TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Mechanical and Industrial Engineering

FEASIBILITY OF COLLABORATIVE ROBOTS IMPLEMENTATION AT ENSTO ENSEK KEILA ASSEMBLY PLANT

KOOSTÖÖROBOTITE RAKENDAMISE VÕIMALIKKUSEST ENSTO ENSEKI KEILA TEHASE NÄITEL

MASTER THESIS

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AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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THESIS TASK

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Thesis topic:

(in English) *Feasibility of collaborative robots implementation at Ensto Ensek Keila plant*

(in Estonian) *Koostöörobotite rakendamise võimalikkusest Ensto Enseki Keila tehase näitel*

Thesis main objectives:

1. To investigate the potential of routine work automation at Keila factory
2. To find out possibilities of cobots implementation in the production
3. Provide cost benefit analysis

Thesis tasks and time schedule:

No	**Task description**	**Deadline**
1.	Literature study and data mining	25.02.2019
2.	Selection of suitable workstation	11.03.2019
3.	Testing parts and process of selected workstation with cobot	15.04.2019
4.	Analyzing results	13.05.2019

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Supervisor: Tatjana Karaulova "15" February 2019

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CONTENTS

PREFACE

This work was carried out as part of an Ensto's project to obtain knowledge about new automation technologies such as automated material transportation and collaborative robots and their possible usage at Ensto's manufacturing facilities. Enso has previously got some basic information about cobots from various Estonian robot resellers and other manufacturing companies (i.e., Ericsson, Glamox etc.) who has already done their first steps towards cobot integration.

Moreover, Ensto has issued a scholarship to TalTech master's student who will get the possibility to test cobots on the production site in the selected in this thesis work center(s). Also, he or she will get possibility to define real-life cobot's benefits and challenges through analyzing the real impact on resources, efficiency and comparing them with theoretical ones brought out in this thesis.

However, it is needed to say that initial obtained information has an advertising character, and only one Estonian company has successfully implemented cobots in their production, which usage scenario is unfortunately is nonexistent at Ensto's plant. Unfortunately, other companies failed to successfully implement cobots in their production processes.

In the regard to the above said, during thesis work were conducted test runs with the real parts, used in production and real equipment available today on the market. Test runs were conducted with the help of Pickit company's test lab in Belgium and I would like to thank Filip Vrancken and Rob Mertens - test lab engineers for their help in conducting essential experiments for this thesis.

Also, I would thank my supervisor Tatjana Karaulova for her support and guidance through the whole thesis project. Thank Nadežda Dementjeva - production manager at Ensto for trust and letting conduct this thesis at the Ensto Keila facilities; Kristina Aprelkova - process engineer and Kert Kerem - NPI manager at Ensto for their assistance during research process.
Also, thank the rest Taltech an Ensto Ensek employees for their help in data mining.
Without your support this thesis would not have been possible.

Keywords: Machine vision, Collaborative robot, Manufacturing automation, Flexible manufacturing

INTRODUCTION

1.1 Background & Motivation. Problem description

This Master's thesis was done with the objective to adapt modern technologies at Ensto Ensek in its production processes and to take advantages of new technologies to stay competitive on the market. In the same time collaborative robots could eliminate workers from proceeding with repetitive tasks, and help to use their human capital in more sophisticated way - i.e., to use workers in more complex assemblies such as quality control or troubleshooting etc. [1] That could be explained not only by current state of the Estonian labor market, showing that companies struggle to find not only white collars but a blue one as well. [2] But also, to increase ergonomics at the factory and to boost workers' motivation.

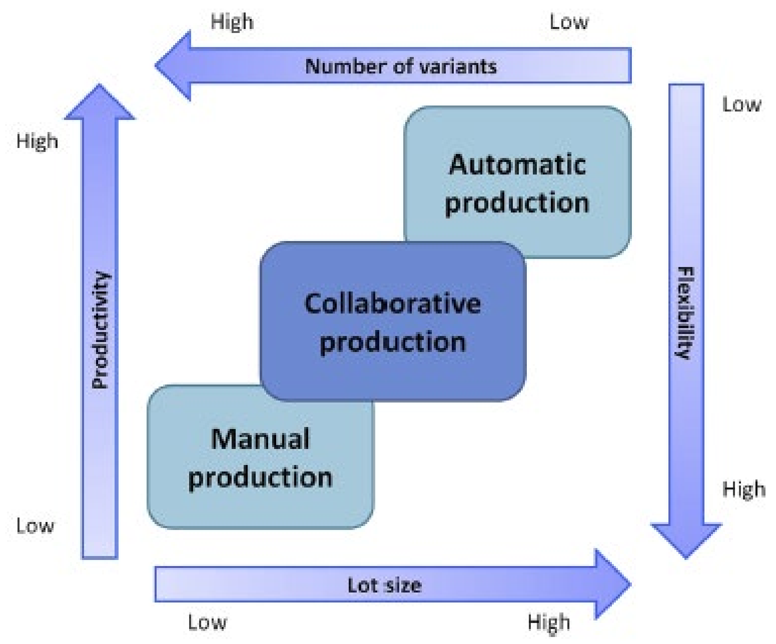

Figure 1.1 Key factors of collaborative production [3]

As it is shown on Figure 1.1 before 1970s, when first robots have been developed, the manual production was the only option, which was characterized by high flexibility but limited productivity of a production.

Between 1970s – 2010s with developing of industrial robots the automatic production was highly used. Industrial robots have high productivity but at the same time limited flexibility. [4]

Since 2010s new types of robots were developed, named cobots (collaborative robots) because of their capability to work with humans.

Cobots are offering something in between of manual and automatic production, acquiring the best traits of both types - high flexibility and high productivity respectively.

Human-robot collaboration offers significant potential for improving how work is organized. This creates an opportunity to change manual assembly work that has previously tended to be monotonous and contained a lot of repetitive physical tasks by eliminating overhead work -i.e., taking the strain off employees in terms of both physical and mental workloads (monotony). At the same time cobots provide quality improvements when strict customer requirements appear e.g., usage of adhesive compounds; sensitive surfaces; precise application, high process reliability. [5]

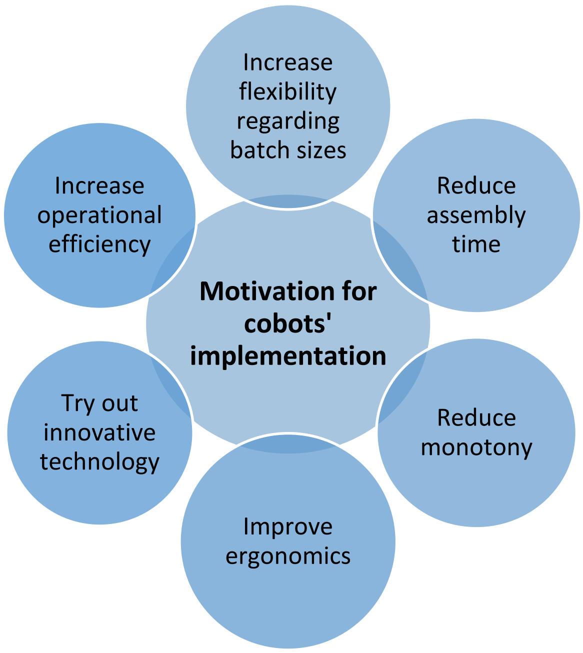

Figure 1.2 Key motivations of cobots' integration [5], [6]

Keila plant has wide range of products produced upon a certain client's order, what makes possible to describe production method as a batch production or low volume production. All above said, combined with a limited space on a shop floor requires large flexibility from production. Collaborative robots are one of the possible solutions to achieve desired flexibility. [7] The main task of the following thesis is to take into consideration cobot application efficiency and conduct the cost analysis with the reference to the fact that Ensto Ensek AS is planning to use current thesis findings as a starting point for an investment proposal to the main office in Finland.

1.2 Objectives and tasks

Main objective of this work is to find possibilities of cobots implementation in the production by the example of Ensto Ensek Keila factory. The aim is to investigate the potential of routine work automation at Keila factory. To answer on this research question, certain tasks should be done:

1. Study available literature
2. Study the best world practices
3. Find out the process(es), where it is more appropriate to use cobots
4. Analyze the influence on the resources and efficiency using cobots
5. Provide cost benefit analysis

1.3 Research approach

Literature studies and world best practices with triangulation methods were considered, when compiling this thesis.

Triangulation involves using multiple data sources to guarantee deep understanding of studied area and to ensure that sources are decent, comprehensive and contains relevant information.

To get more information observations were made. During observations current processes and workers were examined in natural occurring situations and filmed for further analysis.

Data gathering from company's ERP system were also performed as well as interview with personnel.

The reason of using different methods in this thesis is that single method can never adequately shed light on a phenomenon. Using multiple methods can help facilitate deeper understanding.

1.4 Work structure

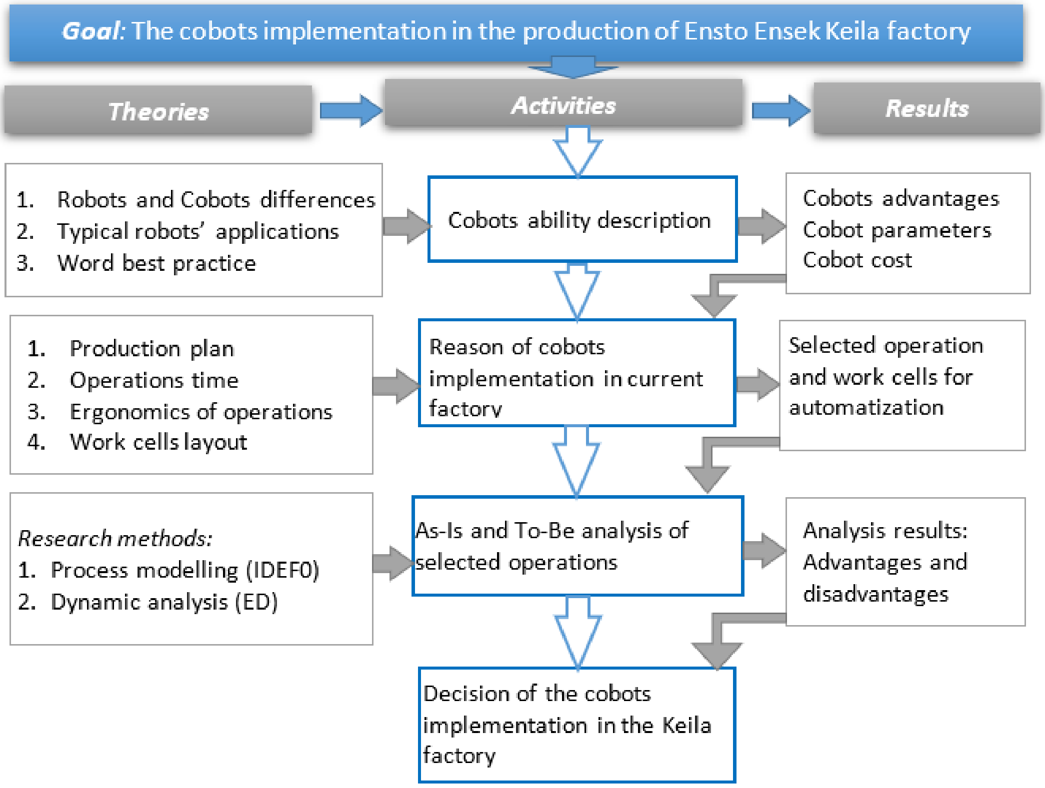

Figure 1.3 Main structure of the work

2 Human - Robot Collaboration

2.1 Definition and fundamentals

Industrial robots have begun their development in the middle of 1950s, in 1961 General motors first applied an industrial robot in manufacturing process - robot lifted hot metal pieces from a die casting machine and stacked them. In the middle of 1970s first industrial robot with six electromechanically driven axes and the world's first microcomputer controlled electric industrial robots were developed by KUKA and ABB. [8]
Cobots, however, got its present popularity due to the Danish company Universal Robots, which was founded in 2005. The Company was convinced that robots' market was dominated by heavy, expensive, and bulky robots. Therefore, Universal Robots developed cheap and easy robot technology available to small and medium-sized businesses. In 2008 company released their first serial model - an UR5 robot. In 2012, the company released a second robot - UR10 One year later, in 2015 the table-top cobot UR3 was launched. [8], [9]
Only after success of Universal Robots other conventional robot companies (e.g., FANUC, ABB, KUKA etc.) and some new startup companies – e.g., Rethink Robotics began to develop their own cobots.

The collaborative robot is a new direction in the development of industrial robotics. According to ISO, cobot is a lightweight robot designed to directly interact with a human within a certain shared space without safety fencing (cage-free), approximates the human arm in size, and can be moved easily. [10]

2.2 Company overview

Referring to the fact that the following thesis was done with the objective to analyze the rationality to apply collaborative robots at Ensto Ensek, it was necessary to describe the company.

Ensto is a Finnish family company, which is specializing on manufacturing of various electrical solutions for smart buildings and utility networks.

The company was founded in 1958 by Ensio Mettinen in Porvoo. Ensto factories located in Finland, Estonia, France, India, Italy and Russia. Research and development units located in Finland, India, Italy and Poland. In Total there are approximately 1600 employees among all countries.

Estonian branch was established in 1992 and currently has approximately 350 employees. In Estonia there are three plants which located in Tallinn, Paide and in Keila.

Figure 2.1 Ensto Ensek AS Production Area at Keila

Keila plant delivers high-voltage fittings for the construction of power lines, also produces industrial electric heaters, floor heaters, luminaires, charging stations for electric vehicles, equipment for construction of air and underground cable lines.

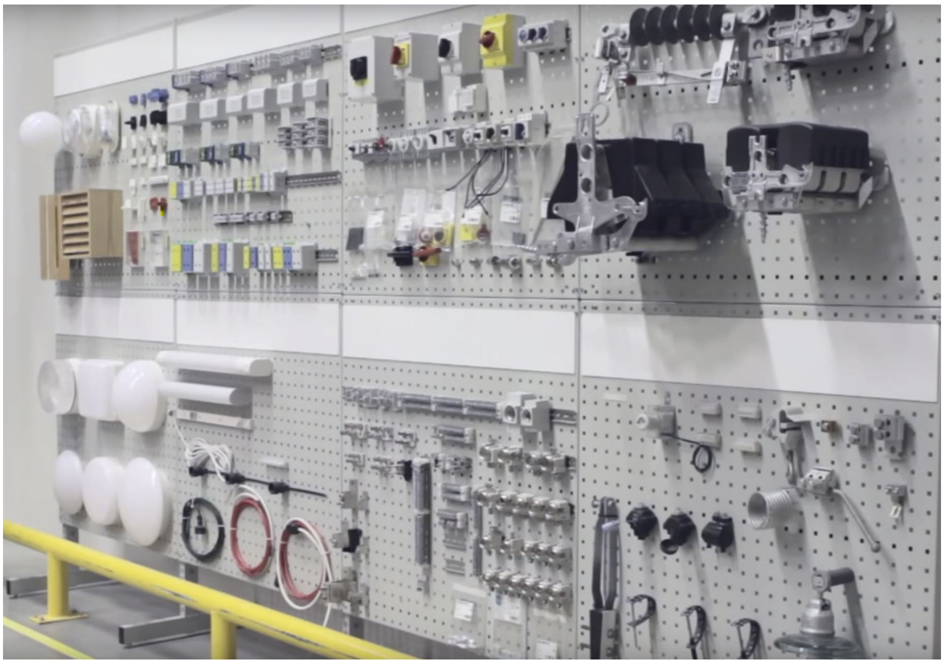

Figure 2.2 Ensto Ensek AS Products

2.3 Drivers to use cobots

For the purpose to find and analyze the reason to substitute human force by collaborative robot, it was essential to definite all drivers for potential application of cobot at Esnto Ensek.

According to Wilson [11], there are several drivers that could describe the reasons to purchase robotic solution:

1. Market globalization:

Cobot is cheaper than ordinary industrial robots (around 20 000 € instead of 50 000 - 200 000 €) - the entry threshold for small and medium business (SME) is reduced.

