TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical
and Industrial Engineering

DEVELOPMENT OF ROBOTIC ASSEMBLY CELL FOR ELECTRONIC DEVICES

ELEKTROONILISTE SEADMETE JAOKS ROBOTISEERITUD KOOSTERAKU ARENDAMINE

MASTER THESIS

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Tallinn 2024

(*On the reverse side of title page*)

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Department of Mechanical and Industrial Engineering

THESIS TASK

Student: Juri Kuznetsov, 211971MARM
Study programme: MARM Industrial Engineering and Management
Supervisor(s): Jüri Riives, +372 501 0107

Thesis topic:
(in English) Development of a robotic assembly cell for electronic devices.
(in Estonian) Elektrooniliste seadmete jaoks robotiseeritud koosteraku arendamine.

Thesis main objectives:

1. To conduct a comprehensive analysis of the prospects for automating the assembly process through the integration of robotic systems, while establishing rigorous criteria for assessing their suitability.
2. To examine potential applications of small robots in automating assembly processes and to assess the extent of human involvement in man-robot cooperation.
3. To create clear guidelines for the efficient use of robot-cell applications in assembly processes.

Thesis tasks and time schedule:

No	**Task description**	**Deadline**
1.	Master’s thesis structure. Research objectives	6.03.2024
2.	Main topics of the master`s thesis: robotization suitability analysis, robot-cell design, human role in robot oriented workplace, efficiency analysis	8.04.2024
3.	Completion of master’s thesis. Updating and making corrections. Formalization of work.	16.05.2024

Language: English **Deadline for submission of thesis:** ‟.20.”May 2024a

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PREFACE

The author selected the specified topic to explore the automation of simple yet repetitive manufacturing processes. The apparent simplicity of these actions often obscures the potential for automation and cost reduction within the process. As a result, enterprises tend to address these challenges by employing low-skilled workers. Robotization could be the one of the ways to make the production more efficient, raise the customers satisfaction and ensure production quality. The author has questioned the feasibility of automating the assembly process of simple and uncomplicated objects in today's reality. They aim to explore whether small and medium-sized businesses can access the benefits of automation, traditionally leveraged by large manufacturers since the mid-20th century.

The course "Industrial Robotics and Advanced Manufacturing," which was undertaken at TalTech in the spring semester of 2023, provided valuable support to the author in this endeavour.

The author is profoundly grateful to their supervisor, Jüri Riives, for dedicating time and providing consistent support throughout the research process, and Madis Käärma, for his support in design and creation of product functional model.

Keywords: assembling, screw tightening, robotization, scara, cobot, master thesis, production, robot cell design, production cycle optimization, workplace performance.

List of abbreviations and symbols

ERP – enterprise resource planning
IR – industrial robot
Cobot – collaborative robot
EOAT – end-of-arm-tooling
MB – main board
Small mechanics – fastening or connection components, such as screws, washers, etc
SMA – surface mount assembly
AOI – automated optical inspection
OHS – occupational health and safety
DoF – degrees of freedom
SCARA - Selective Compliance Assembly Robot Arm
TCP – tool center point
QC – quality check

INTRODUCTION

The author's interest in this work is rooted in their professional journey. Beginning their career in the early 2000s, they witnessed the influx of foreign employers to Estonia seeking skilled yet cost-effective labour and leveraging the country's advanced electronic and informational infrastructure. Estonia's streamlined administrative processes, swift banking and tax systems, and the ease of starting businesses swiftly attracted investors. Despite lower wages, the qualified workforce, stemming from experience in Soviet-era enterprises like "Punane RET," "Volta," and "Eesti Kaabel," facilitated the establishment of electronics and communications equipment enterprises in Estonia.
In 1999, Estonia joined the World Trade Organization, and in 2004 - the European Union.

The arrival of foreign companies brought to Estonia both new ideas and a real spirit of competition. Cheap labour has ceased to be the main argument; product quality and production efficiency have become more important arguments. Production, planning, and logistics have undergone a digital transformation, integrating management and planning systems. Eventually, the author found a disconnect between his work experience in logistics and production and the knowledge gained during higher education. While scientific articles discussed Industry 4.0, the Internet of Things, and Big Data processing, the author observed enterprises making hesitant strides, merely installing robots in select packaging or transport areas. CAD system designs were printed on paper and handed over for manual implementation in production, highlighting this disparity. This sluggish evolution didn't raise concerns during the prosperous early years of the 21st century. However, everything swiftly changed on a global scale with the arrival of 2020.

The emergence of the COVID-19 crisis in late 2019 brought significant changes. Economies experienced a dual impact: reduced product demand due to consumer caution and industry shutdowns in major raw material supplier countries. Furthermore, global production faced another setback in February 2022 with the Ukraine military crisis. Calls for sanctions against major energy and metal market players, like Russia and China, prompted urgent reformatting of production chains. Responses varied, with some companies closing facilities, redistributing capacities, or shifting production to the United States [1].

The challenges of 2020-2022 caused crises of overproduction, when planned and paid batches of goods could not find their final consumers. This served as a signal to revise the policy of uncontrolled production and excessive saturation of markets with goods. Crises of overproduction are an integral part of the capitalist economic model [2]. However, overproduction poses a particular threat to goods with flexible demand. Essential items like food, hygiene products, medications, and fuel maintain a steady demand. On the other hand, certain products like electronic gadgets, communication devices, furniture, or automobiles experience flexible demand, potentially plummeting to zero if their costs become prohibitively high [3]. Since this study is related to the manufacturing of a product with flexible demand, the author raised the issue of increasing the efficiency of such production, and therefore reducing its price and increasing profits.

In this thesis, the author explores the possibility of creating a workstation for robotic assembly of small electronic devices with minimal human involvement, suitable for small and medium-sized enterprises. This is considering that simple processes are often overlooked for automation, as an ordinary person can handle such tasks with minimal training and equipment.

The research consists of five chapters. The first chapter delves into the use of robots in production and delineates their characteristics. Following this, the second chapter scrutinizes a specific product slated for robotic assembly. The third section concentrates on selecting the appropriate robots, End-of-Arm Tooling (EOAT), and designing the workspace, drawing insights from the previous chapter's data. Subsequently, the fourth part navigates through the implementation tasks involved in integrating the "robot + EOAT + workstation" system into product assembly, while also addressing associated risks. Finally, the fifth chapter tackles the project's cost analysis and evaluates the performance of this system.

1. USING ROBOTS IN ASSEMBLY OPERATIONS

During the research, the author constantly studied articles on industrial robotics and analysed trends in the use of robots in production, as well as directions for the development of robotics for the next decade. This was done with the aim of writing a modern study, so that the result, if possible, could be consistent with industry development trends. In addition to the well-known information about the growth of the market for both robots and cobots [4], the author discovered interesting features of the development of robotics designed for manufacturing tasks. Latest robotics exhibition iREX 2023 which claims to be the world’s largest robotics show, revealed new future paths of development of robots and cobots. Key industry players showcased advanced cobots like Yamaha's seven-axis cobot and Universal Robots' UR30 for larger loads. FANUC, DENSO, and UR demonstrated applications like torque tightening, precision assembly, and welding. “Zero teach” technology - a combination of machine vision and advanced automated path generation model - becomes a new trend for robotic manufacturers: FANUC demonstrated automated path creation for arc welding, while both FANUC and Yaskawa exhibited programming-free solutions tailored for effortless palletizing [5]. OMRON and Yaskawa showcased automated lines designed for handling different product mixes and volumes. These setups, featuring mobile cobots and layout-free production, aim to provide adaptability within the production environment while managing on-site data for continuous improvements in productivity and quality. The International Federation of Robotics pointed out two crucial trends in robot development in 2023: improved energy efficiency and user-friendly programming interfaces. These aspects are vital for effective robot utilization in production. Energy efficiency reduces operational costs, while simplified initial programming (not reprogramming) enables trained operators to quickly adjust robot operations. This enhances production flexibility and saves money [6].

