly estimate the error of processing a whole product, the half of minimum processing time and maximum processing time for Products T1-5 were calculated from the time study measurements presented on appendix f. The results of the calculation can be seen in Table 26.

Table 26. *Reliability analysis showing the effect that the time study error has on the manual work time saved and on yearly savings.*

Reliability analysis

Aspect \ Product	Product T1-5
Manual work time saved per part with error [min]	
Yearly savings per product with error [€]	6865 ± 1535

As can be seen from the Table 26, the error on yearly savings caused by the time study unreliability is 22% for Products T1-5 . The payback period calculated with minimum yearly savings would be 22 years and 8 months and with maximum yearly savings it would be 11 years and 10 months. The payback period calculated with averages is 15 years and 6 months.

It could be argued that the minimum yearly savings and longest payback period should be used as the basis on robot work cell investment decision making. This is because by standardising working methods and teaching the workers, the minimum measured processing time could be made a standard. However, the company is aware of this and has been trying to create work instructions and uniform working methods, but in spite of their efforts high variations in working methods and time was observed during time study. Thus it is debatable if the teaching of employees and standardization of working methods is easier or cheaper than investing to a robot work cell.

7. COMPARISON

All of the planned work cells are technically possible to implement and all would improve the production system of the target company. In this chapter the three work cell designs are compared to find out the best alternative for Finncont's current circumstances. The comparison is focused on the economic aspects of the investments but some physical and operational comparison is also included.

First area of comparison is economics. This includes comparisons of investment cost, payback period, return on investment and net present value calculated for each work cell.

7.1 Economic comparison

Investment cost and payback period were already calculated in the previous chapter and can be used as is. Return on investment can be calculated for each work cell with the equation (3). The base values and resulting ROI for each work cell are presented in Table 27.

Table 27. *Calculation of ROI.*

ROI calculation			
	FMS	Min investment	Collaborative
Investment	73 000 €	31 900 €	75 500 €
Yearly average cash flow	15 467	2 947 €	4 865 €
Return on investment	21 %	9 %	6 %

The FMS work cell has the highest ROI, which is over two times higher than the ROI of the minimum investment work cell which is the second highest with a ROI of 9 %. The collaborative work cell has a ROI of 6%. All of the work cells are profitable on absolute values, because the ROI is over 0 % and higher than interest paid on bank deposits currently (2016-2017).

Next, the NPV is calculated with equation (4). The starting values and result of the calculation can be seen from Table 28.

Table 28. Calculation of NPV. Calculation period is 10 years and the discount rate is 1.8 %.

NPV calculation	FMS	Min investment	Collaborative
Total number of time periods (n)	10	10	10
Average cash flow per period (CFt)	15 467 €	2 947 €	4 865 €
Discount rate (k)	1,8 %	1,8 %	1,8 %
NPV	142 900 €	27 200 €	45 000 €

The NPV was calculated for a period of 10 years. The discount rate (1.8 %) was chosen as the estimated inflation rate in Finland for the year 2017. Constant average cash flows were used for each period and they are based on the calculations on chapter 6. The FMS work cell has the highest NVP of 143 000 € and the collaborative work cell has the second highest NPV of 45 000 €. Minimum investment work cell has the lowest NPV of 27 200 € A summary of the comparison of the economics is presented on Table 29.

Table 29. Summary of the comparison of the economic aspects of the work cells.

Economic comparison summary	FMS	Min investment	Collaborative
Investment cost	73 000 €	31 900 €	75 500 €
Payback period	4,75 y	11 y	15,5 y
ROI	21 %	9 %	6 %
NPV (10 years)	142 900 €	27 200 €	45 000 €

As can be seen from the table both the NPV of the minimum investment work cell and of the collaborative work cell are lower than their investment costs. This is also reflected on the payback period which is over 10 years for both work cells The NPV was calculated for 10 years. Based on the comparison the FMS work cell is the best option for Finncont's current situation from the economic point of view.

7.2 Size comparison

On technical aspects the work cells are compared on size and technical complexity. The size of the work cells is calculated from the 3D models that were presented in chapter 6. A comparison of the sizes can be seen in the Table 30 below.