2. Shortening product life cycles:

Cobot is easier to set up: it is not necessary to be able to program. After one day of training, the worker will be able to configure the robot to perform tasks of average complexity. It is not necessary to hire service engineers or system integrators so the input threshold for SMEs is again reduced.

3. Individualization:

Cobots are easier to move: they are lighter than industrial ones, they do not need a local infrastructure in the form of a protective cage so attractiveness for SMEs is high, because it possible to quickly change production.

4. Labor and social cost development; demographic change:

The increase in the cost of manual labor due to the aging of the population and the decrease in the number of available people on the market (working hourly rate: € 27 in Germany, € 12 in the USA, € 11 in Eastern Europe and € 9 in China. The cost of the work is € 6 / hour). [11]

5. Agility – capacity flexibility, changeability

Reshoring. The synergy of previous factors leads to the fact that the US and the EU are returning production from China to their homeland. This could potentially help to reduce the cost of maritime logistics and improve product quality.

6. Digital Transformation. Government programs aimed at automating and robotizing production.

They can stimulate and support (including financially) the acquisition and use of robots: Industry 4.0 in EU, Made in China 2025 in China, National robotics initiative 2.0 in the USA

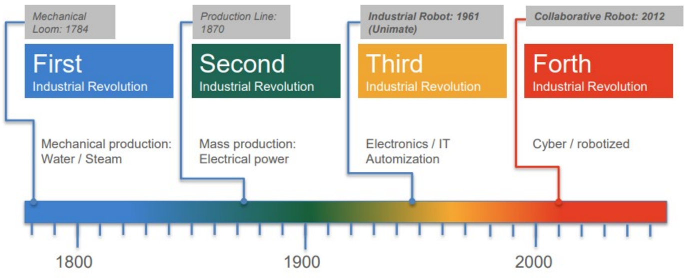

Figure 2.3 production development from industry 1.0 to Industry 4.0 [4]

Even though in some countries of EU (e.g., Sweden, Germany) are high wage costs - most assembly jobs are still performing manually. The reasons for this are [12]:

- wide variety of product variants
- small batch sizes
- shorter product lifecycles

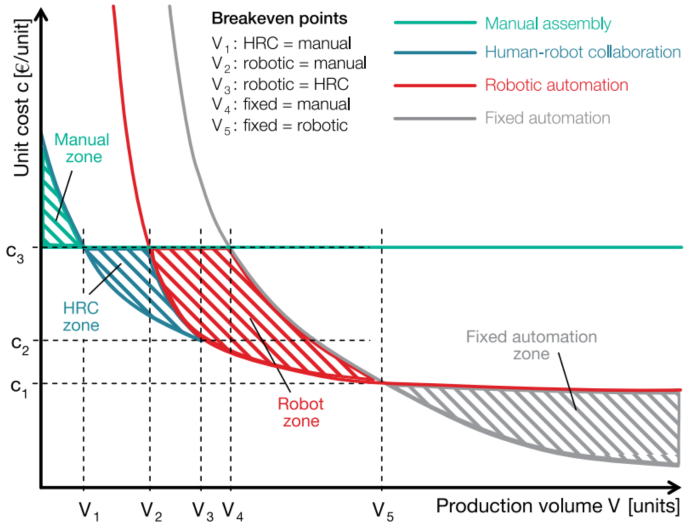

Figure 2.4 Economic comparison of alternative production [13]

v1 Human Robot Collaboration = Human Work

v2 Conventional robots = human work

v3 Conventional Robots = Human-Robot Collaboration

v4 Fixed automation = human work

v5 Fixed Automation = Conventional Robots

These reasons apply particularly to small and medium-sized enterprises. Automation is not cost-effective in this situation, because small production does not give reasonable payback periods and because of products' high variance it makes automation even more expensive to integrate.
Cobots can overcome some of these constraints. They are offering automation potential with affordable price that was previously inaccessible for manual assembly tasks at SME companies. Cobots are designed for cage-free work and do not have limitations that conventional robot does. [5]

2.4 Typical robots' applications

In order to understand whether cobot can be used to proceed with the specific operation instead of human, the author defined and described the possible cobot application implementation as well as listed the tasks that cobot can potentially perform.

Collaborative robot skills can be implemented in different applications. These applications are seen to have maximum value at the following situations [14]:

- Ergonomic and occupational health improvements, by relieving operators from performing tough, painful, and repetitive tasks
- Use as a third hand for the operator to ensure efficient and ergonomic operations
- Line balancing activities to achieve a whole number of operators on the line
- Quality improvement for tasks that require high precision
- Better floor space utilization
- Versatile and flexible operations

Typical task that collaborative robots can perform [15]:

1. **Pick & Place:** pack & palletize / depalletize; load / unload; moving objects
2. **Sequence of actions:** move; handle; trigger; check
3. **Machine tending:** tool insert; material handling; loading / unloading parts in the machines, loading unloading parts on conveyor belt
4. **Testing and sorting objects**: checking or sorting random objects on the conveyor
5. **Packaging:** collecting and placement of items in containers for transportation or storage
6. **Easy assembly:** screwing; assembly and disassembly of electronics
7. **Operations requiring high precision and repeatability:** welding and soldering; paint spraying; liquid adhesives dispensing (gluing, sealing); surface polishing
8. **Quality control:** visual inspection

2.5 Industrial Robots and Cobots differences

The rationality of cobot application at Ensto Ensek factory can also be evaluated by comparison of the usage of collaborative robots and conventional industrial robots.

According to Fasth, Cobots have advantages over conventional industrial robots [16]:

1. Able to work safely with a person (thanks to high-speed sensors and different types cameras)
2. Ease of installation and configuration (in some cases it possible to go without programming);
3. Lower cost - many of them are cheaper than the usual industrial robot: 20 000 € instead of 50 000 €
4. Easier to install and configure - robots weigh about 30 kg, you only need a 220v outlet
5. Flexible, easy to adjust - there is a GUI, an intuitive programming interface

Figure 2.5 industrial robot on the left - safety fences are required to prevent harming humans. Collaborative robot on the right - allow human worker to work together [17]

Table 2.1 conventional and collaborative robots' comparison [3], [5], [18]

Traditional industrial robots	Collaborative robots
Fixed installation	Flexibly relocated
Repeatable tasks rarely changed	Frequent task changes
Lead-through and off-line programming -high programming skills required	On-line programming (lead-through walk-through), no programming skills required
Hard to integrate	Relatively simple to integrate
Rarely interaction with the worker, only during programming	Frequent interaction with the worker, force/precision assistance
Worker and robot are separated through fence	Sharing workspace
Cannot interact with people safely	Safe interaction with people
Profitable only with medium to large volumes of production	Profitable even at low volume production
Big, very fast, hard to move, hard to start using	Small, slow; easy to use and easy to move
High payload	Limited reach and payload
ROI achieved in 3-5 years	ROI achieved typically in 1-2 years

Summing the literature findings up, the overall advantages of implementing cobots instead of conventional robots the author see following advantages:

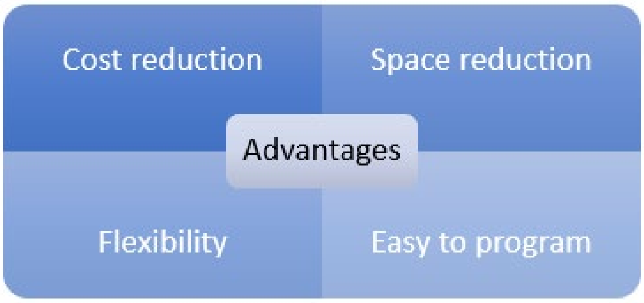

Figure 2.6 Advantages of implementing cobots instead of conventional robots

- Lower cost of implementing due to cage-free robotics, which eliminates costs for guarding
- Reduces floor space
- Reduces Engineering Costs
- Gives flexibility – cobots are portable, adaptive and reconfigurable
- Easy and intuitive programming

2.6 Differences between programming cobot and conventional robot

The previous chapter illustrated the advantages of cobot application over the industrial robot. The following chapter aims to describe the main differences between programming of two different types of robots.

Lead-trough programming

The first approach to robot programming relies on the use of the teach pendant (joystick) for on-line moving the robot through the required motion cycle by jogging. Trajectories and endpoints are then recorded into controller memory for later playback. [19]

Although the concept is simple and does not require strong technical expertise, some programming skills are still required and teaching trajectories to the robot in this way turns out to be a tedious and time-consuming task. Moreover, it is only suitable for programming simple tasks on workplaces with a simple geometry (programming complex geometries dramatically increase complexity). Further, this method requires reprogramming for each new task, even in case of little changes, thus stopping the production every time.

Therefore, in industry, this type of robot programming can be justified economically only for production of large lot sizes and is not suitable for small and medium sized enterprises, where small production batches require frequent task reprogramming and such a time-consuming and demanding procedure is unaffordable. [9]

Off-line programming (OLP) (Visual components).

This approach resorts to remotely simulating the task in the 3D model of the complete robot work cell. Specifically, the robot can be programmed from a computer rather than on the robot itself, thus virtually replicating the system in the shop floor. Additionally, these programming tools come with a set of modelling and simulation functions that allow for graphical representation of the robot cell, automated program generation and simulation of robotic tasks, with the possibility to check for possible collisions. [20] Unfortunately, typically each robot manufacturer has its own specific OLP software, whose license is usually very expensive, and employing an OLP system requires great programming effort. Indeed, OLP approaches move the burden of programming from the robot operator in the shop floor to the software engineer in the office. Time required to program the robot is still remarkably long, but the production does not need to be stopped during programming, thus the uptime can be maximized. [9]

Walk-through programming

The basic idea behind this robot programming method is that the user can physically move the end-effector of the robot through the desired positions in a freeway. At the same time the robot's controller records the desired trajectory and the corresponding joints coordinates and is then able reproduce the trajectory thereafter. [12] Thus, the robot can be programmed in a very intuitive manner and no knowledge of the robot programming language is requested to the operator. In addition to intuitiveness of interaction, this implies also that, thanks to tangible manipulation, that is the possibility of moving the robot along the desired path, the operator manipulates the robot, having tactile contact and feeling haptic feedback. [9]

Programming by demonstration

Further extension to walk-through programming is provided by the concept of programming by demonstration. Indeed, while the former allows the mere reproduction of motions performed by the human operator, the latter considers the possibility for the robot to learn the movements to perform under varying conditions and to generalize them in new scenarios. Accordingly, the robot is endowed with some learning skills, rather than pure imitation. [9]

2.7 Human and cobot differences.

Cobot application rationality analysis also involved the comparison of the working process between human and collaborative robot.

The term human-robot cooperation generally refers to the use of robots without safety fencing, i.e., cage-free robots. The various levels of cooperation between a human and a robot are shown on the Figure 2.7

- Cell - No cooperation. The robot is surrounded by a traditional cage.
- Coexistence – Human and cage-free robot work alongside each other but do not share a workspace. [5]
- Synchronized – The design of the workflow means that the human worker and the robot share a workspace but that only one of the interaction partners is present in the workspace at any one time. [5]
- Cooperation – Both interaction partners may have tasks to perform at the same time in the (shared) workspace, but they do not work simultaneously on the same product or component. [5]
- Collaboration – Human worker and robot work simultaneously on the same product or component.

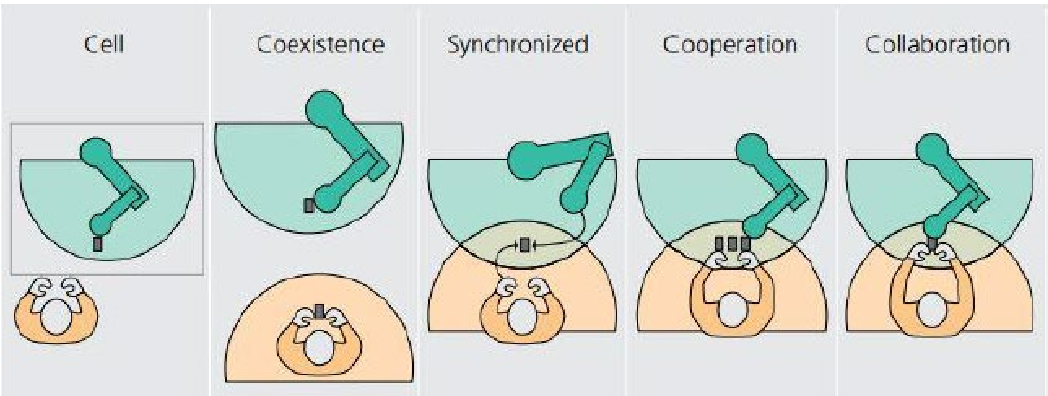

Figure 2.7 The various levels of cooperation between a human worker and a robot [5]

Initially, shop floor operators were separated from the robot with physical protection devices, such as cages. With collaborative robot this state has changed: nowadays human can closely work with robots together.

That could be considered as a positive side since human can get synergy of the robots' strengths (high speed and accuracy when performing routine operations) and a man (creative thinking, working in unusual situations). This increases productivity in industry, which means it has a positive effect on the economy. [21]

There are two types of collaboration modes by Krüger: workplace sharing mode and workplace and time-sharing mode. See Figure 2.8

Table 2.2 Collaborative robot and human comparison [3], [5], [18]

Collaborative Robot	Human
Can use sensors to “see” certain trained things (camera, laser scanner, light curtain, pressure mat)	Vision –can see and understand what they are seeing
Can limit forces imparted to the environment by programmed means	Can have a gentle touch, and understand how to use contact forces to acquire or position parts
Specific process switches and other inputs can be used to make decisions	Other senses available –hearing, taste, smell
Strong and never tire	Relatively weak and prone to repetitive stress injury
Can be moved and explicitly re-programmed	Easy to redeploy, very flexible, with minimal instruction
Can be pre-programmed to handle process variation	Handles process variation well
Highly precise positioning	Imprecise
Can be explicitly programmed for assembly	People are naturally good at assembly

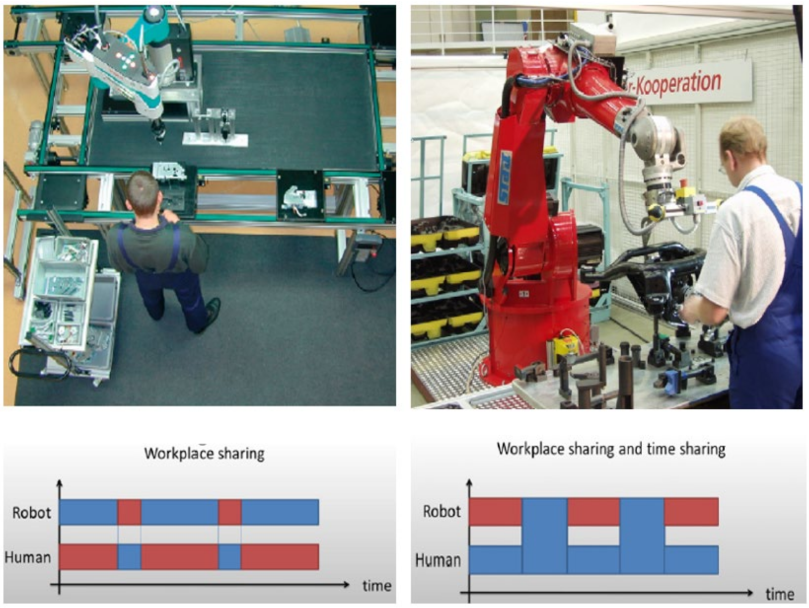

Figure 2.8 On the left: Time distribution between human and robot in workplace sharing systems. On the right: Time distribution between human and robot in workplace and time sharing [3]

In first case, robot is performing an assembly task and the human worker is performing a handling task or vice versa: the robot is performing a handling task and the human worker is performing an assembly task. [3]

In the second case robot and the human worker are jointly performing a handling task and the robot and the human worker are jointly performing an assembly task.