Combining these trends paints a clear direction for the evolution of production robots: envision a cost-effective, user-friendly robot equipped with advanced self-learning capabilities. It seamlessly integrates into automated systems made for flexible, high-mix production scenarios, with varying volumes and product types.

Robotization emerged as a result of humans wanting to offload difficult and repetitive tasks onto something or someone else. Technological advancements enabled this workload to shift from living beings to machines, “programmed” initially through mechanical systems like springs and gears, and later through digital programming.

In recent decades, the integration of robotics in industrial processes has ushered in a paradigm shift within the manufacturing and production landscape. This transformative trend is propelled by a convergence of factors, including rapid technological advancements, heightened demands for efficiency, and the imperative to remain competitive in an ever-evolving global market. With recent developments in automation technology, robots have become an indispensable component of modern production industries, revolutionizing traditional workflows, and augmenting human capabilities.

The advent of advanced sensors, machine learning algorithms, and sophisticated control systems has endowed robots with high levels of adaptability and precision. As a result, they have seamlessly assimilated into diverse sectors, from automotive assembly lines to pharmaceutical manufacturing, fundamentally altering the way tasks are executed. This integration has not only bolstered productivity but has also elevated safety standards, particularly in environments that pose inherent risks to human workers.

Such positive changes also come with limitations. Different types of robots have their own characteristics, dictated by the tasks they were designed to perform. Robotization began in the mid-20th century in the automotive industry - the first digitally programmable industrial robot, UNIMATE, went into operation at the General Motors plant in New Jersey in 1961 [7]. However, during that period, robots were primarily viewed as substitutes for human labor rather than as aids or collaborators for human workers. Robotic technologies were developed to mimic human actions with the intention of replacing human workers.

1.1 Industrial and collaborative robots

International standard ISO 8373 „Robots and robotic devices” makes clear in defining manipulating industrial robot as „an automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications” [8].

Robots find application in a wide array of scenarios and for various purposes. In situations where factors like confined spaces, air quality, or other hazardous conditions are a concern, robots are employed in manufacturing processes where human presence may be impractical or unsafe [7]. Both in commercial and industrial settings, robots have been and continue to be utilized worldwide due to their ability to perform tasks at a lower cost while exhibiting greater precision and reliability compared to human workers. However, IR is a potentially dangerous robotized mechanism and IR’s working zone must be separated from the manned area with a fence [Figure 1] to avoid accidents. The high cost of an industrial robot, as well as the difficulty of setting it up, make the issue of purchasing it for small firms almost insoluble.

Figure 1.1.1. ABB industrial robots at work [9]

Nevertheless, humans remain the most adaptable component in the production process. A person can be trained swiftly, exhibiting intricate and accurate movements. Moreover, individuals possess the cognitive abilities and accumulated experience that enable them to approach problem-solving with creativity. Hence, human involvement in production is both essential and advantageous.

Robots can perform complex, monotonous, utilitarian tasks. According to Karasek [10], people are more prone to perform tasks that involve both creativity and a fairly high degree of control and responsibility. Given this, the creation of robots to directly assist humans on dull and monotonous tasks was only a matter of time.

In the late 90s of the 20. century, the first collaborative robots had come to the stage. The idea behind this was to give human a helper, who would not exceed his speed, his power, would be less dangerous to work with, and would allow the possibility itself of working inside the work cell along with the human. Cobots were initially called "programmable constraint machines", highlighting a passive and safe method for allowing a computer to create a constraint surface for a human user (and optionally a payload) to follow [11].

The ISO standard for Robots and robotic devices – Collaborative robots (ISO/TS 15066:2016) defines the collaborative robot as a „...robot designed for direct interaction with a human within a defined collaborative workspace" [12]. The collaborative workspace is a space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation [12]. Collaborative robot, collaborative workspace, and human operator nearby, form a complex whole, which can be defined as a collaborative robot system. This system is a system in which human and robot system can occupy the same workspace [Figure 1.1.2], at the same time, while the system is in automatic mode.

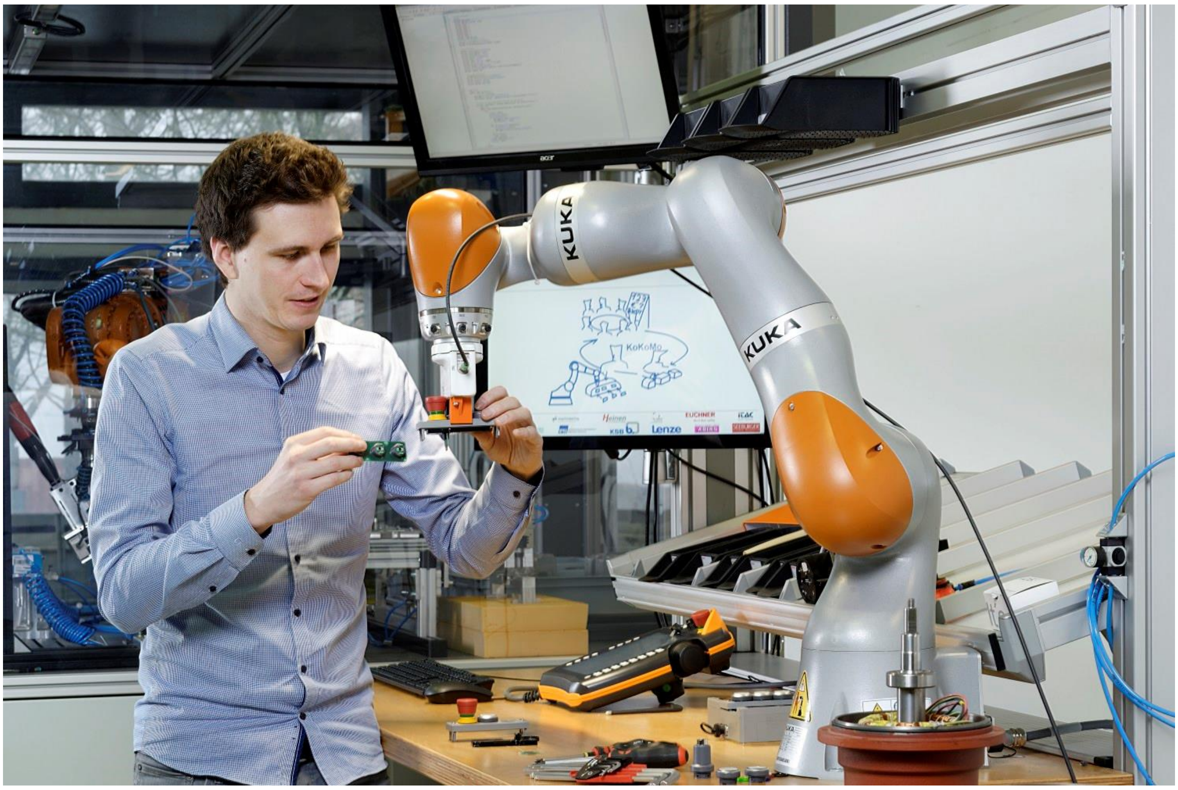


Figure 1.1.2. Cobot collaborates with human [13]

These definitions explain the way of how the human will be interacting with a collaborative robot on the shopfloor. Direct interaction with a cobot should be safe for human worker, for this reason cobots are equipped with a set of sensors and programmed to have in-build safety features, which are not present in IR. Collaborative capabilities are safety monitored stop, hand guiding, speed and separation monitoring, and power and force limiting—can all be achieved using sensors, control systems, and peripheral devices [14].