Table 30. *Size comparison of the work cells in square meters. The core cell refers to the area occupied by the actual robot cell equipment, excluding storages, manual work areas etc. The whole cell refers to the whole work cell size including storages and other equipment.*

Work cell sizes			
	FMS	**Min investment**	**Collaborative**
Core cell (m2)	24.9	9.1	-
Whole cell (m2)	67.3	40	32,1

From the comparison, it can be seen that the FMS work cell requires the largest floor space with 67 m2 total area. On the other hand the collaborative work cell is the most compact, requiring only 32 m2. The absence of turn tables and fences degrease the size of the work cell. However, the safety system monitored area will reach outside of the work cell boundaries.

7.3 Operation comparison

On operations side the work cells are compared on the number of products they are able to process and on the processing capabilities they possess. First is the number of products they can process. The FMS work cell is designed for processing the group 1 products. The group 1 consists of 11 products, but other products filling the requirements of group 1 could also be processed in the work cell. For each new product a fixture and robot program has to be added. With the current design the work cell can process 5 products.

The minimum investment work cell can process one product. The work cell is designed similarly to the FMS work cell which means that adding more products is possible as long as they are of the same general size as the Product N and require the same processing tasks.

The collaborative work cell can processes, or handle, one product family. Currently that product family contains five products. The work cell could handle even more products, as long as they share the same design features as the existing ones. However, the handling capability is mostly depended on the gripper design which has not been done in this thesis. Therefore it cannot be said yet how difficult or easy it is to add more products to be processed in the work cell. Table 31 below has a summary of the number of products each work cell design is able to process in current plans.

Table 31. *Number of different products each work cell can process.*

Number of products each work cell can process			
	FMS	**Min investment**	**Collaborative**
Products	5	1	5

Both the FMS work cell and the collaborative work cell are able to process 5 kind of products while the minimum investment work cell can only process a single product type. For the FMS work cell it is easy to increase product types. The collaborative work cell can process all the products from one product family and it is easy to increase the product types as long as they are from the same product family.

The second operation comparison point is the processing capability of the plans. The summary can be seen below in Table 32.

Table 32. *Process capabilities of the work cells. Y means that the work cell includes the processing capability.*

Process capabilities of the work cells			
Processes	**FMS**	**Min investment**	**Collaborative**
Cutting	Y	Y	
Measuring	Y	Y	
Chamfering	Y		
Drilling	Y	Y	
Handling			Y

As can be seen from the Table 32, the group 1 work cells are able to do machining processes to the produces. The FMS work cell includes an automatic tool changer and more tools so it can do more versatile processing than the minimum investment work cell. The collaborative work cell is only able to manipulate the products and not process them.

7.4 Summary of the comparison

A summary of the comparison is presented in this chapter. The summary is presented in Table 33. Each of the three plans has its strengths and weaknesses and it is not possible to define a clear all-around winner.

Table 33. Summary of the comparison of the planned work cells.

	Multi-product	Single-product	Collaborative
Investment cost	73 000 €	31 900 €	75 500 €
Payback period	4.75 y	11 y	15,5 y
ROI	21 %	9 %	6 %
NPV (10 years)	142 900 €	27 200 €	45 000€
Capacity utiliza-tion	13,3%	3,2%	41,5%
Core size	24.9 m2	9.1 m2	-
Whole size	67.3 m2	40 m2	32,1 m2
Number of products	5	1	5
Production pro-cesses	4	3	1

As can be seen from the Table 33, with different criteria a different plan will be the best. For example, if whole work cell size is used as decision criteria, the collaborative work cell is the best. If minimum investment of capital is used as the criteria, then the minimum investment work cell best fulfils that criterion.

For Finncont, the main criterion is the payback period and the FMS work cell has the shortest payback period. The second criterion for Finncont is the positive image the new work cell can bring to the company. In this respect collaborative work cell might be the best, since it represents most state of the art technology among the planned work cells. The final decision remains on the company.

8. FUTURE POSSIBILITIES

During the making of this thesis several potential future prospects were identified. Common for all of the future prospects is that they need some testing or maturing of technology to be reliable. Some of the future possibilities would make the corresponding work cell much more desirable than with the current designs.