To jointly handle or assemble objects the robot has to interact with the human worker on a level which is much higher than just the avoidance of collision. More closely this will be written in the next chapter concerning safety standards. [21]

2.8 Cobot's safety - ISO safety standards

Robots are hazardous to humans due to their payload inertia, weight, structure (sharp edges), speed and applied forces. To protect human from machines, preventive actions should be made, based on the criteria outlined in the safety standards. [22]

There are different types of safety standards, starting from basic acknowledgment and ending with specific requirements for exact machines:

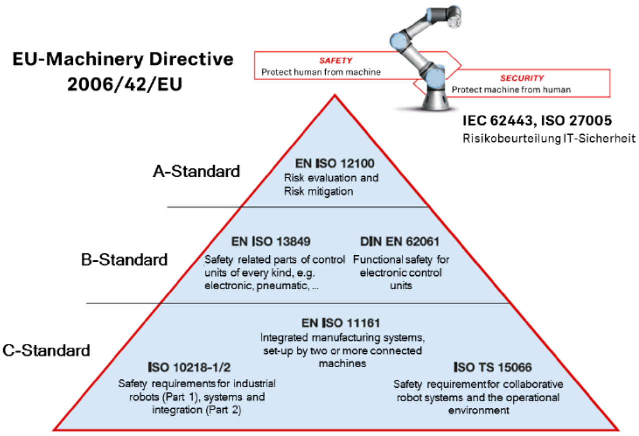

Figure 2.9 Applicable Standards and Guidelines [6]

- A-type standards (ISO 12100, IEC 61508) define basic terminology, general requirements, and methodology used in achieving safety of machinery (i.e., risk assessment and risk reduction, functional safety of electrical, electronic, and programmable electronic equipment). [22]
- B-type standards (ISO 13849-1, IEC 62061) are generic safety standards for specific safety aspects and safeguards which describe the specific functional aspects of emergency-stop devices and two-hand control devices.

- C-type standards have priority over the other two standards categories. There are two standards for industrial robots. First, (ISO 10218-1:2011) collects the safety requirements for robot manufacturers and addresses the design of robot and its controller. Second, (ISO 10218-2: 2011) is intended for system integrators and describes the safety requirements for an industrial robot system, consisting of an industrial robot and any auxiliary devices. (ISO 10218 -1/2 new, 3rd edition is currently under development) [22]

  For collaborative robot currently exists only technical specification (ISO/TS 15066:2016), which provides additional information and guidance on collaborative robot operations for those who conduct risk assessments when humans and robots work together. It is first in the word safety requirement for collaborative robots. ISO/TS means technical specification, showing what safety requirements that exists nowadays, are still under development and the final version of safety standard will be released in the future. (Collaborative robots are a relatively new technology). [22]

2.8.1 Collaborative operative modes

Basic safety principles are covered by ISO 10218-1/2. These are [22]:

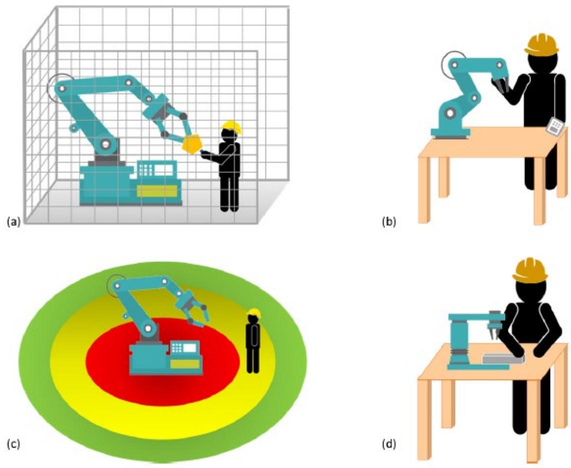

Figure 2.10 The 4 types of Human-Robot Collaboration [22]

a) Safety-rated monitored stop (SMS) – the simplest type of collaboration in which the robot is mostly working on its own and stops when an operator enters its workspace. [21]

   Difference between conventional robot and collaborative is that cobot drivers' power remains on, motion resumes after obstruction clears, cobot motion resumes without additional action.

   This form is used when the robot acts mostly independently, but sometimes a person needs to enter the workspace. For example, the robot processes the workpiece, but in the middle of the technological process a person must perform an operation with it that the robot cannot do. If a person enters a predetermined security zone, the robot will stop moving. At the same time, the power to the engines does not disappear - they pause. [17] This is a very important point, because after a person leaves the security zone, the robot will immediately resume work. This allows you not to waste time on a full restart of the work program, as is the case with a complete stop of the robot. If people constantly passed by the robot - he simply would not have time to work.

- The stop is provided without loss of engine power (pause, not stop)
- The operator can interact with the robot
- Automatic work may resume when a person leaves the workspace
- At one time, either a human or a robot can move
- It can be used with ordinary industrial robots, but you need to add safety light barriers (laser range finders, photo detectors)

b) Hand guiding (HG) - where robot movements are controlled by the operator, who shows trajectories by guiding it with his/her hands. This type of collaboration allows faster path teaching without programming the robot. Robot stops when operator arrives. Operator grasps enabling device. Robot motion responds to operator commands. Non-collaborative operation resumes when operator leaves collaborative workspace. [11](it is particularly suitable for limited or small batch production or tasks that are difficult to automate – highly variable applications)

c)

This form of collaboration is used for precise operations with heavy objects (for example, installing car doors). [9]This form can be used to work with ordinary industrial robots, but with an additional device that "feels" the forces that the worker applies to the manipulator, as a rule, this is the force-moment sensor on the robot's flange.

- The operator is in direct contact with the robot.
- The robot is under manual control.
- Both man and robot can move simultaneously (movements are controlled by man).
- Conventional industrial robots can be used.
- Additional equipment required (torque sensor).

d) Speed and separation monitoring (SSM) where the robot speed is being reduced when an obstruction is detected the robot adapts its speed relatively to the operator's location in the workspace. Three safety zones (green, yellow, red) are defined, and the position of the operator is controlled by a vision system: the closer the operator is, the slower the robot works. When the operator is too close to the robot (i.e. in the red zone), the robot stops. [1]

Here, the environment of the robot is controlled by light security barriers, which tracks the position of people, as in the first form of collaboration. The difference lies in the scenario: if in the first form the main task of the robot is to stop, then here is the simultaneous work of man and the robot. [18]The robot's behavior will depend on the zones preset in its control program: as the person approaches, the robot reduces the speed of its movements, and if the person comes so close that a collision is inevitable, a stop occurs. As the person moves away, the robot resumes work and accelerates.

- The speed of the robot decreases as the person approaches.
- The robot stops when a collision with a person can occur.
- Human and robot can move simultaneously. [12]
- It can be used with ordinary industrial robots, but you need to add safety light barriers (laser range finders, photo detectors).
- Used for operations requiring frequent presence of personnel.

e) Power and force limiting (PFL) incidental contact initiated by robot is limited in energy to not cause operator harm Power and force limited robots are equipped with an embedded and programmable electromechanical system, which allows controlling forces and torques to operate within a tolerable level of risk in all reasonably foreseeable modes. [14]These robots can work alongside humans without any additional safety device required.

Most people, representing a cobot, meaning a robot that uses this particular form of collaboration. Therefore, we consider it in more detail. [7]

In the robot joints there are installed force-moment sensors that can determine the fact of a collision with a person. If the sensors detect an excess of allowable effort, the robot stops. These robots are also designed to disperse forces on a wide surface, in the event of an impact, which is why parts of their hulls are most often made with rounded shapes.

The functionality for limiting power and strength, as a rule, is included in the standard software. [19]

- The strength and power of the robot is controlled so that casual contact between the robot and the operator will not cause harm.
- Human and robot can move simultaneously.

2.8.2 Power and force limiting (PFL) mode in cobots

There are different force limiting techniques applicable. These are [19]:

- Series Elastic Actuators (Rethink Robotics) have a spring between the motor/gearing elements and the output of the actuator. Springs in these actuators are deformable by human level inputs. This deflection is an inherent safety mechanism -spring element is able to measure torque output from the actuator.
- Motor current control (Universal Robots) - measures the motor's magnetic flux and torque is calculated based on the measured voltage and current of the motor.
- Torque sensors (e.g., Kuka Iiva is equipped with embedded sensors able to identify forces across their whole structure) These sensors can accurately measure if an external force has been exerted but they also come at a significant cost depending on the payload because they uses a semiconductor strain gauges, which works thanks to piezoresistive effect - when mechanical strain is applied a semiconductor changes its electrical resistivity.

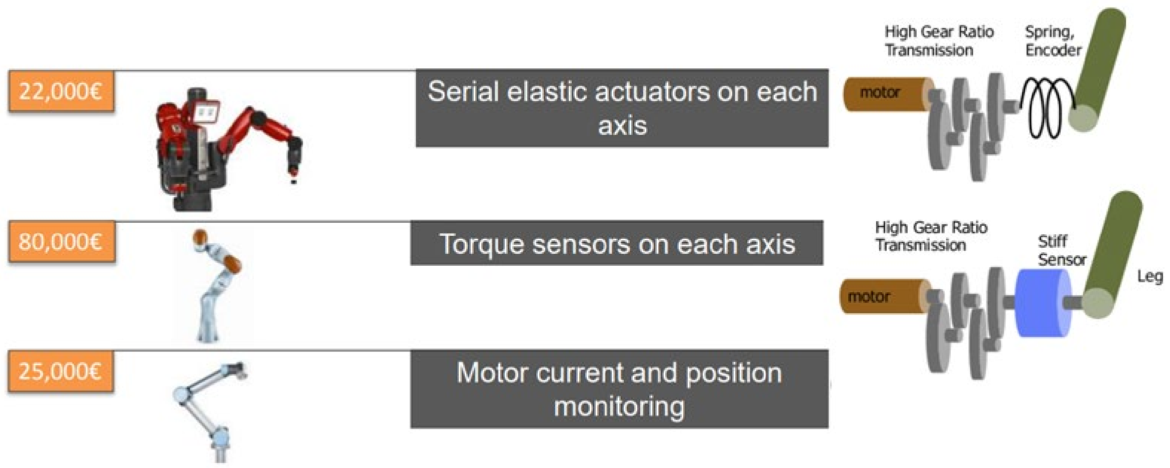

Figure 2.11 Force and pressure limiting economical compression [7]

2.8.3 Risk reduction measures for collaborative robots

When operating a collaborative robot, SMS, GH, SSM safety levels may not be required if the application forces / pressures are under the ISO TS/15066 biomechanical limits for the onset of pain. [23]That eliminating the need for slowing or stopping the robot if human is entering a robot operating zone see Figure 2.10

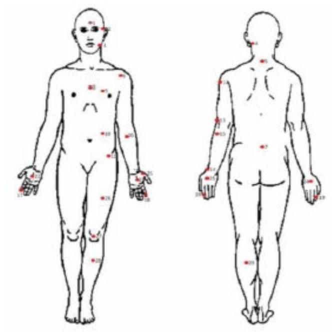

Figure 2.12 Impact measurement points [22]

Table 2.3 Force limiting defined in TS15066 based on affected body area [22]

Body region	**Specific body area**		**Quasi-static contact**		**Transient contact**	
			Maximum permissible pressure [a] p_s N/cm²	**Maximum permissible force** [b] N	**Maximum permissible pressure multiplier** [c] P_T	**Maximum permissible force multiplier** [c] F_T
Skull and forehead [d]	*1*	*Middle of forehead*	*130*	*130*	*not applicable*	*not applicable*
	2	*Temple*	*110*		*not applicable*	
Face [d]	*3*	*Masticatory muscle*	*110*	*65*	*not applicable*	*not applicable*
Neck	4	Neck muscle	140	150	2	2
	5	Seventh neck muscle	210		2	
Back and shoulders	6	Shoulder joint	160	210	2	2
	7	Fifth lumbar vertebra	210		2	2
Chest	8	Sternum	120	140	2	2
	9	Pectoral muscle	170		2	
Abdomen	10	Abdominal muscle	140	110	2	2
Pelvis	11	Pelvic bone	210	180	2	2
Upper arms and elbow joints	12	Deltoid muscle	190	150	2	2
	13	Humerus	220		2	
Lower arms and wrist joints	14	Radial bone	190	160	2	2
	15	Forearm muscle	180		2	
	16	Arm nerve	180		2	

Forces and points of application in PFL contact are divided into two separate groups [22]

- Transient Contact - contact duration is short (< 50 ms). Human body part can usually recoil.
- Quasi-Static Contact -contact duration is significantly longer than 50ms. Human body part usually trapped.

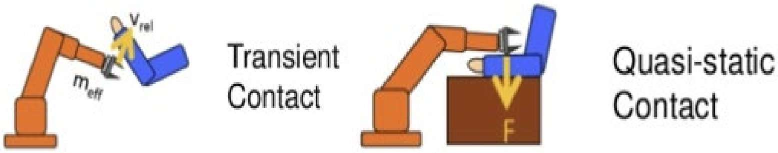

Figure 2.13 Transient and quasi-static contacts [19]

However, in some cases it is extremely hard to have forces and pressure that are less than the ISO TS/15066 limits (i.e. the end effector design or processed detail has sharp edges). [24] If the forces or pressure are too high, the use of auxiliary safety measures is a must. These can be:

- administrative controls (fences, floor markings, light curtains)
- laser scanners (to reduce speed on approach)
- Suitable robot design (soft materials, rounded covers)

Possible risk reduction measures: [25]

- robot design factors (for example, round shapes, ductile materials);
- a suitable choice of applications and the design of the robot cell (for example, gripping, harvesting, trajectory, etc.).

Table 2.4 Risk reduction measures [22]

	Transient contact	Quasi-static contact
Cobot construction	Reducing cobot’s mass Increasing contact area Increasing contact duration	Increased contact area
Cobot control	Decreasing cobot's speed	Reducing maximum force Reducing contact duration

The final configuration is a balance between safety and performance.

2.8.4 Limitations of collaborative robotics

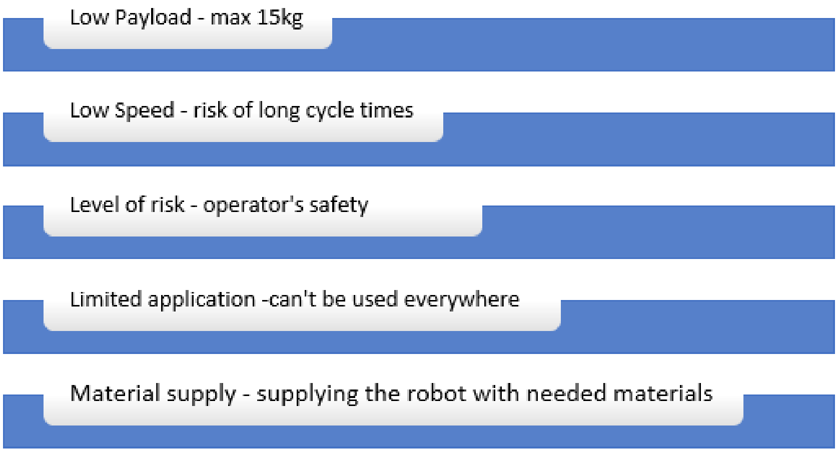

Figure 2.14 Cobots limitations [5], [18], [6]

The range of collaborative applications are restricted due to the following [11]:

- Low payload: in most cases, the payload does not exceed 15kg, which limits the type of workpieces to handle
- Low speed: in collaboration mode, truly collaborative robots do not run at their highest speed considering the speed limitations given by the standards, which can cause difficulty to meet short cycle times;
- Level of risk: to ensure operators safety, collaborative applications will present risks which could be mitigated. However, the uncertainty of human behavior needs to be taken into account which increases the level of perceived risk.
- Limited applications: shared workspaces for the robot and operator solve very specific problems within the automotive industry, other automation solutions have been deployed in a cost-effective manner. [14]
- Materials supply. The overall time and cost efficiency of assembly processes does also only depend on how assembly parts are fed to cooperative workplaces.