Table 1.0.1.1 Features of industrial robots and cobots [15], [16]

Characteristic	**Industrial robot**	**Cobot**
Role	Replacing a worker	Assisting a worker
Human interaction	Commands, and programming assigning locations movements and gripping	Intelligent interaction: gesture recognition, speech recognition, and anticipating operator moves.
Camera and computer vision	External camera, and external system when exists.	Built -in standard (as part of the cobot), coupled with artificial intelligence.
Batch	Large	Small
Variability	Little	High mix
Payload	May be heavy	Not heavy
Work envelope	Essential and rigid	Not relevant
Reprogramming	Rare	Frequent
Physical disruption	Mostly hazardous. Setup required for re-initiation	Safe with easy re-initiation
Deployment	Complex programming	Quick and easy programming
Agility	Rapid motions	Slow motions
Safety	Must be separated	Can share same workstation with human
Ability to work in dynamic environment, possibly with moving entities	No	Yes
Focus	On robot	On tooling
Investment	Larger	Smaller
ROI	Larger	Faster

So, there are two different types of robots under consideration, both designed for work in manufacturing. Both have their own characteristics that can become both strengths and weaknesses. Features and qualities are described in [Table 1.0.1.1]. Generally, cobots allows to create more flexible and quickly modifiable production systems for high product mix, with direct involvement of human workers, without significant expenses, and with faster ROI. On the contrary, IR is best for mass production, with rare changeovers, operating with heavy tools or objects, in man-less environment, or behind the physical border. Their ROI is larger and robotization of process with IR requires significant funding and complex personnel training.

However, progress does not stand still, and developments are emerging in the market that allow transforming hazardous industrial robots into much more powerful and faster versions akin to collaborative robots. Industrial robots can be equipped with adapted interfaces simplifying robot programming [17], and fitted with a manipulator casing made of contact sensors, or safety flange [18], instantly halting the manipulator's movement upon collision with an obstacle.

1.2 Opportunities to improve the assembly process through robotization

Assembly plays a crucial role in manufacturing, as the final product is achieved through this process. Assembly transcends mere part integration; it stands as the pinnacle process in manufacturing, consolidating design, engineering, manufacturing, and logistics efforts to yield functional objects. Assemblies emerge from this process, yet they also embody the culmination of a multifaceted design journey. This journey entails delineating the requisite functions of the item and subsequently specifying physical entities (parts and subassemblies) that harmonize to fulfill these functions [19].

Given the complexity of products, they can consist of a few, tens, hundreds, or more details, often organized into subassemblies. The complexity of the assembly system is closely tied to the intricacy of the assembly itself. Assembly can take place at a fixed workstation or on an assembly line, with the latter providing opportunities to enhance productivity and streamline the assembly process. There is a notable trend towards utilizing robots in assembly to shorten cycles and enhance flexibility [20]. The use of IRs removes a person from dangerous or difficult processes. The use of collaborative robots facilitates efficient task-sharing between humans and robots within a company.

The presence of many parts, as well as the general complexity of modern products, requires a high level of training of personnel, their resistance to stress and the ability to accurately perform repetitive steps of the assembly process, time after time, throughout the entire work shift. Such qualities must be systematically cultivated in the team and must also be adequately remunerated. Both points involve the employer’s constant costs for personnel and their training, the need to pay for vacations, sick leave, and adjust the schedule during seasonal illnesses.

These costs must be covered by either the manufacturer or the consumer. In the first case, this will reduce the company’s profit; in the second case, this will affect pricing and demand: the consumer will look for a better offer on the market from the company’s competitors.

The integration of robotics in the product assembly process, despite the initial investment, provides enduring advantages for the company. There are several opportunities in assembly process robotization [21]:

- minimize risks;
- minimize product handling time;
- minimize damage to product;
- minimize failure opportunities;
- minimize operator intervention;
- minimize times of product change over;
- minimize maintenance time;
- optimize operational performance;
- assembly data collection and analysis;
- scalability of production according to demand.

Robotization eliminates the need for maintaining a large assembly workforce and associated expenses. By automating routine and mentally taxing tasks, robots allow employees to focus on more critical duties. This transition improves result consistency, leading to enhanced overall quality. Furthermore, the capacity of robots to execute predefined programs contributes to the flexibility of the assembly process. For example, a standardized robotic workstation can simultaneously tighten screws on diverse products with standardized small mechanics, varying only in the quantity and sequence of screw tightening.

Also, components and parts will be processed with greater care and precision, eliminating the risk of scrapping the sensitive electronic component in case it was accidently dropped to the floor by exhausted operator.

In addition to saving costs, improving product quality, and enhancing process flexibility, incorporating robots into the assembly process enables a company's existing employees to fully leverage their potential. This empowers them to approach their tasks with greater creativity, without the worry of adding excess complexity to their workflow. The author sees these considerations as compelling reasons to explore the integration of robots into the assembly process.

1.3 Assembling tasks in production

The assembly process is a set of operations involving the joining, coordinating, fixing, and securing of parts and assembly units to ensure their relative positioning and movement, as required by the functional purpose of the assembly unit and the overall assembly of the device. The labor intensity of assembly processes in the overall production volume of modern instruments ranges from 30% to 50%. The assembly process encompasses the mechanical assembly of parts, the assembly of electrical components, soldering them together, as well as setup, adjustment, and quality control operations [22].

Mechanical assembly of parts refers to the process of joining individual components or pieces together through physical means such as fastening, fitting, or connecting, without the use of electrical or electronic elements. This can include techniques like **welding, screwing, bolting, riveting**, or other mechanical methods to securely assemble parts into a functional unit or subassembly [23].

The assembly of electrical components is commonly done by welding and soldering. **Welding** is the process of using heat or pressure to create a strong joint between components, primarily for metal assembly. Welded joints are rigid and permanent. Welding necessitates specialized equipment and protective gear due to its inherent hazards [23].

Adhesive bonding (gluing) can also be used as a method for assembling the product. Adhesives have different properties and curing times, allowing them to bond parts made of various materials. For instance, cyanoacrylate bonds parts very quickly, while epoxy resin-based glue takes longer to cure but creates an almost inseparable connection. Adhesive bonding requires good ventilation in the workspace, and often, preparatory work on the parts is necessary (cleaning, degreasing, priming) to ensure a strong adhesive bond [24]. As evident from the provided data, adhesive bonding has both distinct advantages and significant drawbacks. Moreover, working with adhesive substances often requires skilled personnel [24].

Components setup and adjusting are processes which are mostly done by hand, those operations are required in case of problematic or complex design. Quality control in assembly is required to ensure that the product corresponds to the standards or requirements.

1.4 Tools for robotized assembling process

The assembly of a product involves a series of standardized, repetitive actions. The need for consistent quality, coupled with the high repeatability of these actions, necessitates consideration of process robotization. However, a robot, in essence, serves as an exceptionally precise platform for executing pre-programmed movements and operations. To engage in productive tasks, the robot must possess the capability to utilize specific tools that facilitate the transformation of the product over time. Tool can be a dedicated part of the robot manipulator, can be connected via tool changer (so the tool may be changed when needed) or can be a part of the “multitool” solution, when one EOAT has two or more tools at the same time.

Figure 1.4.1. Options for attaching the EOAT to the robot arm [25], [26], [27]

A wide array of diverse robot tools is presently accessible in the market [28]. These tools enable robots to engage in tasks such as object manipulation encompassing pick-and-place operations, product holding and transportation, and the affixing of components through methods like screwing, gluing, welding, soldering, or riveting. Additionally, robots exhibit proficiency in tasks like applying paint or lubricants, all the while conducting quality assessments employing machine vision and integrated sensors. Provided below is a concise compilation of EOAT tools suitable for deployment on robots during product assembly.

Grippers are the most used EOAT in robots. They are used for picking up and manipulating objects of various shapes and sizes [29].

Tool changers are used to switch between different types of EOAT quickly and easily. They are commonly used in industries that require frequent changes of EOAT [30].

Cameras are used for visual inspection and quality control. They can be mounted on the cobot's end effector to provide a close-up view of the workpiece.

Force sensors can be used as an EOAT for cobots to provide feedback on the force being applied to a workpiece or object. These sensors can be integrated into various types of grippers and other end effectors [31].