Automatic packing cell

The task for this thesis was to add automation for the product finalization phase. Early on packing was left out of the research because it was thought that adding automatic packing would not be economical because of low production volumes and varying packaging methods for different products. During the work measurements and time study it was noticed however, that a considerable amount of the packing time on some products is used by the worker for picking up a wooden pallet and installing pallet collars for it and wrapping up a pile of boxes and transferring the pile out of the work station for a forklift to move to storage. In some cases the pile of the boxes reaches over 2 m high which makes it difficult for the shorter workers to lift the last boxes on top of the pile. It was thus though that in case of box packed products a system of overhanging conveyors from the workstations to a new designated packing area could be constructed. The workers would pack the products to boxes, put the boxes on the conveyors which transfer them to a palletizing robot which reads barcodes on the boxes and automatically constructs piles of boxes on pallets according to the information on the barcodes. The robot could also automatically wrap the piles.

Possibility to add products to the cells

The capacity usage of the work cells could be increased by adding more products for processing in the work cells. For example, in the general analysis 11 products were identified as suitable for production in the multi-product cell. Due to time constraints only 5 of them was eventually measured in time study and used in the calculations of the economics of the cell. It is possible that adding the other 6 products for production in the cell, the utilization would increase and payback period decrease, and make the cell more economical. Completely new products could also be designed with a consideration of the capabilities of the robot work cell.

Addition of deburring

In time study it was noticed that deburring accounts for a significant amount of the whole finalization time for many products in both groups 1 and 2. Deburring capability was omitted from the designs because of a lack of reliable information and data of suitable deburring method for hollow plastic products. More detailed research should be conducted on the deburring methods. With the addition of deburring capability, both work cell designs for group 1 products would have shorter payback periods. Based on rough approximation from the time study results, the payback period of the minimum investment work cell would drop from 11 years to 9 years. The FMS work cell's payback period would drop from 4.75 years to just 2 years. For minimum investment work cell the added deburring capability is estimated to increase the total investment cost by 15 000 €. For FMS work cell it is expected to cost 30 000 € extra on the total investment cost of the work cell.

Non chip producing cutting method

Rotating tools were chosen for cutting process for both multiproduct work cell and single product work cell. The drawback of this choice is the large amount of cutting chips produced. The work cells employ waste collection boxes underneath the pallets, but it is highly likely that the small chips spread to a large area partly outside the work cell. Some of the chips will also remain inside the products. Cleaning of the chips will consume valuable working which should be avoided. A non-chip producing cutting method would be beneficial and laser cutting might be the answer. However, some open questions remain such as, damage inflicted on opposite wall, possibility of the cut edges to reattach while still hot and the economics of laser cutting.

Addition of colour capable marking method for the sake of implying graphics to products

Currently none of the analysed products have coloured markings or graphics added in finalization. The colour and texture of the products is controlled with the raw material and mould coating. These methods can usually only produce mono coloured products. By adding a colour capable marking method for the work cells it could be possible create permanent or almost permanent coloured marking and graphics on the products. Inkjet printing is one possibility but there are other options as well and some testing should be conducted for determining the best option for Finncont's products. Also a market research should be conducted in order to find out if demand for such production capability exists.

Advances in safety devices could improve the performance of the collaborative work cell

The collaborative work cell could be made more productive with the advancements in safety systems. The separation distances could be made shorter with variable separation distance control. Shorter separation distances would allow the worker to approach closer to the robot in some situations and could increase productivity at least in theory. Estimating the actual productivity gain remains a topic for further research. However, some technological advancement is still required for bringing the variable separation distance systems to market.

Another possibility to increase the productivity of the collaborative work cell is to combine speed and separation operation with hand guiding. This way it might be possible to set the last joint of the robot arm free for the operator to hand guide to desirable position on the course of normal operation. The advantage is that when the product held by the robot has to be turned around the operator would not have to step out from the stop safety zone, which has to be done in normal speed and separation monitoring operation. This way a more natural feeling towards the robot control could also be provided for the operator that could make psychological aspects of collaborative robotics easier.