  As human–machine cooperation targets to higher flexibility and adaptability, the parts feeding process also needs to be highly flexible. [3]

Several unpublished studies performed in Norwegian medium size manufacturing industries have revealed that much of the manual work effort in assembly is not in the primary assembly tasks. The task of fetching components from storage areas and bringing them to the workplace for assembly has in many cases been found to constitute 60–70% of the total work hours spent on assembly. [26]

In automatic assembly solutions it has been found that more than 75% of the equipment cost is on feeders and transport systems that automates the logistics of assembly while the actual assembly operation equipment account for less than 20% of the total cost of a typical assembly line. [21]Feeding parts into an operation is essential for all manufacturing operations; therefore, automated as well as cooperative assembly requires automation of this process.
Automatic feeding has however proved to be rather challenging because of the large diversity of parts. Even today there is no general theory or methodology that gives a straight road forward to an automation solution. There are on the other hand large libraries of solutions that can be applied to specific subclasses of the general class of automatic feeding. [27]

Stiffness, fragility and size are brought into consideration components initially are stored in large numbers in bulk, not oriented and fairly close, in the order of one meter or less, from the point of usage. Given this border condition, the feeding task comprises the following steps [3], [17], [18]:

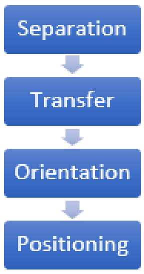

Figure 2.15 Component transferring steps

1. Separation: One unique component is separated from the bulk volume.
2. Transfer: The component is brought to a point very close to the point of pick up or treatment in the next stage of the manufacturing operation.
3. Orientation: The component is brought from a general orientation into the specifically wanted orientation for the operation next in the process.
4. Positioning: The component is positioned precisely within required tolerances for the next handling step in the process.

Some feeder techniques combine all these steps into one feeding device or system. Such systems are the most common ones in large volume manufacturing where small rigid parts are handled. For large parts, small volume, limp or fragile parts it is more common to see these steps of feeding separated. Feeders for small parts in large volume production are:

- vibratory bowl feeders
- elevator feeders

- belt feeders
- drum feeders

Simple photocell sensors to detect various part orientations can be used, Active elements like pneumatically operated wiper blades are used to wipe away incorrectly oriented parts. The belt feeder is also the backbone of systems that use camera based active orientation. [14]The need for gentle feeding for particularly sensitive parts has led to the development of the vibratory brush feeder. This feeder has the advantage of silent operation and small risk of surface damage of the part due to the part falling into a bulk storage area.

Orientation of the component is an essential part of a feeder system. Bringing the part into its required orientation is a necessity for the next step in almost all manufacturing or assembly operations. Orientation devices are often seen as integrated parts of the feeder. But in almost all cases the orientation can be seen as a function independent from the separation and transportation part of feeding. Basically, there are two principles used for orientation [14] :

- Passive orientation which utilizes the potential and movement energy to create the necessary force to reorient or eject an incorrectly oriented part.
- Active orientation uses externally supplied energy to either reorient or eject incorrectly oriented parts.

In certain cases, a hybrid solution combining active and passive techniques are applied. The typical case is the use of gravity for reorientation, but some sort of active mechanism is applied to make gravity work in the way wanted. [5]The simplest procedure is to push the part into a position where gravity will ensure proper orientation when the part tips over an edge [15]. Here the part must be fed in a well-defined manner so that only the outcomes that give correct orientation after the act of gravity reorientation can occur. Another more sophisticated method uses vision system in combination with a robot that can pick up randomly oriented parts on a table or conveyor.

The flexibility challenge starts already at the gripping stage. In a cooperative assembly between human and machine, the worker normally carries out complex handling operations, where the high senso-motoric abilities of the human hand are needed. [21]

Robots are inherently very flexible, but their performance is often limited by the ability to grip the object that shall be handled are very complex gripping systems with several degrees of freedom. But the price of these systems can easily exceed the price of a robot system.

3 Word best practices

Wilhelm Bauer from Fraunhofer Institute for Industrial Engineering, one of the leading facilities in terms of collaborative robots and Industry 4.0 research and implementation, carried out a research among 25 different industry companies in Germany, who has already implemented cobots in their manufacturing applications. Research were conducted in an interview form among new technology users at manufacturing facilities. [5]

All examined applications have been already integrated or are in the process of being integrated to existing assembly lines. Companies looked at an existing assembly system and then selected a suitable application for human-robot collaboration. [25] All the applications are running satisfactorily.
Over 70 percent of the applications are in the assembly area. There was only one application where a worker genuinely collaborates with the robot. In the majority of cases the applications involve a form of coexistence in which the humans and robots only occasionally share the same workspace (e.g., replacing a feeder tray). All the rest were in form of coexistence. [5]
Needed to point out that three quarters of the applications fall within the electrical engineering and the automotive sectors.

Research sum-up will be outlined below, as it gives a perfect understanding of how new cobot technology is used nowadays.

3.1 Easiness to ramp-up

Combination of extensive media coverage and prices for simple robots starting as low as 15 000 euros has prompted significant interest in this technology among corporate decisionmakers and manufacturing engineers. [10]
Lots of videos in the internet and even some scientific articles give the impression that cobots are so easy to implement that even manufacturing engineers start to believe that almost everyone, without any previous experience with conventional robots and automation, can simply ramp-up a robot out of the box and program any application with no trouble in less than one hour. That creates high and exaggerated expectations of how easy it will be to implement a new cobot technology. Study showed that even companies which have considerable experience with automation and their own industrial engineering departments have admitted that their expectations had been unrealistic. [12]

Difficulties emerged in relation to the planning process, the choice of application and the best configuration of the human-robot interface. According to interviews, companies are sure that [6]:

- they would be pursuing follow-up projects in the future to enhance initial experience with cobots
- they learned a lot during their first cobot experience
- they are still on a learning curve, in relation to cobots use
- it was harder than companies thought it would be going to be at the very start.
- companies will tackle the next project differently

Summing up the feedback – currently truly collaborative applications are almost non-existent in production. Human workers and robots still work alongside each other in a form of coexistence, where new cobot technology is very reliable.

3.2 Choosing a right application

Users were asked how they would approach a project to implement cobots in the future, based on their first experiences and the knowledge they had gained. All respondents suggested to simply choose an application that will work with cobots i.e., a process which has [16]:

- Simple application
- Has simple requirements to materials provisioning
- Does not involve sharp or pointed parts
- Includes a reliable production process

In terms of choosing the type of interaction, respondents stated that best is to start simply, hence "coexistence" is a right way to start. It allows the company to show workers that they can approach and even touch a modern, properly implemented cobot without any risk or danger. [11] That is also proved by the fact that in practice, most cobots currently work separately from human workers, either working in a shared space at different times or working in a separate space.

3.3 Cobot limitations - Cost

In conventional automation projects, the cost of the robot represents just one third of the total investment. All the other costs combined come to two thirds of the total project cost. This rule of thumb is also applicable to cobots as well.

The key cost drivers behind the investment are provisioning the material in the manner required by the robot and providing the necessary guarantees, including certifying the safety of assembly workers. [24]

No doubt that flexible use of mobile robots in various applications and/or in various assembly systems would allow the investment to be spread over multiple products, making new technology financially more attractive.

However currently companies are focused on building up some initial experience with stationary applications, because improving operational efficiency by using a single robot for multiple manufacturing processes would create an additional degree of complexity. [18]

Operational efficiency was a major reason behind the choice of application in all the examined applications, though none of the respondents carried out traditional analyses of efficiency and profitability at that point in time. This means that currently investments in human-robot collaboration are in a transitional phase, explained by the novelty of cobot technology. [28]Once this transitional phase is over, companies will shift to viewing the calculation of whether HRC will be profitable in the same way they treat other investments – in other words it will become a prerequisite for making the investment in the first place. In the meantime, it is optimistic to assume that the price of robots will continue to fall.

Respondents pointed out that even though the cost of cobot operation is significantly higher than expected at the start of the planning process - companies are willing to accept longer payback periods when it comes to improving ergonomics.

3.4 Cobot limitations - Parts feeding

It is important not to underestimate the cost of supplying the materials required for assembly when switching from a purely manual system based on containers of unsorted parts to a system suitable for providing materials to a lightweight robot. [12]

Large parts can be made available in containers, clearly separated and arranged using inserts. Depending on the shape of the parts it may be necessary to use a camera or similar system to determine the exact position of each part. [15]
Smaller parts can be supplied to the assembly system using methods such as a spiral vibratory bowls.
The fundamental questions of whether part provisioning can be automated at all and how much this will cost must be investigated for each part separately.

3.5 Cobot limitations - Cycle time

In many cases, robots perform assembly tasks significantly slower than human workers because cage-free operation puts constraints on their maximum speeds. In addition, a robot can generally be equipped with only one tool or one specific gripper, which can often only be used to hold one specific part. That somewhat limits the tasks robots can take over from humans and that can be offset as potential savings. [29]

It is therefore necessary to consider the robot's higher performance capabilities. The savings that can be potentially achieved by a robot taking over from a human worker in an assembly process for a specified period are relatively low, hence the use of cobots requires an alternative justification (e.g., ergonomics), or longer running times (e.g., three-shift operation) to achieve adequate levels of operational efficiency in a traditional sense. [25]

3.6 Ergonomics

One of the goals of using cobots in industry is to unlock ergonomic benefits and minimize existing deficiencies. This primarily concerns the following areas [17]:

- Providing support in situations where workers must maintain a certain posture or hold themselves in an awkward position, e.g., unnatural postures, overhead work, static positions, uncomfortable reaching distances.
- Take the strain off workers in tough physical/chemical work environments (e.g., noise, light, climate, contaminants).
- Provide power assistance to employees whose performance has become diminished or limited in some way, especially against the current backdrop of demographic change.
- Releasing people from highly repetitive tasks (such as attaching clips) or tasks that require a level of precision which is beyond the capabilities of a human worker.

According to the respondents, these kinds of ergonomic improvements are a key reason for deploying lightweight robots. [25] On the other hand, optimized ergonomics of human-robot systems does not however mean improvements in financial performance indicators.

In particular, automakers view the ergonomic optimization of their assembly workstations as part of their social policy, which cannot be measured on the basis of strict criteria for operational efficiency or profitability. Automakers therefore tend to show greater flexibility when it comes to ergonomic investments, for example by accepting a longer payback period (e.g., 4 to 6 years instead of 2 years). [27]

A thorough, systematic analysis and design of a human-robot system should look at human performance prerequisites/capabilities on the one hand and task-specific requirements on the other and then use the adaptability of modern robot technology to neatly dovetail these two points. [21]The goal is to allow humans and robots to make the most of their respective strengths in the assembly process.

4 Analysis of cobot implementation into Ensto production

4.1 Station choosing for cobot integration

Ensto Ensek Keila assembly plant uses 13000 different details in 83 work cells to produce 3500 different products. The main question is related to the decision about what exactly should be automated.

Back in the middle of 20 century answer was simple – automate everything you technically can. [30] However simply increasing the degree of automation is not very good solution - because of the complexity of the assembly operations, the high number of product variants and fluctuating quantities produced. [1]. Thus, the question of what to automate has no simple answer.

The most widely spread method for analytical approach to the question what to automate is Dynamo++This method defines levels of automation by combining physical / mechanical and information / cognitive components into 7x7 matrix resulting in 49 possible solutions for task allocation between human and machine. [26]

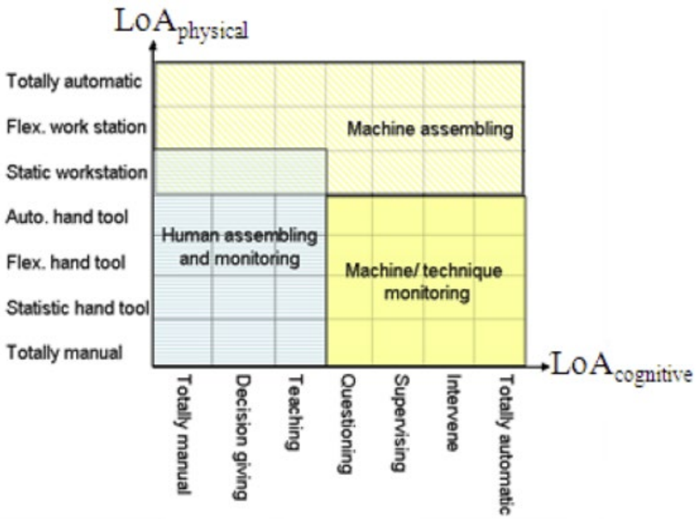

Figure 4.1 Dynamo ++ matrix [4]

A low score in the cognitive part indicates that the task is easier to control, while a lower physical score shows that the tools used can be less complex.

The more steps of a task that are on a low physical level, the easier the process is to mechanize. And the same applies to cognitive part - the lower level, the easier it is to computerize. [4]

Matrix shows tasks that can be performed by humans as well as through automation, thus matrix represent company current levels of automation in assembly systems and visualizes potential for automation. However, this method is complex and more suitable for scientific researches. It has little application by engineers at manufacturing facilities. [16]

Table 4.1 different scientific techniques for defining possibilities for automation [16], [26], [18], [31]

	Assesment Methods /Models	Assessment Objectives		Assessment methods
		Direct Measurenments	Indirect Measurenments	
	DFAA, DFA2, DFAA Index Eskilander (2001)	Cost Quality	Cost Flexibility	**Qualitative**
	DYNAMO++ (Fasth and Stahre, 2010)	Time, LoA matrix	Proactivity Flexibility Complexity	**Qualitative** Semi structured interviews Observations HTA- Hierarchic Task Analysis VSM -Value Stream Mapping
	TUTKA production assessment tool (Koho, 2010)	Cost Quality, Time (lead, delivery time)	Flexibility (volume and product)	**Quantitative** 33+6+6 predefined criteria Process maps
	Systematic Production Analysis (SPA) (Ståhl, 2007)	Quality(Q) Down-time parameters (S) Production speed/tact (P) cost.		**Quantitative** Measurement in production (machines)
	Productivity Potential Assessment (PPA) (Almström and Kinnander, 2007)	Performance (Speed)	Method (LoA) Utilization (how well) Productivity	**Quantitative** Questionnaire (40 "Yes" or "No" questions), Time study
	Lean Customisation Rapid Assessment (LCRA) (Comstock, 2004)	Cost	Flexibility	**Qualitative** 3 different rating sheets
	A model for types and levels of human interaction with automation (Parasuraman, et al.,2000)		Information processing	**Qualitative** Human performance, Cost of decision/action outcomes
	Complementary Analysis and Design of Production Tasks in Socio-technical			**Qualitative** Semistructured interviews, Work place observations
	Cognitive Reliability and Error Analysis Method (CREAM)	Probability of a human error occurring		**Qualitative**
	Task Evaluation and analysis Methodology (TEAM) (Johansson, 1994, Wäfler,		Efficiency	**Qualitative** Interviews questionnaire, observations, evaluation matrixes
	Taxonomy for Cognitive Work Analysis (Rasmussen, et al., 1990)		Cognitive LoA	**Qualitative**

To simplify selection, the author applied an adaptation of classical task allocation strategy from 1951, proposed by Paul Fits - The MABA-MABA list (machines are better at, men are better at). Those kinds of list are an attempt to suggest allocation of tasks between humans and machines by treating them as system resources, each with different capabilities. [16] [28]

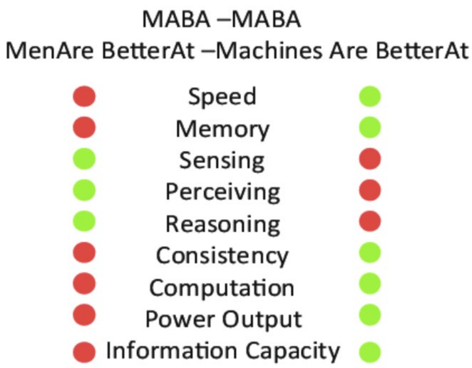

Figure 4.2 Fits' MABA-MABA adaptation [32]

They basically give an overview of what tasks can be performed by robots instead of humans. These lists practice what Erik Hollnagel calls "function allocation by substitution". Idea is that new technology can be introduced as a simple substitution of machines for people -preserving the basic system while improving it on some output measures (lower workload, better economy, fewer errors, higher accuracy, etc.). Also, Raja Parasuraman define automation as "automation refers to the full or partial replacement of a function previously carried out by the human operator" [10]

As Ensto Ensek Keila assembly plant uses details placed in buckets in their 83 work cells, identification of the suitable work cell for implementing a cobot was done through task/function allocation list. Complexness of a task were assigned from 0 to 100 % of potential automatization.