Screwdrivers can be used as EOAT for cobots to perform various tasks, such as assembly, disassembly, or maintenance operations that require precise torque control. Screwdrivers can be equipped with sensors, such as torque sensors, to ensure that the correct amount of torque is applied to the screws [32]. A **screw feeder** can be a separate component that is used in conjunction with a cobot screwdriver.

Dispensers [33] can be integrated with robots to automate the dispensing of liquids, adhesives, thermal insulation materials or other substances. which can be programmed to dispense precise amounts of material with high accuracy and repeatability.

A **soldering tool** for robot is a device used to automate the soldering process.

There are several types of soldering tools that can be used with cobots, including hot air soldering guns, soldering irons, and soldering stations [34].

In the introduction, the author provided a concise overview of the integration of robotics in the assembly process within production, delving into the various processes involved, the available robot options, their comparative features, and the assortment of tools suitable for assembly process robotization. The subsequent section will focus on a specific product slated for automation in its assembly process. The selection of the type of robot and the precise processes to be implemented will be guided by a meticulous analysis of the product's characteristics and the sequential stages of its assembly.

2. PRODUCT AND MANUFACTURING PROCESS DESCRIPTION

2.1 Products description

For this work, the author has chosen two objects: protective case-enclosure designed for microcomputer, and the microcomputer itself, as a finished assembly. Protective case-enclosure was designed and 3D-printed on author’s request by Madis Käärma, with written permission to use this object for any required purpose [Figure 2.1.1.]. Second component, the microcomputer (Raspberry PI) is a type of open-source computers which is widely used for creation of smart-home systems, for implementation of IoT and building of internal network in manufacturing facilities [35], for educational purposes, internet connectivity, programming, multimedia playback, and other tasks. Raspberry PI foundation keeps the Raspberry PI hardware schematics and documentation open. The author incorporates photographs, dimensions, and descriptions of the microcomputer found on the manufacturer's website to support this thesis. The microcomputer, specifically the Raspberry Pi, is treated as a unified and indivisible product within the framework of this research.

Using the open-source information, models of protective enclosure and the microcomputer were created in Fusion 360 software by Madis Käärma on author’s request.

Protective case-enclosure (further: case), is considered as a set of parts, and microcomputer Raspberry PI model B+ (further: microcomputer) is considered as a subassembly.

The case is designed to safeguard the microcomputer board from impacts, contamination, and dust. It is essential for the utilization of the microcomputer in industrial production zones, on machinery or forklifts, as an Internet of Things controller, or as a wireless communication node. The protective enclosure is also required for deployment as a controlling node in a Smart Home system, as well as for shielding the microcomputer from damages when utilized by personnel or third-party subcontractors.

General technical parameters of the case:
Length x Width x Height: 90 mm x 61 mm x 23 mm
Total product weight: 0,03 kg

Figure 2.1.1. View of protective case in assembled state (Torx screw heads are not presented) [M. Käärma]

The case consists of two halves, with cutouts for microcomputer cooling and for providing the access to different ports on the microcomputer’s board. Case halves are produced of ABS-ESD (Acrylonitrile butadiene styrene) plastic, due to its rigidness, impact resistance, shape stability, flame-retardant, and ESD properties [36], [37]. Case halves are assembled and affixed by four M2.5 x 12 (DIN 7985) pan head Torx screws [38], and heat inserts molded into the structure of the case. The chosen method of fastening is based on the potential need for repair or upgrade of the microcomputer during its operation. There may also be a need to replace one of the case halves in the event of impact (for example, when using the product on forklifts or other warehouse equipment). Adhesive or welded connections of the housing halves are also reliable choices, but these options are one-time solutions and adversely affect repairability. Case assembly with clasps will be more challenging to manufacture (the mold will be more complex), and vibrations and temperature fluctuations may negatively impact the strength of the connections between the halves.

The case can be ordered as a set of injection-molded parts [39] from the third-party supplier or can be 3D-printed onsite [40].

Figure 2.1.2. Raspberry PI model B+ isometric view [41]

The microcomputer is obtained from the manufacturer and installed into the case according to demand. It is a small, single-board computer that typically measures around the size of a credit card, though the specific dimensions may vary slightly between different models. Microcomputer typically has a rectangular shape, with rounded corners, and often it consists of multiple layers, with components mounted on both sides of the board [Figure 2.1.2]. On the surface of the microcomputer board, a variety of components are visible, each playing a crucial role in its functionality. These include microchips, connectors, and ports, which enable various interactions and connections. Among these components are those facilitating storage, such as the microSD card slot, and those enabling communication with external devices, such as HDMI ports for video output, USB ports for connecting peripherals like keyboards and mice, an Ethernet port for networking, GPIO (General Purpose Input/Output) pins for interfacing with other hardware, and a power connector for supplying electrical power to the board [41].

General technical parameters of the microcomputer [42]:
Length x Width x Height: 85 mm x 56 mm x 17 mm
Total product weight: 0,05 kg

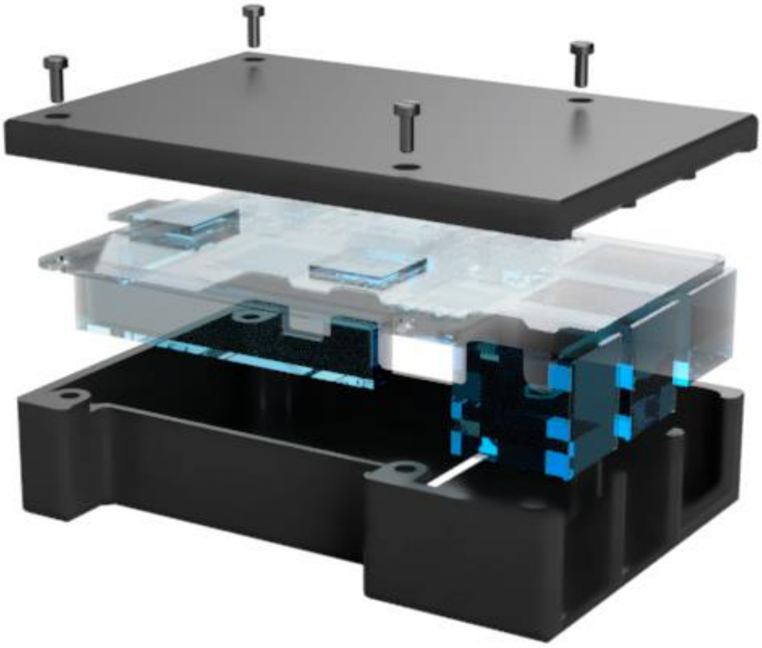


Figure 2.1.3. Product's exploded view [M. Käärma]

The final product consists of an assembly of two halves of a protective case, concealing the microcomputer board inside [Figure 2.1.3]. The ports of the microcomputer are positioned directly opposite the corresponding technological openings of the protective enclosure. The enclosure itself is secured by four screws, tightened to a torque of 1.0 Nm. Following assembly, the product proceeds to packaging.

2.2 Process description

In order to structure the assembly of the product, it can be divided to eight logical parts.

- Preparation of case halves for assembly;
- Preparation of microcomputer for assembly;
- Placing of upper case half to the assembly fixture;
- Visual inspection of microcomputer board;
- Placing of microcomputer board into the upper case half;
- Closing the case with lower case half;
- Tightening the case with screws;
- Visual inspection of finished product;
- Packing.

The flow of the assembly is presented below [Figure 2.2.1.] Sets of parts are delivered to the workstation before the start of the assembly process from the warehouse.