9. CONCLUSION AND CLOSING THOUGHTS

The purpose of this thesis was to research about the possibilities of adding automation on the product finalization stage of the production of plastic products in Finncont Oy. At the beginning of this thesis work practically all of the finalization work was conducted manually mostly with hand held tools. On the same time, the company was starting to feel pressure to automate some of the production processes; partly due to financial concerns and partly due to company image concerns. Some customers had even voiced their wishes for more automation in Finncont's production system. From that setting this thesis was started.

As said, product finalization stage was the area of the production system in focus in this thesis. The research began by analysing the current production methods and products in production. The types, volumes and other information about the products and the work tasks performed on them were acquired from observations of the production, product drawings and work instructions. Based on the information, 14 products were chosen for the time study though later 5 more were added on the wish of Finncont's staff. The purpose of the time study was to identify individual work tasks performed on each product and to quantify the time consumed for each task on each product. During the time study it was noticed that it would not be possible to measure each product because of time concerns. Two product groups were formed based on the product analysis and time study.

On this thesis 3 work cell plans were composed. Two plans for group 1 and one for group 2. The two plans for group 1 both include an industrial robot which holds the tools required for cutting, drilling and measuring the products. Difference between the two designs is that one of them is aimed for minimum payback period and can process multiple products. The other one is aimed for minimum investment cost and can only process one type of product. The two plans represent a traditional robot work cell design and build on earlier research done for the company.

A collaborative work cell was planned for the group 2. In this work cell an industrial robot is used to hold and manipulate products and the actual finalization work is done by human operator. Speed and separation monitoring was chosen as the collaborative operation method on which the safety systems are based on. This work cell plan has a high originality value and represents a new way of thinking in robot work cell design, made possible by the new safety standards.

The work cell designs were analysed and compared to each other on economic basis. None of the work cell plans meet the 4 years payback period requirement imposed by the company management, although the multi-product, minimum payback period design for group 1 comes close with a payback period of 4,75 years with five products or 4,25 years if Product A is left out. The other two designs have payback periods of over 11 years and over 15 years with current production volumes. A summary of the work cell design is presented in Table 33 in chapter 7.4.

Each work cell design has its advantages and weaknesses as was noted in the chapter 7. Depending on the criteria any one of the designs can be chosen. For Finncont the 4 year payback period was the most important criteria which imply that the multi-product work cell is the best option even though it did not reach the 4 year limit either. With some design changes, increase in the production volume or addition of other products to the work cell it is possible to lower the payback period to 4 years.

It was noticed during the making of the thesis that the financial calculations for the work cells are sensitive on the manual work time saved per part. The time study results for some parts have high errors which translate to high error margins for payback period and other calculations. The unreliability of the time study results is caused by the small number of observations during time study and by high variations in working methods among Finncont employees. It is advised to conduct a more thorough time study before to making investment decision on any of the planned work cells.

Like many projects, this thesis underwent some changes during the making due to changes in task description or requirements. For example the products that form the group 2 were added to the scope of the thesis after product analysis had already began due to customer wishes for upgrading the production system of those products. An unfortunate change came after the actual work of the thesis had already finished. Information came from a customer that one of their products will no longer be produced. That product is Product F, which is one of the products in group 1 and with the removal of it the payback period of the multi-product work cell grows to 7 years. A payback period of 7 years is definitely too long for Finncont and some changes in the design of the work cell, for example addition of other products, is needed. Other possibility would be to investigate the possibility of deburring in more detail and add it to the work cell. The information came so late however, that there was no time to conduct time study and other research required. Thus it remains a topic for future studies.