Table 4.2 Potential to automatization represented by function allocation [20]

Category (Color)	**Movement Description**	**Potential** [%]
Pick	Up to 1kg / Easy-to-pick form	100
	Up to 1kg / Hard-to-pick form	25
	Up to 1kg / Hand-full	0
	Up to 8kg / Average form	75
	Up to 22kg / Average form	50
Place	Approximate	100
	Loose	75
	Tight	25
Sequence	Special Movement	25
	Adjust / Align	0
	Replace	0
	Attach / Release	100
Move	Walk	25
	Bend / Raise	50
	Sit / Stand up	75
Handle	Approximate	75
	Loose	75
	Tight	25
Trigger	Easy	0
	Combined	0
Check	Visual	50
Process	Wait	50

In general, table represents tasks that are feasible to automate in terms of providing adequate levels of safety, and how easy it is likely to be.

This is also having a lot in common with survey results of Fraunhofer institute described before, and with experience of Mark Lewandowski- a robotics Innovation Leader at Procter & Gamble company. All respondents suggested to simply choose an application that will work with cobots i.e. a process which has [29]:

- Simple application i.e., dull, monotonous, not require humans to think a lot
- Dirty or dangerous, has ergonomic issues
- Has simple requirements to materials provisioning
- Does not involve sharp or pointed parts
- Includes a reliable production process

A thorough, systematic analysis and design of a human-robot system should look at human performance prerequisites/capabilities on the one hand and task-specific requirements on the other and then use the adaptability of modern robot technology to neatly dovetail these two points. [11] The goal is to allow humans and robots to make the most of their respective strengths in the assembly process Application prerequisites for cobots are [33], [34]:

- small scale operations
- high variability
- frequent operator presence or intervention
- Limited space
- Low speed:6-8 cycles per min
- Low payload -less than 15kg •Little or no robotics expertise available
- Processes/Machinery with Low Utilization
- Processes previously seen as uneconomical or too complex to automate (only manual labor or full automation)

Table 4.3 Criteria to choose work process which is simple to automate

	Simple to automate	Hard to automate
Tasks	Moving objects, following a trajectory without effort or with constant effort	Force control, such as polishing or fine assembly
Objects	A small variety of items (size, weight, material), known and common forms (cylinder, parallelepiped)	A wide variety of items, complex shapes, deformable and fragile items
Objects alignment	Items exactly stacked: in a box or on a pallet stack	Items dumped in a box / basket or moved to fast conveyor
Integration with other equipment	Using interfaces that a person uses: buttons, knobs	Connecting and configuring sensors, software integration with machine tools
Programming	Repetitive movements in the same sequence (without conditions and trees)	Complex logic and a variety of conditions depending on information from sensors

After data gathering and observations on the factory It was found that 3 application are suitable to conditions above. They are [28]:

1. Assembly of pole fuse switch disconnector – SZ 41. Due to its weight – 10.11 kg and the fact that it should be picked up and turned many times during assembly process.

Figure 4.3 fuse switch disconnector SZ 41

2. KE10.1N connectors -due to its large production volumes, simple process requiring only pick and place operations, noise during ultrasonic welding of plastic.

Figure 4.4 KE10.1N connectors

3. Mark cell - Labeling process of parts due to its high production volumes and simple requiring only pick and place operations.

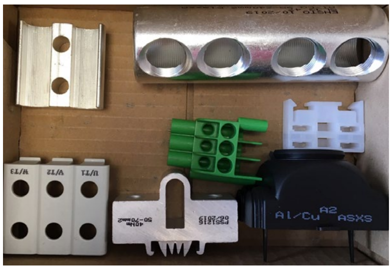

Figure 4.5 Labeled parts at MARK cell

4.2 Initial production process description. Current state

The project scope will include the marking process itself and will not include material supply to the workstation. The current state of a MARK cell was observed, typical work procedure was filmed and analyzed. Workstation personnel and management were interviewed to get insight on the possible problems they face in daily work on this workstation. See Appendix 1 for the interview.
Based on this information basic problems were defined [20] [17] [7]:

- Mark cell is used for marking wide variety of details, ordered by a client,
- Pull production
- Today marking is carried manually
- Challenges: Routine work, Wide variety of different details types (199 pcs.)

Mark cell uses 3 different printing technologies: laser, ink jet, and pad printing (also called tampoprint). Cell layout is represented on Figure 4.6.

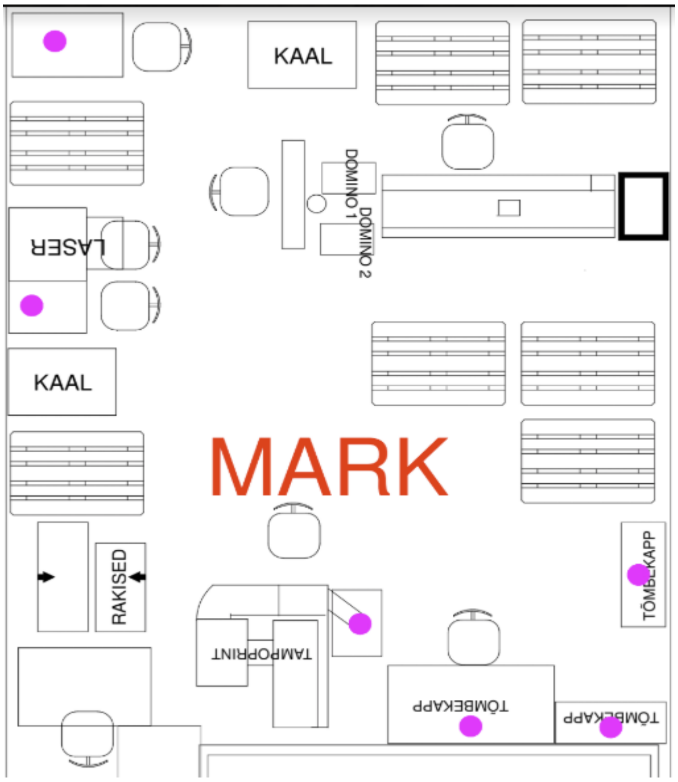

Figure 4.6 Layout of current state of MARK cell

Ink jet and laser printing is placed close to each other and takes almost the same floor area as tampoprint. [9]

The ink jet printing stations consists of two generic conveyors: small one for the printing station #1 and bigger one for the printing station #2 respectively.

The printer itself, consists of a print head connected to a stainless-steel cabinet by way of a flexible conduit. The cabinet contains an ink system and a controlling electronic system operated through a panel on the cabinet upper door. At the factory Domino A-200 series printer is used. It can print up to 4 lines in a variety of print formats and its maximum printing speed is 9 m/s. [24]

Figure 4.7 Ink Jet printer Domino A200

To obtain high quality printing and to slow down printing speed to adequate pace, suitable for employees, at the factory printer is set up at the following values [14]:

Ink Jet printer #1 station Domino A200 series, black ink - 13m/min (0.22 m/s)

Ink Jet printer #2 station Domino A200 series, white ink - 23m/min (0.28 m/s)

To understand productive capacity of the MARK cell, data from the company ERP system were gathered and transformed into simple tables, which easy to understand. Reported working hours for year 2018, forecast for year 2019, variety of different parts processed through the MARK cell is outlined in Table 4.4

Table 4.4 Hours spent for labeling in 2018 and forecast to 2019

Operation Description	Number of different parts (pcs)	Sum of Reported labor (h) in WC	Sum of Forecast (h) 2019-02 to 2020-01
Ink Jet printing #1 & #2	81	2645.9	3435.6
Laser printing	71	2251.2	2818.1
Tampoprint #1 & #2	45	566.9	871.2
N/A	1	8.9	0.0
Total	198	5472.9	7124.9

Due to wide variety of products, only most hours demanding Ink jet printing will be studied and tested further. All three printing techniques shares similar principles in work process and studied result of one technique could be transferred on others as well [29].

Current state analysis:

Details for marking arrives in two types of boxes: plastic boxes contain preliminary aluminum parts coming from other Ensto plants (Finland) and cartoon boxes, containing plastic parts, coming from either subcontractor – Plastone (Saue, Estonia) or Ensto plastic plant (Tallinn, Estonia).

Parts are generally picked from plastic bins. You can see them on the pictures, they are about 50x30x20 cm.

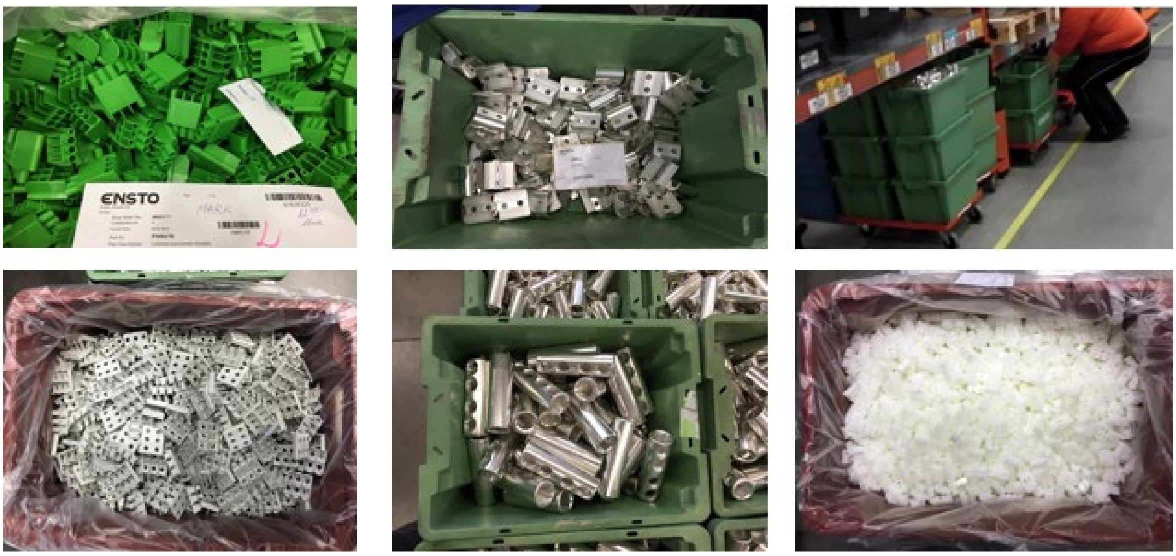

Figure 4.8 Parts processed through MARK cell

Parts are randomly oriented in the bins and overlapping each other. Basically, process could be described as follows:

Step 1. Employee takes detail from the box and put it on the conveyor

Step 2. Marking process performs automatically, when details is passing underneath the printer

Step 3. After marking, detail falls from the conveyor into the empty box.

Application is simple. Worker takes parts from a bin and places them onto conveyer belt. Then parts are being labeled automatically by Domino A200 printer. After they fall in an empty bin.

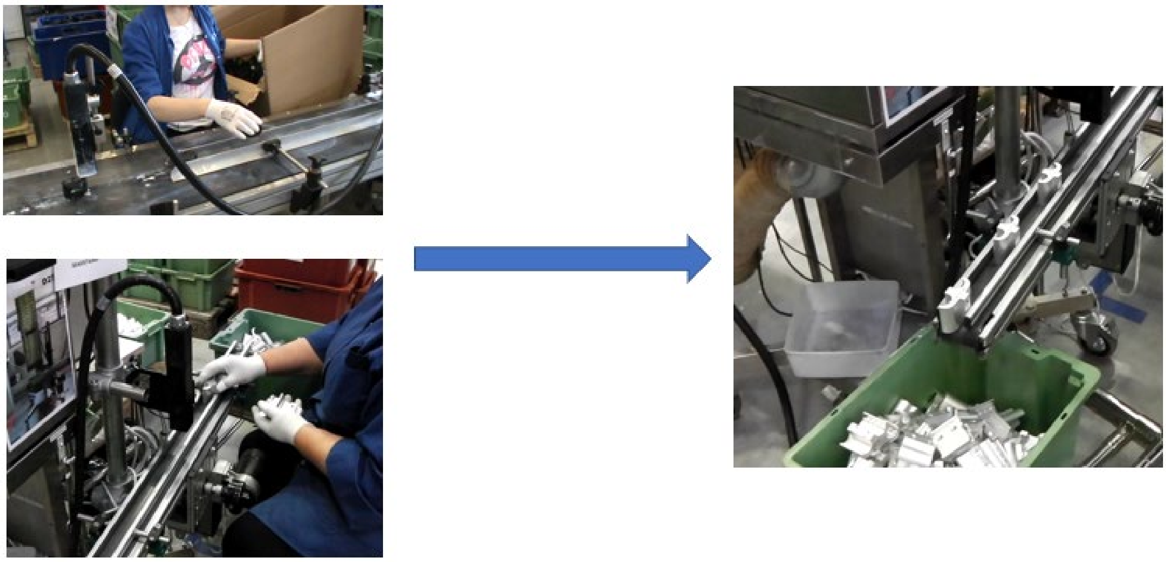

Figure 4.9 Labeling process

4.3 Production process modelling. Current state

To make improvements to the production processes it is crucial to understand how process is currently working. To do so, an IDEF0 (Integration Definition for Function Modeling) method will be used. It is a common modeling technique for the analysis, development, re-engineering, and integration of information systems and business processes. It is used to show data flow, system control, and the functional flow of life cycle processes.

IDEF0 is capable of graphically representing a wide variety of business, manufacturing and other types of enterprise operations to any level of detail. It is well-tested and proven through many years of use by government and private industry. [27]

IDEF0 may be used to model a wide variety of automated and non-automated systems. For new systems, it may be used first to define the requirements and specify the functions, and then to design an implementation that meets the requirements and performs the functions. For existing systems, IDEF0 can be used to analyze the functions the system performs and to record the mechanisms (means) by which these are done. The result of applying IDEF0 to a system is a model that consists of a hierarchical series of diagrams, text, and glossary cross-referenced to each other. [35]. For the processes modelling was used *AllFusion Process Modeler* 7.1 *of Computer Associates* company.