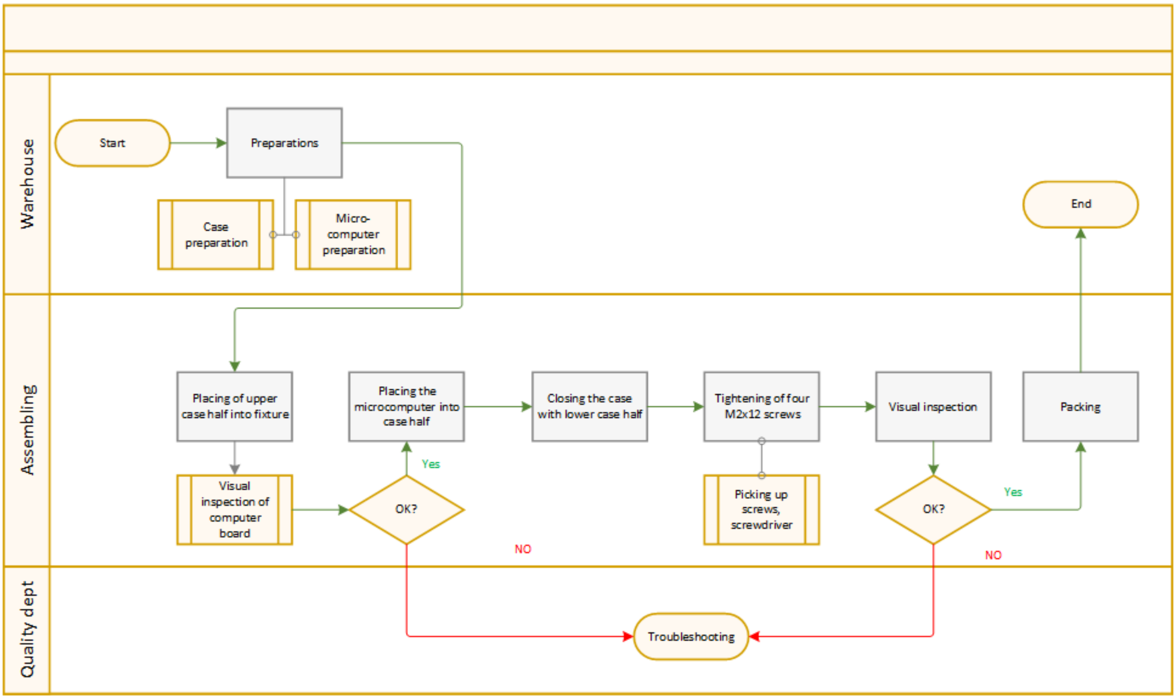


Figure 2.2.1. Flowchart of product manual assembly [Author]

The work is carried out by the operator and involves assembling the product from a set of components. To secure the subassembly on the workbench, it is decided to use a fixture [43]. The operator assembles the product manually, placing the top cover of the case into the fixture first, with the inner part of the cover facing upwards. Then, the operator takes the microcomputer board from the rack and places it inside the top cover of the housing, considering the positioning of the microcomputer ports and the technological openings of the housing. Next, the operator places the bottom cover of the housing over the microcomputer board, ensuring that it connects with the top cover and forms a protective capsule. Using an electric screwdriver [44], the operator screws in four screws, finalizing the assembly and obtaining the final product. Subsequently, the operator conducts a visual inspection of the product, and it is sent for packaging. If quality checks show imperfections or flaws, the parts are left in the quality check area for further inspection.

2.3 Workstation description

The product assembly process, leading up to testing, occurs at a single workstation managed by one operator. This workstation comprises a worktable which is equipped with a light source, a touchscreen with a PC to check the work steps and quality notes, and a side shelf for parts storage. The assembly could be done by an electric screwdriver [Figure 2.3.1] and set of Torx bits, or by manual screwdriver. To hold the case in steady position and free operators' hands, the assembly fixture is used [Figure 2.3.2], which is modelled by author according to size of the product in Solid EDGE software and printed out by M. Käärma on author's request.

Figure 2.3.1. Corded electric screwdriver Etensil E8C [44]

Such simple workstation requires little effort to build and low expenses to fund, it may be used for a variety of production and support tasks, but it requires an operator to do the work, who is not only gaining the income but also is a source of expenses, and a critical part of the production system, due to its human nature.

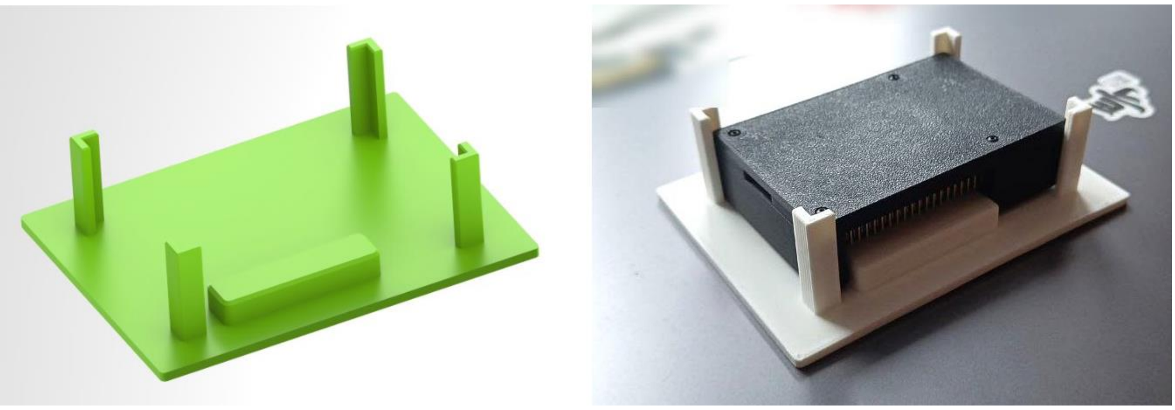


Figure 2.3.2. Isometric view on assembly fixture, and assembled product in the fixture [Author]

2.4 Assembling risks, opportunities, and robotization justification

The responsibility of assembling the device now solely rests on the worker. Although the product's design might appear straightforward, it doesn't negate the potential benefits of integrating robots into the assembly process. The product is easy to assemble, and the work itself may look as something not important and which may be done without any effort.

This effects on very important element of the assembly process - the physical and mental state of the worker. In total, when assembling one device, the operator must tighten 4 screws of small size, which are uncomfortable to grip and hold, using the bulky screwdriver, and remembering to check his actions with the instructions and quality notices, and constantly control himself. This work is sedentary, monotonous, constraining, and mind-numbing. This provides space both for making mistakes and for the employee to develop occupational diseases. In addition, the monotony of work can have a negative impact on the mental state of the employee.

Additionally, the production system exists in the collaboration with external actors, whose actions affect the production but cannot be controlled by the company. Those might be acts of local and international law, changes in market situation, competitor's actions, global pandemics, or even rocketed product demand.

The table below outlines a concise list of potential risks associated with the assembly process of the specified product.

Table 2.4.1. Risks of the assembly process of the specified product

Product related risks	**Process related risks**	**External risks**
Small size of fasteners	Monotonous, numbing work	Extensive, growing demand
Materials of the casing	Risk of breaking, damaging	High oil and plastic prices
Microcomputer	Risk of breaking, damaging	High components price
High cost and complexity of electronic components	Quality requirements	Economic situation

Mentioned risks might be mitigated with an implementation of robot. Dualistic nature of things and events modifies the risk into development opportunity if the observer can change his attitude and review the risk under the different angle.

Table 2.4.2. Mitigation of product related risks

Product related risks	**Robotization outcomes**
Small size of fasteners	Smart screwdriving by robot + feeder
Materials of casing	Robotized Pick-and-place tasks, AOI
Microcomputer	Robotized Pick-and-place tasks, AOI
High cost and complexity of electronic components	Minimizing the risk of damaging the microcomputer board during assembling

Introducing robots into the assembly process offers a solution to precise small objects and “too easy” work challenges, ensuring optimal workload during the assembly. Exceptional repeatability of the robot ensures the safety of the subassemblies during the mounting and affixing them together. AOI will prevent the human errors in assembly and self-control [Table 2.4.2].