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APPENDIX A VARIABLE *Z* VALUES FOR TIME STUDY CALCULATION

Table 34. *Variable Z values for time study calculation of number of observations for various confidence levels. Adapted from (Aft 2016).*

Variable Z values

Confidence Level (Percent)	Z Value (Approximate)
50	0.67
60	0.84
70	1.04
75	1.15
80	1.28
85	1.44
90	1.645
95	1.96
99	2.575

APPENDIX B SAMPLE OF INFORMATION COLLECTION SHEET FOR PRODUCT ANALYSIS

Table 35. *Example of information collection sheet and the information collected for product analysis.*

Product	**Product B**
Size (LxWxH) (mm)	390x216x315
Work tasks	Cutting, measuring, deburring and leak testing
Features to be cut out	Front opening and refill hole
Length of the cut	0,556 m + 1 hole (M12) Number of holes 1 Number hole sizes 1
Approach directions	2, Front and back (180°)
Production volume	
Measurements	Height
Tools	12mm drill, 10mm or bigger mill
Notes	Leak test. Can all of the cuts be performed before the leak test? Quality check on the correct location of inserts.

APPENDIX C PRODUCT ANALYSIS TABLE

Table 36. A table used in product analysis.

Product analysis

	Products		Has to fit to EUR pallet		No manual flip needed	Minimise the tools required in the work cell	Fills all requirements
0	Product	Size	Fits to EUR pallet	Tool approach directions	Doesn't need manual flipping during processing	Required tools	
1	Product A	621x620x220	x	2, top and front (90°)	x	10mm	x
2	Product B	390x216x315	x	2, front and back (180°)	x	12mm, for cutting 10mm or bigger	x
3	Product C	920, kork.500		6, separation to two and from top and bottom (2 halves) (360°)	0	?mm, for cutting 10mm or bigger	
4	Product D	1350 kork.500		6, separation to two and from top and bottom (2 halves) (360°)	0	?mm, for cutting 10mm or bigger	
5	Product E	1700 kork.500		6, separation to two and from top and bottom (2 halves) (360°)	0	?mm, for cutting 10mm or bigger	
6	Product F	1214x427x367	x (almost)	2, Top and back (~ 110°)	x	44,5mm, 78mm, for cutting 10mm or bigger	x
7	Product G	566x441x286	x	3, Top, front and bottom (180°)	x	4mm, 5mm, 6mm, for cutting 10mm or bigger, Chamfering?	x
8	Product H	450x330x150	x	1, front	x	for cutting 10mm or bigger, chamfering?	x
9	Product I	1261x1212x290		2, front and bottom (90°)	x	3mm, for cutting 10mm or bigger. Grinding manually?	
10	Product J	600x804x981	x	2, Top and back (90°)	x	15,5mm, 80mm, for cutting 10mm or bigger	x
11	Product K	799x799x470	x	0	x	0	x
12	Product L	913x780x875	x	4, Top, back and both sides (180°)	x	5mm, 100mm, for cutting 10mm or bigger	x
13	Product M	500x300x350	x	6, Drilling top and bottom (14x M3) and separation to two halves (360°)	0	3mm, for cutting 10mm or bigger	
14	Product N	1130x715x640	x	5, Top or bottom and all sides (360°)	(x) if holes are drilled from top	5mm, 27,5mm, for cutting 10mm or bigger	x
15	Product O	500x500x300	x	2 or 1, top and bottom or on bottom (180°)	x	10mm or 16mm, 17mm and 21mm	x
16	Product P	1400x350x230	x (standing)	4.5, front, top both sides and in 45° direction from bottom (180°)	x	3mm, 3,8mm, 6mm, 8mm, for cutting 10mm or bigger	x
17	Product Q	785x575x636	x	2, Top and bottom (180°)	(x)	110mm, for cutting 10mm or bigger	x
18	Product R	1500x1500x500		1, Top	x	for cutting 10mm or bigger	
19	Product S	870x847x2041		4, Top, front and both sides	0	13mm, for cutting 10mm or bigger	

APPENDIX D REGOGNIZED ELEMENTS FOR EACH PRODUCT

Table 37. *Elements for each product that was measured in time study.*

APPENDIX E CALCULATION OF NUMBER OF OBSERVATIONS FOR TIME STUDY

Table 38. *Calculation of number of observations for product number 14. Accuracy used was 10% and confidence level was 90% that corresponds to z value 1,645.*

APPENDIX F TIME STUDY RELIABILITY ANALYSIS

Table 39. *Reliability analyses of the products calculated with a confidence level of 95%. Unit for each figure is second except for accuracy the unit is percentage.*