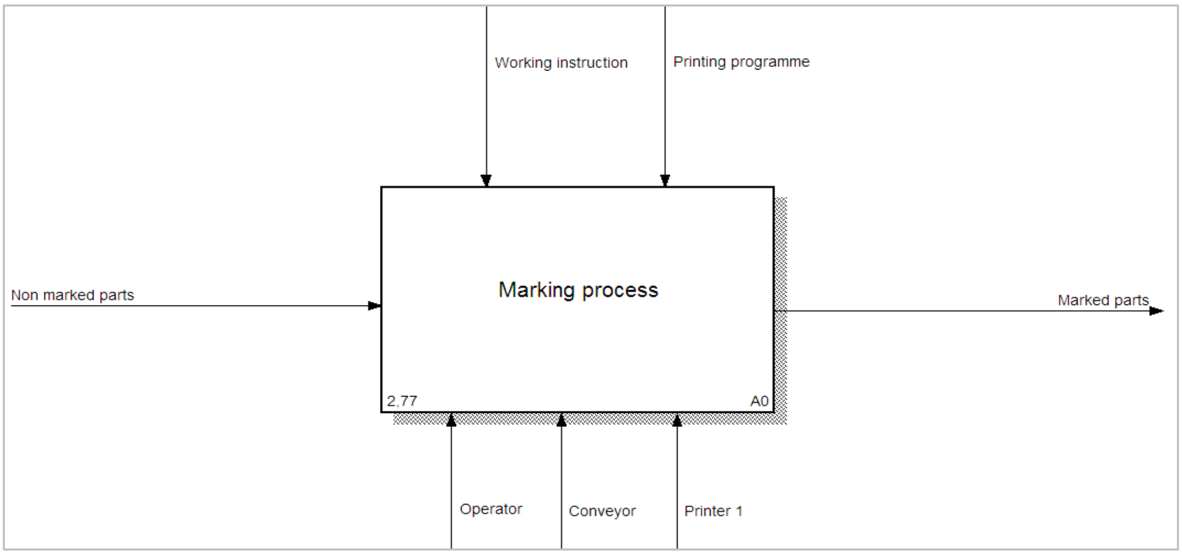

Figure 4.10 IDEF0 Top level diagram of the of current process

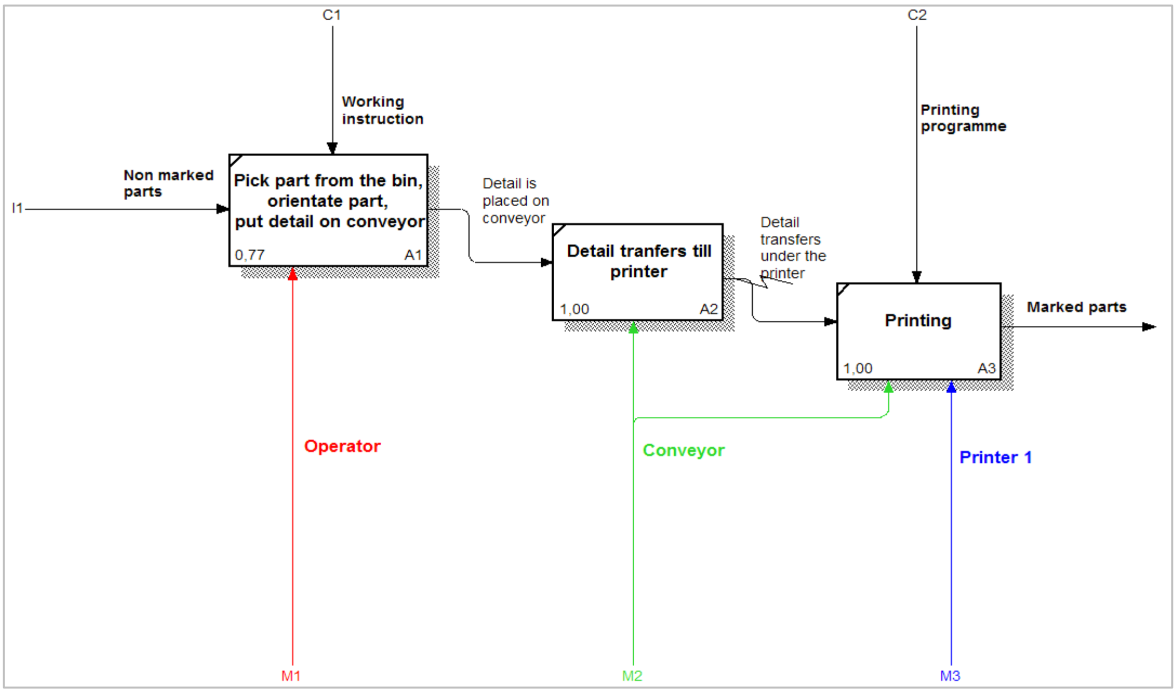

Figure 4.11 IDEF0 current labeling process description

Activity Number	Activity Name	Duration (Seconds)
A0	Marking process	2,77
A1	Pick part from the bin, orientate part, put detail on conveyor	0,77
A2	Detail tranfers till printer	1,00
A3	Printing	1,00

Figure 4.12 Report of activities duration of the current state, created by *AllFusion Process Modeler*

Figure 4.13 Simulation model of current state, created by *Enterprise Dynamics Simulation Software*

4.4 Developing a new solution. Future state

The purpose is to develop a collaborative work station, which will be capable to handle marking operations, which today is performed by hand. Another purpose is to make a showcase to a new technology and influence others to adapt it to other process in the future.

Having all needed equipment at the plant available, makes easier in the future to test collaborative robots in other tasks and test various application scenarios – some tasks are too difficult for the robot to handle and they should remain manual.

4.5 Determining application parameters and goals

1. Details should be picked from the default plastic boxes used in a factory
2. Workstation shouldn't occupy more space than it currently occupies
3. Cycle time shouldn't be the same or faster than it is with human workers. First, it is needed to achieve a state where it simply works – to learn from a new technology.
4. Takt time should be enough to cover another workstations demand.

4.6 Testing set-up description

For testing application possibility has been used UR3 cobot with a Pick-it M-HD camera because of the availability of this equipment in test lab and prerequisite from Ensto to use Universal Robots equipment. Pick-it M-HD camera works out of the box with Universal Robots, ABB, KUKA, Fanuc and Stäubli what enables to start using it without heavy programming skills with almost any contemporary robot. 3D camera allows to detect parts with different shapes, materials and sizes. See Table 4.5

Table 4.5 camera detection characteristics

3D complex shapes	Basic geometric features	Basic geometric shapes in a clear pattern
Typical applications: Picking complex parts	Picking random boxes, cylinders	Picking stacked boxes, rings
Typical detection times: 1 to 5 seconds	Typical detection times: 0.1 to 3 seconds	Typical detection times: 0.1 to 3 seconds

Machine vision camera can find parts in bins, boxes, on pallets, tables or shaker tables (vibratory feeders). Afterwards parts can be ordered, placed, picked or fed into a machine or a process / co-worker's hand

Table 4.6 Machine vision technical specs.

3D measurement method	Structured light
Image processing speed	10 Hz (100ms snapshots)
3D Camera accuracy	0,1mm
3D Camera repeatability	< 1mm
Power consumption	Idle: 70W, Heavy processing: 160W

The testing facility has been using a Pickit M-HD camera, placed stationary and Robotic 2-finger gripper.

Parts have been testing using a 300x00x200mm bin. Camera can be mounted stationary or mounted on the robot.

However, the stationary position gives faster detection times as the content of a bin can be seen in 1 capture - the shorter camera placed to the parts, the more details it can detect in 1 capture.

Otherwise if bin is too big, camera should be mounted on a robot and be programmed multiple robot detection positions to cover the larger area. The movement of the robot to navigate camera under the observing parts plus the detection time camera needs at each area increases drastically the cycle time. For example, if there are an euro pallet filled with objects, then it is needed 4 - 8 detection positions to cover the entire euro pallet.

Figure 4.14 Testing equipment

For the testing were chosen aluminum cylinders - MPTS248 and molded black plastic parts - PMR2547, which are handled in standard Ensto box, see Figure 4.15 Selected parts for testing are the most frequently using parts in the marking cell.

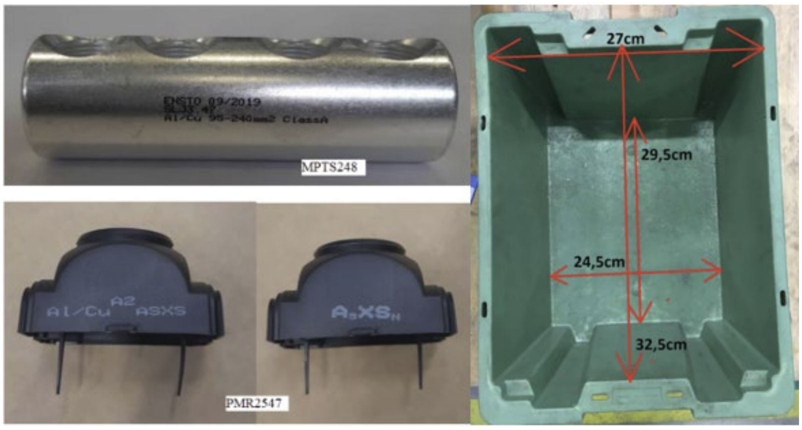

Figure 4.15 Test parts and its box

It is necessary to test different materials, shapes and colors because camera uses a structured light technique to detect parts in space. It projects a light pattern on the details which afterwards is scanned with a camera and calculates the distortion from other perspectives to create 3d image and calculate coordinates for the robot. This is optical system and due to that reflective, transparent and semi-transparent surfaces pose an issue because of double reflections and inner-reflections. Therefore, chosen parts are not only the most used but are the most challenging for the camera to detect. If it is possible to built-up working process with these parts and to get decent cycle times, then it will be possible to do so with other parts as well.

4.7 Testing aluminum cylinders.

Option 1

During testing were found that cylinders in the bin pose too many reflections.

Generally, the 3D image that camera creates for the cylindrical parts is acceptable, however due to excessive reflection it is impossible to define holes in the cylinders immediately from the bin, see Figure 4.16

Figure 4.16 A lot of reflection from cylinders lying in the bin. Some cylinders have a lot of distortion.

Nevertheless, it is possible to pick up cylinders from the bin, but for the exact dimensional orientation and rotation must be done a second step.

Some parts however can be detected with a right orientation straight from the bin without a 2nd visual check as the could accidentally be in right position. However, the majority of rest parts need a 2nd step because they have various orientations in the bin and would acquire a repick.

For the second step, machine vision can be used also, but this will increase cycle time significantly – up to 4 times, as cylinder should be turned around its axis several times allowing camera to check holes in every check. Moreover, holes can be detected only when cylinders are being stationary and do not moving. Detection time with option 1 is in average 3.52 seconds. However, to this time adds robot movements and time needed to detect cylinder in a new position. See Table 4.7

Table 4.7 Option 1 processing times

	Best scenario (rare)	Typical Scenario			
Detection from the bin	3.52 sec	3.52 sec	3.52 sec	3.52 sec	3.52 sec
Picking detail from the bin	2.83 sec	2.83 sec	2.83 sec	2.83 sec	2.83 sec
1st rotation to find holes	0	4.48 sec	4.48 sec	4.48 sec	4.48 sec
2nd rotation to find holes	0	0	4.48 sec	4.48 sec	4.48 sec
3rd rotation to find holes	0	0	0	4.48 sec	4.48 sec
4th rotation to find holes	0	0	0	0	4.48 sec
Placing cylinder on the printing conveyor	2.83 sec	2.83 sec	2.83 sec	2.83 sec	2.83 sec
Total time	**9.18 sec**	**13.66 sec**	**18.14 sec**	**22.62 sec**	**27.1 sec**

It is better to align cylinders in another way - with a help of a jig: a custom-made tool which is used to control the location of processed parts. To find out where the cylinders' holes are situated the jig should be able to rotate the cylinder around its axis. There are several options to do that. First, is to use custom made vibration jig, so that cylinders will rotate under the force of vibration, and holes will be found purely mechanically.

See figure 4.17

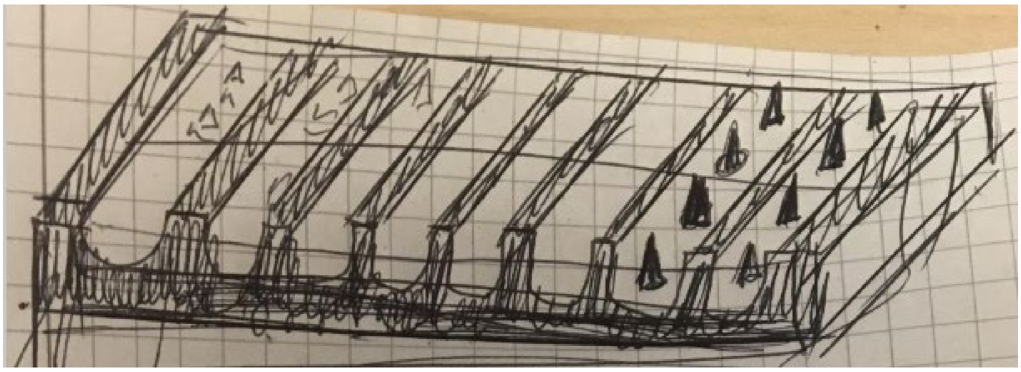

Figure 4.17 Vibratory jig concept

Second is to build up a jig which will use additional optical sensors to find the holes in cylinder and use electric motor to turn the cylinder around its axis. Sensor is measuring the distance. While cylinder is turning the distance remain relatively the same, but once sensor detects significant distance increase – the hole would be founded. See figure 4.18

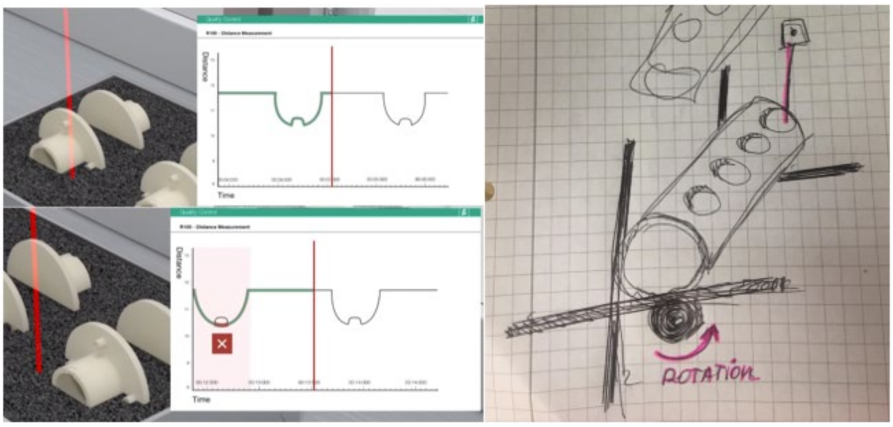

Figure 4.18 Laser sensor jig concept [36]

Option 2

In the second test run were observed how affects bin on the processing speed and how is possible to make detection time shorter. To cope with excessive reflection and to create higher contrast between cylinders and surrounding surfaces in the second test-run cylinders were placed on a black matt table. Parts were placed in chaotic order and were overlapping each other like it would be in a real life. When parts are lying on the table there are a bigger chance of correct axial rotation in the 1st step, but to get an exact orientation and rotation of a cylinder the 2nd step is needed just like in the first option mentioned above.

Option 3

Another option is to pick up cylinders from vibratory feeder and make an estimation between hole/no-hole cylinders. In this case robot will pick up only cylinders with the holes pointing upwards – this way it is not needed to orientate a cylinder using 2ns step – robot will assume by default that holes are pointing upwards and can place cylinder on a marking conveyor with 100% accuracy in the way that holes will not appear under the printing nozzle. See Figure 4.19

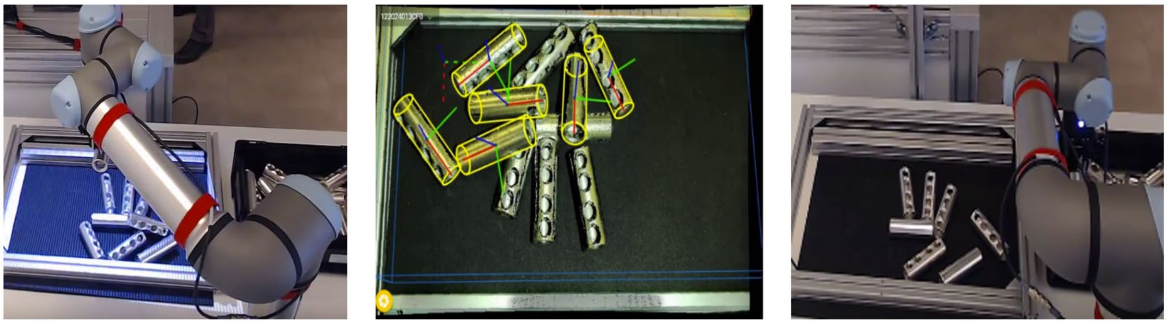

Figure 4.19 From left to right: picking cylinder, projecting structured light, detecting hole/ no hole cylinders for next cycle, placing cylinder onto conveyor

After 3rd test run it is clearly visible that having less objects in front of the camera significantly reduces detection time - from 3.52 second in a bin case to 1.16 seconds in surface case. See Table 4.8

Table 4.8 Detection times of 3rd test run

Cylinder #	Cylinders detection time (sec)	Total processing time, including cobot movements (sec)	Number of objects detected per frame (pcs)	Number of cylinders left on the table (pcs)
1	1.24	4.2	6.0	11
2	1.26	5.4	5.0	10
3	1.17	4.8	4.0	9
4	1.11	4.2	5.0	8
5	1.12	5.4	2.0	7
6	1.8	10.2	3.0	6
7	1.05	22.2	5.0	5
8	1.05	4.8	3.0	4
9	1.01	4.8	3.0	3
10	0.97	4.2	2.0	2
11	0.97	4.8	1.0	1
Total	12.75	75.0		
Average	1.16	6.82		

To save floor space, printing conveyor can be removed, and printing could occur while robot holding detail this would increase cycle time however.