Table 2.4.3. Process related risks mitigation

Process related risks	**Robotization outcomes**
Monotonous, numbing work	Smart screwdriving by robot
High level of control, need to follow work instruction	Program and AOI-based task execution
Labor cost	Minimizing the labor time
Operator requirement	Robotization
Quality requirements	Highest level of repeatability and AOI control

Robot integration addresses occupational hazards associated with repetitive tasks, safeguarding worker health while enhancing assembly consistency and reliability. It also improves product quality, operational efficiency, and provides flexibility to adapt to evolving assembly requirements [
Table 2.4.3].

Table 2.4.4. Mitigation of external risks

External risks	**Robotization outcomes**
Growing / falling demand	Agile, flexible manufacturing
Competition	Faster response to changes, higher quality
Local and international law	Excluding humans from hazardous or health-compromising tasks
Pandemics	Greater production sustainability
Economic situation	Greater efficiency and lower costs

The challenges originating from external factors can also be addressed through the implementation of robotization in assembly processes. Robots ensure the utmost level of consistency and repeatability in their work, functioning across multiple shifts with minimal maintenance requirements. Preparing task programs beforehand significantly accelerates changeover times, reducing the gap between different product productions. The variety of available EOATs facilitates the repurposing of robots from production to diverse tasks like packaging or servicing, and vice versa. Robotization enables swift, adaptable, and cost-effective responses to external changes, fostering sustainability and granting the company a competitive edge in the market [Table 2.4.4].

Having enough confirmations of the correctness of robotization, from the point of view of the product, processes, and the influence of external factors above, it is now necessary to determine whether robotization of these processes is justified in a given company.

For the justification analysis, the author adopted a template crafted by the Innovative Manufacturing Engineering Systems Competence Center, successfully applied in robotization's justification analysis here [45]. This comprehensive analysis encompasses four main categories: technology, products, company objectives and situation, as well as the company's experience and opportunities. Each category comprises 5 key questions, assessed with predetermined scoring criteria. The summation of points within each category determines the suitability of robotization. Finally, a comprehensive decision is formulated based on the accumulated points across all categories [Table 2.4.6].

Table 2.4.5. Assessment within the category

Range of points	**Conclusion**
0-12	Robotization is not needed
13-18	Moderate expediency
19-25	Robotization is essential

Table 2.4.6. Aggregate assessment

Sum of points	**Conclusion**
5-40	No need
41-55	Moderately necessary
56-75	Reasonable enough
76-100	Very expedient

In this study, the product under examination is a set of subassemblies, which must be assembled before sending it forward to the end customer. The microcomputers are obtained from the manufacturer in bulk quantities, protective casing sets are supplied in bulk by third-party suppliers or 3D-printed inhouse. Smart factory projects often require big numbers of microcomputers for implementation of smart network and IoT. The company’s goal is to assemble required batch of finished products and send it to the customer with lowest expenses and losses possible.

Employing the method applied in this study [45], the author evaluated the rationale behind implementing robotics in this business.

The outcomes of this assessment are outlined in the subsequent table [
Table 2.4.7], while the detailed analysis can be found in the Appendix 1 [Table 2.4.8].

Table 2.4.7. Results within the categories

Category	**Number of points**
Technology	13
Product	17
Objectives	17
Opportunities	13

Considering this, the aggregate overall result will be the sum of all points: 60 points, which makes the robotization a „reasonable enough" enterprise. Having a positive result of the justification of robotization, the author should move on to the process of robotization of the workplace and the assembling process itself.

2.5 Choosing the type of robot

To decide on the appropriate robot type, the author must consider key details about the production, product specifications, and the company itself, as highlighted in the sections above. Particularly beneficial is the comparative table presented earlier in this work [Table 1.0.1].

Larger industrial robots demand substantial financial investments and require highly skilled personnel for programming and maintenance. Small and medium-sized enterprises, especially in developing nations, may opt against robotization due to these significant costs.

The product subassemblies possess compact dimensions and a light weight [see Products description]. Considering the demand does not suggest high production volumes, manufacturing smaller batches is feasible.

According to materials of the course „Industrial Robotics and Advanced Manufacturing ", different tasks demand specific technical abilities from robots. For chosen processes, the robot is expected to handle assembly tasks.

Course materials [46] outline the dependencies between process and technical capabilities of the robot [
Table 2.5.1].

Table 2.5.1. Robot technological capabilities dependency to assembly process

Technological capabilities	**DoF**	**Motion speed**	**Accuracy**	**H-reach**	**Payload**	**Need In sensors**	**Need in EOAT**
Assembly	Strongly	Strongly	Strongly	Weak	Weak	Strongly	Strongly

Basic parameters of IR and cobots define the suitability of the robot to the type of performed tasks [46]. Considering the assembly process and dependencies of robot's capabilities, and by comparing the basic parameters of robots with them, it is possible to determine the framework sufficient for a robot that is minimally suitable for performing these tasks. Basic parameters are listed below:

- Number of axes (DoF): Two axes for a plane, three for space, and additional axes for full end-of-arm control;
- Working Envelope: Defines a robot's reachable space;
- Kinematics: Robot's physical arrangement determining possible motions;
- Payload Capacity: Indicates the weight a robot can lift;
- Speed: Determines the arm's positioning speed;
- Acceleration: Reflects the axes' acceleration capability;
- Accuracy: Measures how closely a robot reaches a commanded position;
- Repeatability: Indicates how precisely a robot returns to a programmed position.

In this case, the assembly shows strong dependency on DoF, speed, accuracy, repeatability, need in sensors and EOAT, while it is not that dependable on reach or the payload. The work envelope should minimally cover the area on the worktable, but due to product compact size, the working area can contain several fixtures, in this case reach is not important. The payload equals the weight of EOATs + weight of the heaviest component, suitable for pick-and-place.

This can be interpreted as a requirement to have fast, accurate, EOAT-friendly robot with more than three DoF's. This robot can be relatively small and can have modest payload. These qualitative descriptions can be transformed to quantitative values. The description of the desired robot would take this form.

Table 2.5.2. Summary table of minimum requirements for the robot

Technological capability	**Dependency of assembly**	**Numerical meaning**
DoF	Strongly	3+
Motion speed	Strongly	1 m/s
Repeatability	Strongly	0,05 mm

Having this input as a starting point, it is possible to outline the robot's basic conception. Determining the robot design is pivotal in the selection process. For assembly tasks where maximizing Degrees of Freedom (DoFs) is key, joint-arm and SCARA robots stand out as excellent considerations. Their capabilities align well with the demands of such tasks.

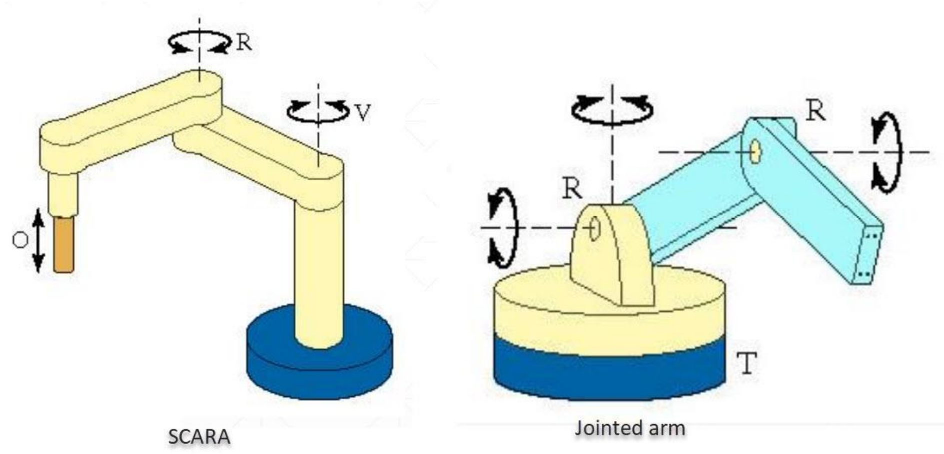


Figure 2.5.1. SCARA and Jointed arm robot types [46]

SCARA and joint-arm robots differ in their design and functionality:

Motion Range: SCARA robots typically have a cylindrical work envelope with limited vertical reach but excel in horizontal tasks. Joint-arm robots often have a spherical work envelope, offering greater flexibility in various directions. Both types can be used in conjunction with robot linear tracks, which alows the robot to move within the lenght of the track [47].

DoF: SCARA robots usually have fewer DoFs, commonly four, restricting their movement primarily to the x, y, and z planes, along with rotation . Joint-arm robots often have more DoFs, allowing for more complex movements and orientations.

Accuracy: SCARA robots typically offer better repeatability and accuracy in planar movements due to their design. Joint-arm robots, with their additional DoFs, may exhibit slightly less accuracy but can perform more intricate motions.

Applications: SCARA robots are well-suited for tasks like pick-and-place operations, assembly, and material handling in a plane. Joint-arm robots are more versatile, applicable to a wider range of tasks that demand multi-directional and complex movements, such as welding or 3D manipulation.

In the current context, given the simplicity of the product assembly process, extensive flexibility and mobility in the joint-arm robot seem excessive and unlikely to be needed. Moreover, these features would escalate the robot's cost, making the project less financially viable. Considering these factors, the author favors opting for a SCARA robot.

In the conclusive phase of robot selection, the author will employ an elimination approach, utilizing a decision-making tree to prune redundant "branches," retaining only those aligning with the work concept.

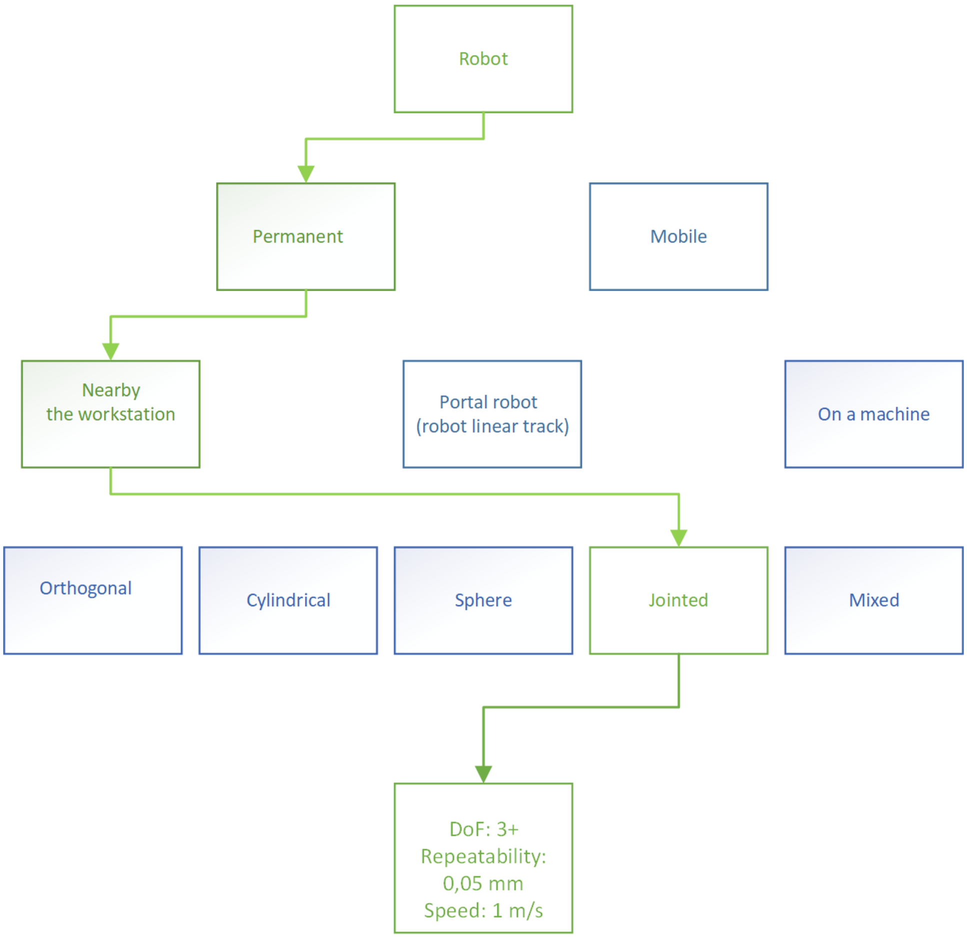


Figure 2.5.2. Decision-making tree with a decision path

Taking into consideration all the inputs provided above, the author leans toward considering a small SCARA industrial robot as the primary means for automating the assembly process. Considering both the simplicity of the assembly objects and the need to reduce both costs and operator fatigue, the author suggests that this assembly should be carried out without human involvement, to allocate human resources to solving more important tasks.

3. ROBOTIZED WORKPLACE DESIGN AND ASSEMBLY PROCESS OPTIMIZATION

3.1 Analysis of possible human-robot collaboration

If a company is receptive to adopting robotics, the subsequent step involves identifying the assembly process stages that would yield the greatest advantage from robotization. Although the integration of robots in major enterprises is no longer novel [14], smaller companies are transitioning from manual labor to optimize production via robotics. Yet, the decision to implement robots shouldn't solely hinge on management preferences or a desire to portray the company as cutting-edge. Mass implementation of robots in all processes might incur costs that could be challenging or unfeasible to recover in the future. Moreover, not all product design solutions may align effectively with robot utilization. Additionally, the use of robots should not increase the risk for human operators in terms of safety.

In order to understand which steps in the assembly process need to be robotized and which should be left without robotization, the author will use Malik’s methodology [48], which is a translation of qualitative descriptions of such aspects of product assembly as Components (Cp), Mounting (Mt), Feeding (Fd), Safety (Sf), Fastening (Ft), and Miscellaneous (Misc), into qualitative indicators for subsequent analysis for robotization suitability and human-robot collaboration (HRC) potential calculations. According to Malik, at least 70% of potential should be considered as a marker for implementing robot for the task reviewed. Malik analysis was applied to each assembly part. The results of this analysis can be seen in the table below [Table 3.1.1.].

Table 3.1.1. Evaluated HRC potential for each task

Component	**Cp., %**	**Mt., %**	**Fd., %**	**Sf., %**	**Jn., %**	**Misc., %**	**Potential, %**
Case upper half	87,5	100	87,5	50	100	66,67	81,94
Case lower half	87,5	75	87,5	50	75	66,67	73,61
Microcomputer board	75	75	87,5	50	75	66,67	71,53
Finished unit	100	100	87,5	50	100	100,00	89,58

The study suggests that both subassemblies and the finished product itself, could be the objects for robotization. The high level of results attained through analysis once again prompts questioning the necessity of having an operator within the assembly process. The operator could be relieved of the assembly function, yet still oversee the robot's operation, adding components for product assembly when necessary, and carrying out logistical tasks.

While industrial and collaborative robots are designed to operate alongside humans, the degree of interaction varies based on the specific application. The interaction between humans and robots is categorized into physical separation, coexistence, cooperation, and sequential and responsive collaboration [49]. The requirement to supply the robot with parts and materials, and taking the finished goods to warehouse, suggests the coexistence of IR and operator. In this case, the operator and the robot work in the different areas, without interfering [Figure 3.1.1.]. Such work requires certain safety measures that will minimize harm to a person or product in the event of a malfunction of the robot, or in the event of a violation of safety regulations by the operator. Cobots have several degrees of built-in protection – collaborative capabilities - that are required from manufacturers, according to the ISO standards [12], IRs can be equipped with light barriers, proximity sensors and bracelets, or other safety measures [50]. Additionally, every workstation should pass the OHS department verification, and according to their prescription, the workstation can be equipped with additional safety measures.