4.8 Testing black plastic molded parts

During the test run it occurred that black plastic parts were too difficult to pick up from a bin with the two-finger grippers available in the lab. Details started to bend when the gripper tried to hold them between its fingers and were to slippery to stay fixed between the fingers of a gripper. Moreover, due to complex shape of details were tending to entangle when they are being gripped. Also, need to mention that complex shape did not allowed to detect a small lid on the bottom of the part either. Hopefully this is not affected overall detection performance.

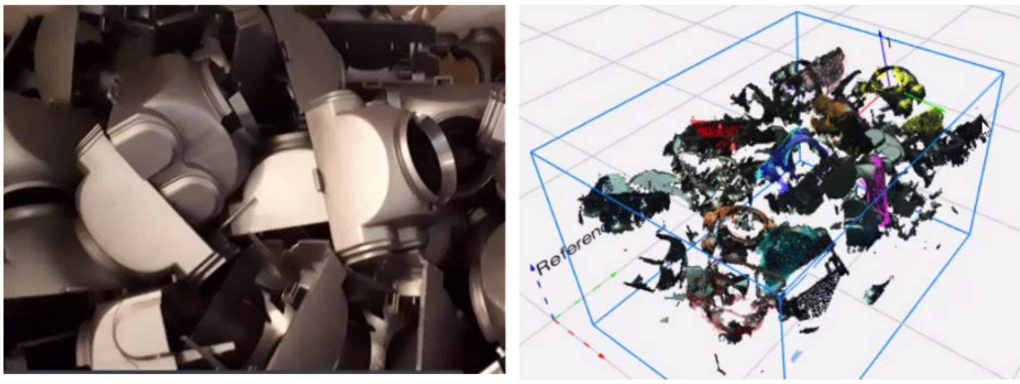

Figure 4.20 real view of plastic parts in the bin on the left. On the right machine vision interpretation of the same parts in the bin.

Because of these limitations only first part of the experiment was deducted – detecting details from the bin and measuring the process time. Second part of the experiment was omitted due to lack of suitable gripper in the lab (possible solution could be a vacuum end effector with suction cups).

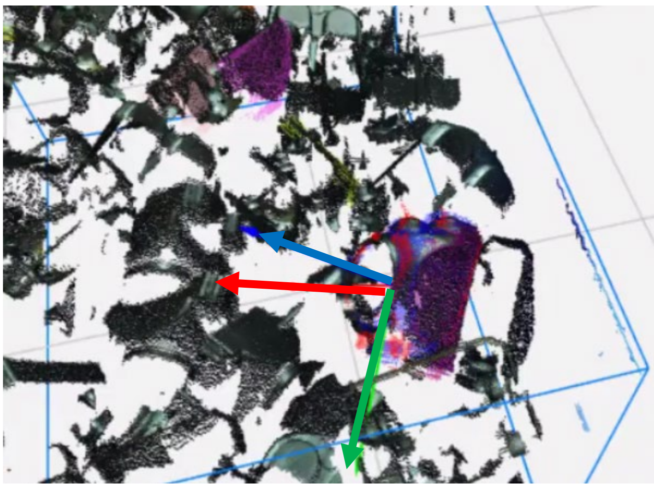

Figure 4.21 X, Y, Z coordinates of part in the bin

Average detection time for the plastic parts is 3.36 seconds. See Table 4.9 This time is comparable with the time cylindrical parts showed in a 1st test run. Thus, to decrease detection time overall recommendations remain the same as it was with cylindrical parts. [11]Vibratory feeder will decrease the detection time by having less parts and thus detections points in each capture. This will drop the detection time.

Table 4.9 Processing times of plastic parts

Plastic Part #	Plastic Part detection time (sec)	Number of objects detected per frame (pcs)
1	3.53	7.0
2	3.51	9.0
3	3.45	3.0
4	3.64	9.0
5	3.5	6.0
6	3.35	5.0
7	3.62	4.0
8	3.62	6.0
9	3.51	3.0
10	3.26	2.0
11	3.25	3.0
12	3.12	2.0
13	3.28	3.0
14	3.21	2.0
15	3.38	1.0
16	3.27	0.0
17	3.14	3.0
18	3.08	4.0
19	3.32	5.0
20	3.23	6.0
21	3.29	6.0
22	3.26	6.0
Average	3.36	

Disclaimer - detecting black parts is one thing, but picking them (gripper design, good pick points on the part) is another thing. This should be investigated more in the future work, using a suitable vacuum gripper.

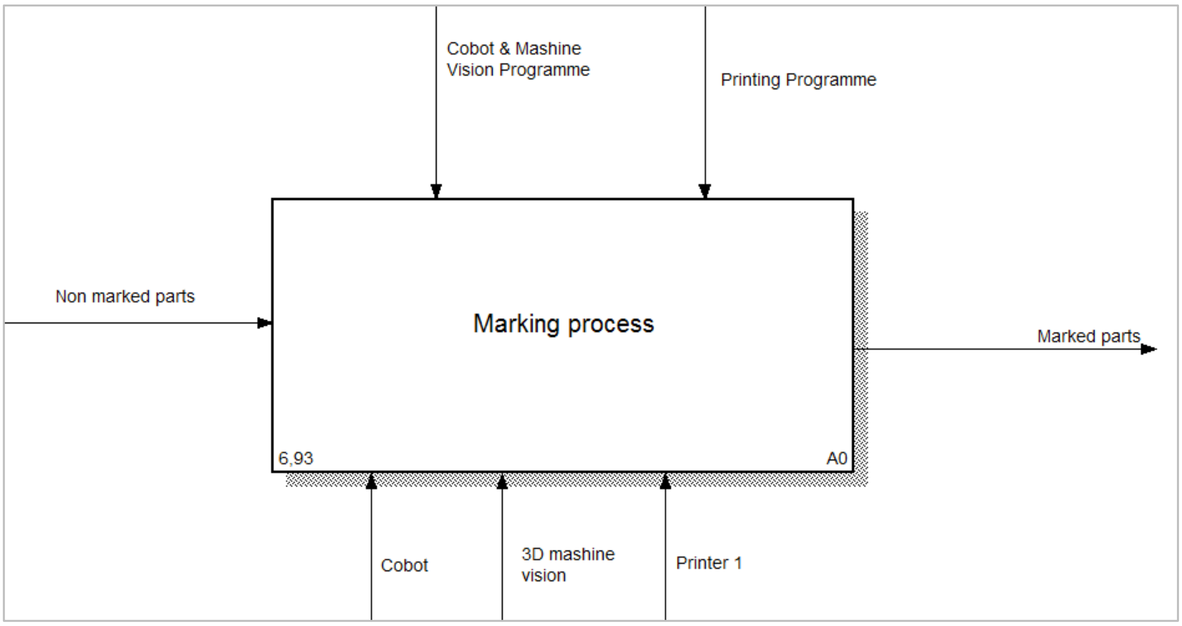

Figure 4.22 Top level diagram of the future process

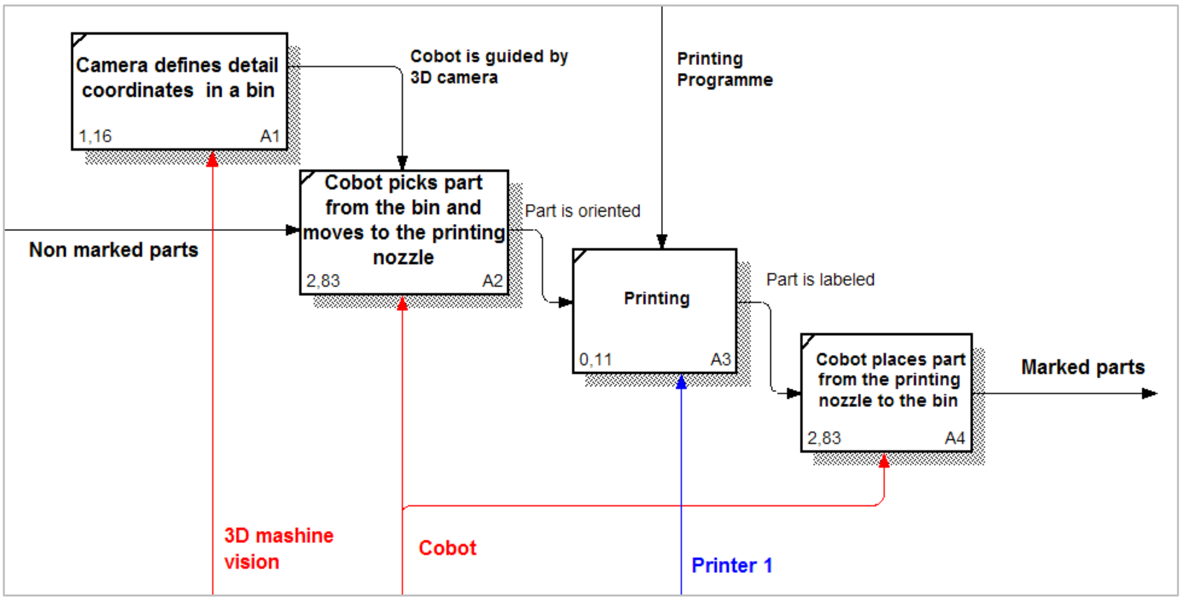

Figure 4.23 IDEF0 machine vision process description

Activity Number	Activity Name	Duration (Seconds)
A0	Marking process	6,93
A1	Pick part from the bin, orientate part, put detail on conveyor	3,99
A11	Camera defines detail coordinates in a bin	1,16
A12	Cobot picks detail from the bin and moves it to the printing nozzle	2,83
A2	Printing	0,11
A3	Cobot places part from the printing nozzle to the bin	2,83

Figure 4.24 Report of activities duration of future state, created by *AllFusion Process Modeler*

4.9 Test results

In the current work was observed operation time for labelling 1 box productions (70 pcs.). It is only operating time (OT). Was done analysis of OT time, for comparison it with the time which needs collaborative robot for performing the same operation.

The functional model performed by using IDEF0 method shows different time for labeling of 1 part:

1. for manual work 2,77 sec/pcs net time
2. for manual work 9,01 sec/pcs reported time
3. collaborative robot with conveyor 8.72 sec/pcs
4. collaborative robot direct printing without conveyor 6.93 sec/pcs

The difference in time arises since when using cobots, orientation of the part is required before installation on the conveyor.

According to British Standard Institute time study has been defined as "The application of techniques designed to establish the time for a qualified worker to carry out a specified job at a defined level of performance."

Let's look at what elements make up the operator's work time, see Figure 4.25 Cobot can work without all these allowances. the operator can fill the boxes with parts during the execution of operations

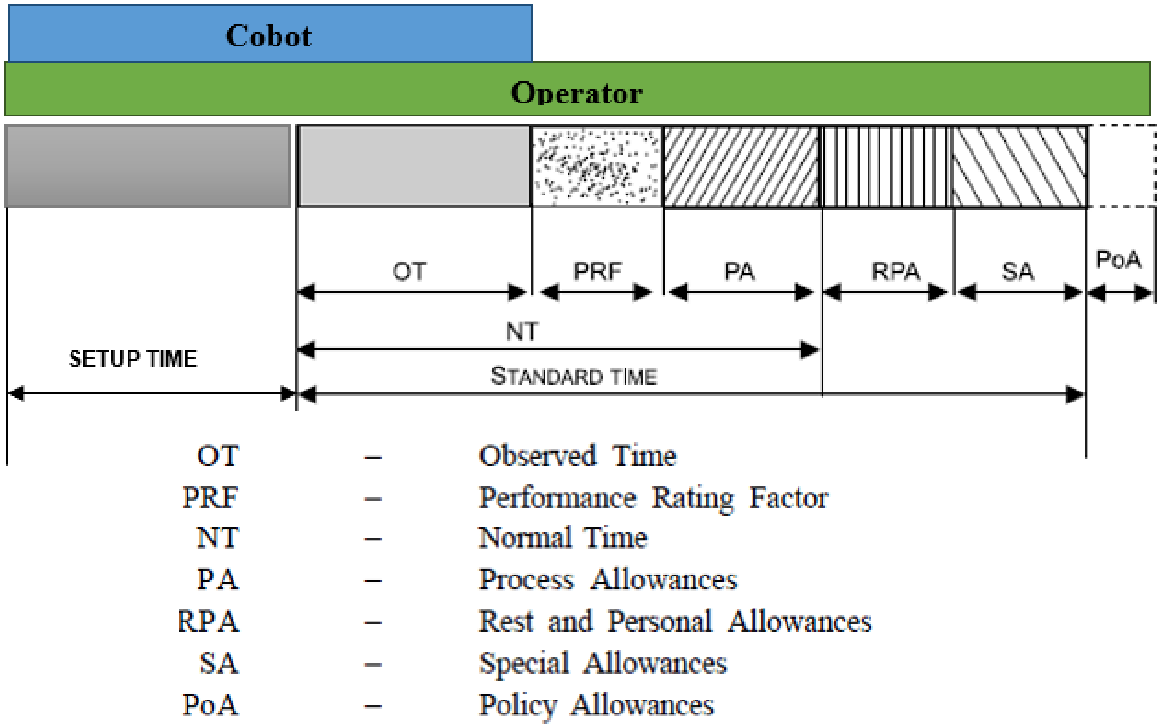

Figure 4.25 Components of time, adopted from Time study in Production and Operation Management [37]

Allowances

The normal time for an operation does not contain any allowances for the worker. It is impossible to work throughout the day even though the most practicable, effective method has been developed.

Even under the best working method situation, the job will still demand the expenditure of human effort and some allowance must therefore be made for recovery from fatigue and for relaxation. Allowances must also be made to enable the worker to attend to his personal needs.

Relaxation Allowance

Relaxation allowances are calculated so as to allow the worker to recover from fatigue. The amount of allowance will depend on nature of the job.

Relaxation allowances are of two types:

- fixed allowances and
- variable allowances.

Fixed allowances constitute:

1. Personal needs allowance:

It is intended to compensate the operator for the time necessary to leave, the workplace to attend to personal needs like drinking water, smoking, washing hands. Women require longer personal allowance than men. A fair personal allowance is 5% for men, and 7% for women.

2. Allowances for basic fatigue:

This allowance is given to compensate for energy expended during working. A common figure considered as allowance is 4% of the basic time.

Variable Allowance

Variable allowance is allowed to an operator who is working under poor environmental conditions that cannot be improved, added stress and strain in performing the job. The variable fatigue allowance is added to the fixed allowance to an operator who is engaged on medium and heavy work and working under abnormal conditions. The amount of variable fatigue allowance varies from organization to organization.

Process allowance:

A process allowance is an allowance of time given to compensate for enforced idleness of an operator due to the character of the process or operation on which he or she is employed. For example- an operator may not be able to work because he has to wait for a machine to complete its own part or he may be the member of an unbalanced line. These are all unavoidable delay for which the operator is not responsible. Process allowances are generally considered as 5% of the basic time.

Summing up all allowances and the fact that human requires from 30 minutes up to 1hour for the lunch, two 15 minutes breaks to rest prescribed by Estonian law and to participate in the meetings – it can be calculated that during 8h change a human worker can label 2411 aluminum cylinders:

Standard Time = (Observed Time) (Rating Factor) (1+ PFD Allowance) [37]

Standard Time = 9,01 sec * (7% + 4% + 5%) = 10.45 sec

8h working day = 28800 sec

Lunch and rest pauses = 3600

Human: (28800 – 3600) / 10.45 = 2411 pcs

Cobot: 28800 / 8.72 = 3302 pcs

Taking into consideration allowances, it is clear that robot will outperform human in a long run as it do not require to rest or go to the rest room and it's performance do not decrease as humans' one due to fatigue.

5 Feasibility and Economic Justification

To calculate the rationality of an automated solution purchase, it was necessary to define the costs for two scenarios: usage of human resources and the application of the robotic solution.

The fist scenario applies the consideration of human recourse usage reported time, which was stated to be 9,01 seconds/ per piece. In accordance to that information, the author was able to calculate the annual production quantity.

Table 5.1 Labor consumption and annual quantities

	2018	2019 Forecast
Labour hours reported	2645,91 (h)	3435,55 (h)
Annual production quantity	1 056 825 (pcs) per year	1 372 475 (pcs) per year - estimation

According to the official source (Ensto AS HR department), the average gross salary of an operator is 800 EUR gross, which means that the employer's cost would be 1070,40 EUR

1070/160 = 6,69 EUR per hour

Assuming that in in 2019 the salary level increased until 820 gross per month, then the labor cost for employer would be 1097,16 EUR per month, which give the value of:

1097,16 / 160 = 6,86 EUR per hour

Table 5.2 Annual labor costs

	2018	2019
Labour hours reported	2645,91 (h)	3435,55 (h)
Labour expenses (Gross+Social tax, per hour)	6,68 €	6,86 €
Total annual labour cost	17675,08 €	23567,87 €

Second scenario applied the usage of the robotic solution together with conveyer. The reported time of the operation was 8,72 seconds/ per piece, in accordance to the data given by the manufacturer, the robot is able to operate with. [25]

Table 5.3 Estimated Collaborative robot application costs

	Total
Robot cost	50 000,00 €
Additional sensors	6 000,00 €
Annual electricity consumption	430,00 €
Installation costs (engineering costs) 2 days	450,00 €
Annual maintenance cost (4% from the total value)	2 240,00 €

Considering the annual salary increase of 3 % at this specific position, the salary costs would consequently increase by 3% during the next several years and with the reference to this fact.

Linear annual depreciation method, when the cost of the machine is being divided by specific period linearly. The total cost the robot and additional service was divided by 6 years – the stated depreciation period. SeeTable 5.4

Table 5.4 Straight line robot cost application division

Year	Robot and sensors	Electricity	Installation	Maintenance	Total
2019	9 333,33 €	430,00 €	450,00 €	2 240,00 €	12 453,33 €
2020	9 333,33 €	430,00 €		2 240,00 €	12 003,33 €
2021	9 333,33 €	430,00 €		2 240,00 €	12 003,33 €
2022	9 333,33 €	430,00 €		2 240,00 €	12 003,33 €
2023	9 333,33 €	430,00 €		2 240,00 €	12 003,33 €
2024	9 333,33 €	430,00 €		2 240,00 €	12 003,33 €

Accordingly, with an application of a straight-line division, the maximum annual value of the robot would be 12 453,33 EUR. See Table 5.5

Table 5.5 Comparison of a human resource usage and automated solution application

Year	Human resource costs	Robot costs
2019	23 567,87 €	12 453,33 €
2020	24 274,91 €	12 003,33 €
2021	25 003,15 €	12 003,33 €
2022	25 753,25 €	12 003,33 €
2023	26 525,85 €	12 003,33 €
2024	27 321,62 €	12 003,33 €

Another option to calculate the rationality of the human resource substitution by the robot would be estimate the fact that the full value of the robot will be considered during the first year of the purchase. Table 5.6

Table 5.6 Robot cost considering the highest value for the first consumption year

Year	Robot and sensors	Electricity	Installation	Maintenance	Total
2019	56 000,00 €	430,00 €	450,00 €	2 240,00 €	59 120,00 €
2020		430,00 €		2 240,00 €	2 670,00 €
2021		430,00 €		2 240,00 €	2 670,00 €
2022		430,00 €		2 240,00 €	2 670,00 €
2023		430,00 €		2 240,00 €	2 670,00 €
2024		430,00 €		2 240,00 €	2 670,00 €

Considering the full robot value including installation costs to be considered in the first year of usage, then comparing human resource costs and robot costs, the robot usage would be rational at the 3th year.

Accordingly, the time period, when the robot is definitely paid off would be 3th consumption year.

Table 5.7 Financial estimation of the robot application paying off time

Year	Human resource costs	Robot costs
2019	23 567,87 €	59 120,00 €
2020	24 274,91 €	2 670,00 €
2021	25 003,15 €	2 670,00 €
Total value by 2021	72 845,93 €	64 460,00 €
2022	25 753,25 €	2 670,00 €
2023	26 525,85 €	2 670,00 €
2024	27 321,62 €	2 670,00 €

Accordingly, after 3th year robot cost will be paid off.

CONCLUSION

The main goal of this thesis was to analyze the rationality of the project to substitute the operator's work with the collaborative robot in any working center at Ensto Keila plant.
For the purpose to conduct the rationality analysis, the following tasks were done:

1. **Finding out the process(es), where it is more appropriate to use cobots.**

This observation showed that Ensto plant has a simple operation at a labeling station. Human tasks there are apathetic, monotonous and do not require high level of mental skills. This is the first prerequisite for a cobot possible integration. Also, labeling work center is characterized by other attributes of suitable working cell for cobot integration:

- It has frequent operator presence – operator utilization is 92.3 %
- It has low machinery utilization - printer utilization – 24.9 %
- It has high variability of labeled parts – 198 different parts are labeled now; this number will be however increased as Ensto is planning to label more details in the future.

In addition to already mentioned findings, it was found out that there are ergonomic problems also. As workers stated during interview there is very limited space at the working cell and workers required to move bins with parts a lot – roughly 31 000 bins per year. There are a lot of standing or sitting in one position for a long period of time, which causes back pain.
According to the questionnaire conducted, team leaders at Ensto Ensek stated that from their perspective there is a lot of set-up time and three workers at labeling work center are waiting from time to time for a technician to finish setting up. This can be eliminated in the future with full cobot implementation on all labeling machines of MARK cell and only one people will be needed for setting up and to arrange material supply from the warehouse and back.

2. **Analyzing the influence on the resources and efficiency using cobots**

Labeling work center with cobot is 3 times slower than human if we compare the operational time. So, to fulfill the demand in marked parts cobot should work in three changes just to match the efficiency of human worker. However, if we compare full reported time in MARK cell with cobot operating time it turns out that it is almost the same. All that means that if material supply from warehouse and back will be organized properly, cobots performance can be compared with humans' ones. The difference occurs because cobot's performance do not decrease with time (human gets tired with time and performs slower by the end of a working day). Cobot do not need to go to the toilet, to have rests, go to a team meetings etc. All that makes possible to substitute 3 workers with only one worker who will collaborate with cobots in the MARK cell.

3. **Provide cost benefit analysis**

The financial results showed that applying straight line depreciation method, the rational application of the cobot is seen at the 4th year of its usage. At the 4th year, the financial analysis showed that in case of human manual work, the cost would be approximately 72 845,93 EUR per year, when the collaborative robot usage annual cost was seen to be 64 460 EUR (including utility and maintenance costs). Accordingly, from the financial point of view, the author sees collaborative robot to be more rational for Ensto Ensek to apply.

Recommendations for further development:

- Use Asycube 530 flexible part feeder for part provisioning instead of a picking parts from a bin. Flexible part feeder uses intelligent 3-axis vibration to pre-orientate details for optimal surface distribution of bulk parts and components. It has full compatibility with all UR robots out of the box and enables to feed parts from 30 to 150 mm and the hopper size is 15 liters what easily contains the full standard Ensto bin, which is 10 liters

The fever details are on the viewpoint of a camera – the faster it detects parts, and the less errors in orientation process occurs. Also, with flexible feeder it is possible to use much more cheaper 2D camera (up to 5-10 times) instead of 3D camera, as no volume and depth measuring is needed when parts are being on a flat surface of flexible feeder.

- Use end effecter with a suction cup to pick up parts. It is more precise than two finger gripper when it comes to small details and also it is more gentle as well – fragile plastic parts are bending when using the two-finger gripper.
- Consider renting cobot, machine vision and flexible parts feeder to test the process from start to end for a couple of months directly at the plant. This will shed light on process reliability and provide personnel with a lot of information.

Concluding the thesis, the author considers the application of collaborative robot to be the rational solution for Ensto Ensek. According to the thesis results, the following advantages can be considered to purchase the collaborative robot:

- Elimination of manual work
- Elimination of ergonomically issues
- Technological advantage in the future of learning from new technology
- Help to stay competitive on the market
- Economically more effective

KOKKUVÕTE

Käesoleva töö põhieesmärk oli analüüsida, kui ratsionaalne on projekt asendada inimoperaatorid Ensto Keila tehase mingis osakonnas koostöörobotitega.

Ratsionaalsuse analüüsimisel tuli lahendada järgmised ülesanded.

1. Selgitada välja protsess(id), mille puhul on koostöörobotite kasutamine sobivam lahendus.

Vaatlused näitasid, et Ensto tehases toimub on lihtne operatsioon sildistamisosakonnas. Inimese ülesanded on seal üksluised ja monotoonsed ega nõua erilist vaimset pingutust. See aga on koostööroboti võimaliku integreerimise esmane eeldus. Samuti iseloomustavad sildistamisosakonna tööd teised koostööroboti integreerimiseks sobivad atribuudid:

- seal on operaatori kohalolek sageli vajalik– operaatori kasutamise määr on 92,3%
- masina – printeri – kasutamise määr on madal 24,9%
- sildistatavate detailide varieeruvus on suur – praegu sildistatakse 198 erinevat detaili; see arv aga suureneb tulevikus, sest Ensto kavandab tulevikus rohkem detaile sildistada.

Lisaks juba mainitule leiti, et on veel ka ergonoomilisi probleeme. Nagu töötajad intervjueerimisel märkisid, on osakonnas väga vähe ruumi ja töötajad peavad liigutama detailide mahuteid väga palju – umbes 31 000 mahutit aastas. Lisaks tuleb pikka aega seista või istuda samas asendis ja see tekitab seljavalusid.

Vastavalt läbiviidud küsitlusele väitsid Ensto Enseki meeskondade juhid, et nende vaatekohast kulub seadistamiseks palju aega ning sildistamisosakonna kolm töölist peavad aeg-ajalt ootama seadistamist tegeva tehniku järele. Seda saab tulevikus vältida, kui minna kõigi MARK-osakonna sildistamismasinate puhul üle täis-koostöörobotitele, nii et vaja oleks ainult ühte inimest, kes seadistab masinaid ja korraldab materjalide toomist laohoonest ning sinna tagasi viimist.

2. Kuidas kostöörobotite kasutamine mõjub ressurssidele ja töö tõhususele

Kui võrrelda operatsioonaega, siis koostöörobotiga sildistamisosakonna töö on kolm korda aeglasem kui inimtööjõu kasutamisel. Seega selleks, et täita nõudlust sildistatud detailide järele, peaks koostöörobot töötama kolmes vahetuses, saavutamaks samasuguse tõhususe nagu inimtöötajal. Kui aga võrrelda MARK-osakonnas kuluvat koguaega koostööroboti opereerimisajaga, siis tuleb välja, et need ajad on peaaegu võrdsed. Kõik see tähendab, et kui materjalide toomine laost ja sinna tagasi viimine on hästi korraldatud, on koostöörobotite sooritus võrreldav inimeste omaga. Erinevus tekib sellest, et koostööroboti sooritus ei vähene ajaga (inimene väsib aja jooksul ja töötab tööpäeva lõpul aeglasemalt). Koostöörobotitel pole vaja tualetis käia, puhata, käia koosolekutel vms. Kõik see teeb võimalikuks asendada 3 töötajat üheainsaga, kes töötab MARK-osakonnas koos koostöörobotitega.

3. Tasuvusanalüüs

Finantstulemused näitasid, et investeeringu lineaarse amortisatsiooni alusel ilmneb koostööroboti rakendamise otstarbekus neljandal kasutamisaastal. Finantsanalüüs näitas, et neljandal aastal oleks inimese käsitsitöö kasutamisel aastane kulu umbes 72 845,93 eurot, sel ajal kui koostööroboti kasutamisel oleks see 64 460 eurot (sisse on arvestatud ka elekter ja hooldekulud). Vastavalt eelöeldule leiab autor, et koostööroboti rakendamine on Ensto Enseki puhul igati mõistlik.

Soovitused edasiseks arenguks:

- Kasutada detailide etteandmiseks Asycube 530 paindsööturit selle asemel et neid mahutist võtta. Paindsöötur kasutab intelligentset 3-teljelist vibraatorit, mis orienteerib detaile eelnevalt nende koguse ja komponentide optimaalse pinna järgi. Sel on täielik ühilduvus kõigi UR robotitega ja see võimaldab sööta osi 30 mm-st kuni 150 mm-ni, kusjuures punkri maht on 35 liitrit, mis kergesti mahutab Ensto mahuti täissisu (10 liitrit).

Sildistatavad detailid on kaamera vaateväljas – mida kiiremini see need kindlaks teeb, seda vähem vigu orientatsiooniprotsessis ette tuleb. Samuti on paindsööturiga võimalik kasutada 3D kaamera asemel palju odavamat 2D kaamerat (5–10 korda odavam), sest detailid paiknevad paindsööturi tasasel pinnal ning pole vaja mõõta ei mahtusid ega sügavusi.

- Kasutage haaramiseks iminappasid. Kui tegemist on väikeste detailidega, on see täpsem kui kahe sõrmega haaramine ja pealegi veel õrnem – kui kasutada kahe sõrmega haaratsit, võivad haprad plastdetailid painduda.
- Kaaluge koostööroboti, masinanägemise ja detailide paindsööturi rentimist, nii et saate mõne kuu vältel kogu protsessi algusest kuni lõpuni otse tehases kontrollida. See heidab valgust protsessi töökindlusele ning annab personalile ohtrasti informatsiooni.

Lõpetuseks märgib autor, et koostööroboti rakendamine oleks Ensto Ensekis ratsionaalne lahendus. Vastavalt teesides esitatud tulemustele on koostööroboti omandamisel vaja silmas pidada järgmisi eeliseid:

- Saab likvideerida käsitsitöö
- Elimineeritakse ergonoomilised probleemid
- Õpitakse tundma uut tehnoloogiat, mis annab tulevikus tehnoloogilise eelise
- Aitab jääda turul konkurentsivõimeliseks
- On majanduslikult tõhusam

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APPENDIX 1 Anonymous interview with production personnel

An interview was made with a team leader and workers who have previously worked with the labeling station. The purpose was to find possible problems human workers experience with the labeling process at current state of MARK cell.

Interview summary is outlined below:

1. **How often details are incorrectly placed on the conveyor and marked inappropriately?**
   Not often, very rarely. If you do not leave enough space between the components, then the printer will not print properly.
   What are ergonomic problems do you experience with the MARK cell?
   Lack of free space, Standing or sitting long period of time. The back position is not comfortable, there are plenty of boxes to lift. The gap between details must be monitored all the time.
2. **What are other problems do you experience with the MARK cell?**
   Setting up, especially the tampo printer. Changing the product takes a lot of time, the employee has to wait for the time of setup.
3. **If you would have a possibility to choose your workplace. What work cell would you choose:**
   a) **MARK cell** - If you can work with different machines then it is ok, because labeling station doesn't have a screwdriver, but if there is only one machine to work with then it is not good work – it is very routine work.
   b) Any of other work cell(s). Name 1-3 of them. Why?

SO3 - more different operations and eyes not get tired

FBOX - not very heavy and at the same time interesting (different operations)

KSX - very many different operations and different tasks, interesting to work

JONO1 - many different operations and interesting to assembly