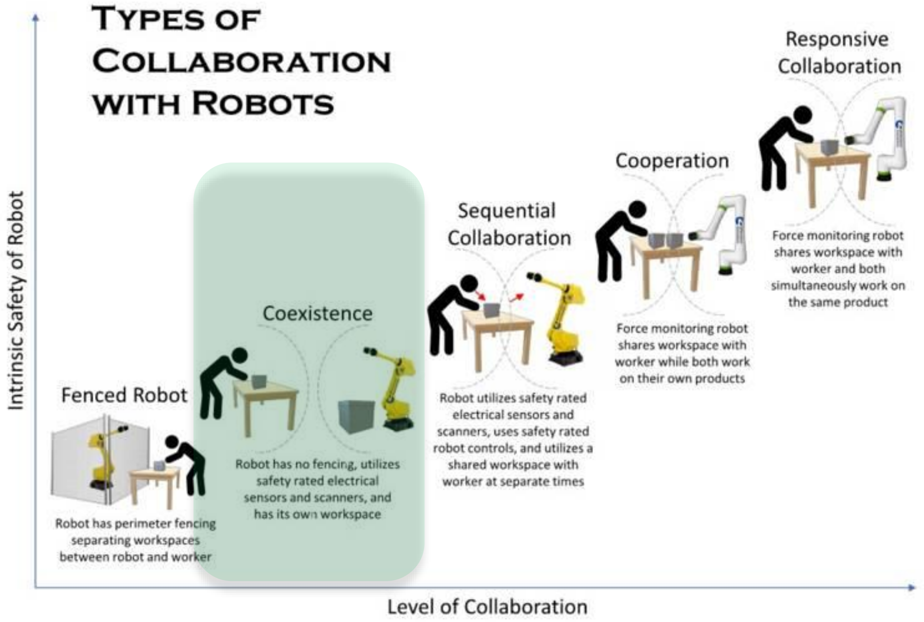


Figure 3.1.1. Types of collaboration with robots [49]

To thoroughly explore the collaboration potential between robots and human operators and assess how automation affects assembly processes, the author conducted a comprehensive analysis of specific assembly stages. This involved a series of hands-on experiments carried out by the author using the 3D-printed functional model of the case, 3D-printed fixture, and a microcomputer board.

During the experimental assembly process, the author conducted several product assemblies using a fixture and a manual screwdriver. To ensure the stability of the product during assembly, the fixture was glued to the workbench surface during the experiments. The assembly took place under artificial lighting, with the author wearing protective gloves. The small size of the screws and the need to handle and hold the microprocessor board with caution had a negative impact on the assembly results.

Precise time measurements were recorded using a stopwatch, and the resulting data was methodically tabulated [Table 3.1.2] to calculate the average duration required for every operation.

Table 3.1.2. Labor times of product assembly operations

Operation	**Labor time, min**
Case preparation	0.5
Microcomputer preparation	0.5
Placing of upper half of case into fixture	0.17
Visual inspection of microcomputer board	0.33
Placing of microcomputer board into upper case half	0.25
Closing the case with lower half of case	0.20
Manual tightening of four M2.5x12 screws	0.66
Visual inspection of finished product	0.20
Packing	0.5
Total	**3.31**

As indicated in the table above, the total assembly process demands 3.31 minutes of labor time, impacting the product costing. Consequently, the engineer's primary objective remains the reduction of labor expenses via process optimization. According to [Table 3.1.1], the potential for robotization of assembly process lays in every assembly step, so the author decided to fully robotize the assembly process.

The implementation of robotics for all assembly processes will effectively eliminate labor time in manufacturing. However, operators will still be essential for overseeing parts and component delivery and performing supportive tasks. This reduction in labor time through robotization will greatly improve operational efficiency, cost-effectiveness, and competitiveness, while also allowing for a more strategic allocation of human resources.

3.2 Defining the processes for robotization

For the case, it involves feeding the upper half of case into the assembly fixture at the workstation. The main board requires several steps: picking it from the rack, visual control of the board, aligning it with case cut-outs for ports and screw holes, and placing the board into the case. Lower part of the case should be picked up, aligned, and placed over the microcomputer board, covering it from above. Then finished case should be picked out from the fixture and moved to the packing.

Table 3.2.1. Process similarities for reviewed tasks

Part of the product	**Process to be done**
Case upper part	Pick-and-place, visual control
Microcomputer board	Pick-and-place, visual control
Case lower part	Pick-and-place, screwdriving, visual control

Such set of different operations may require a complex set of equipment. It would be beneficial if it would cover all the needs of assembling process of the product.

Despite all the components share Pick-and-place task and Visual inspection task, and only one out of three components have also screwdriving task, the components should be also examined for their physical properties such as dimensions and special requirements. Additionally, components may have design features that might make assembly operations difficult for robotization.

Table 3.2.3. Physical properties and features of components.

Component	**Width, mm**	**Length, mm**	**Height, mm**	**Features**	**Material**
Case upper half	61	90	22	Cut-outs for connectors and ventilation	ABS-ESD plastic
Microcomputer board	56	85	17	Electronics	Fiberglass
Case lower half	61	89	20	Cut-outs for connectors and ventilation	ABS-ESD plastic

The [
Table 3.2.3] shows little differences in the dimensions of components and points out features which need to be considered in choosing the equipment. In case of upper and lower case halves, cut-outs limit the use of vacuum gripper; ABS-ESD plastic prevent use of magnetic gripper. Microcomputer board should be handled by ESD-safe equipment.

The requirement to inspect parts before the assembly assumes the implementation of AOI solution, it can be fixed or mobile.

The small size of the screw requires precise screwdriving solution with automatic screw feeder and regulated torque.

3.3 Determining the required EOAT parameters

To perform the tasks of screwdriving, pick-and-place and quality check, robot or robots should operate different EOAT:

- Screwdriver;
- Gripper;
- Camera.

Robots ensure precision and smooth operation, but this is only possible with the right equipment. In the case of this product, the screws used are small, and the parts they fasten are made of plastic. These features require the use of a screwdriver capable of automatically adjusting the screwing speed and ensuring the correct torque to prevent over-tightening, which could strip the threads and damage the product. To accomplish this task, the author proposes using an electric smart screwdriver [51] in conjunction with an automatic feeder [52]. The first element will address the complexities of screw tightening, while the second element will solve the issue of feeding small screws to the screwdriver bit.

Gripper is a device attached to the end of a robotic arm designed to grasp, hold, or manipulate objects during automation processes. For task of pick-and-place of electronic component, the gripper should be ESD-safe [53], precise and should have an advanced actuators to operate with gentle electronic components.

The integration of cameras for quality control checks should supersede the reliance on human operators. Given the simplicity of the product, operators are currently inspecting their own work, and employing additional personnel solely for quality control tasks would lead to an unjustifiable increase in operating costs.

3.3.1 Proposed EOAT setup

As previously stated, the setup should comprise devices adept at managing electronics and small parts, executing "pick-and-place" tasks, performing controlled screw tightening, and overseeing quality control. Given the lightweight and compact nature of the components, the devices should not require high lifting capacities, which will help control the overall equipment costs. Additionally, it's crucial for the equipment to be compatible with robotic systems and easily adaptable for producing different products. Essentially, it should offer a versatile solution with potential for future applications.

Based on this, the author decided to primarily utilize equipment from a single manufacturer to ensure consistent programming principles and a unified user interface. Such standardization will expedite robot setup and help address issues related to programming or hardware components more efficiently.

Since in [Section 2.5] of this research the author concluded on the necessity of using SCARA robots for such tasks and is unaware of technical solutions allowing for an automatic tool-changing adapter on a SCARA robot, the author opted to employ separate robots for "pick-and-place" tasks and screw tightening. Two AOI cameras will be mounted separately: on the manipulator of one of the robots, alongside its gripper, to control the correctness of microcomputer board installation, and other will be affixed to the workbench, to control the upper surface of the microcomputer board, prior its installation into case.

The author explored EOAT options available in the market and identified Robotiq SD100 smart screwdriver as a suitable option for screwdriving task, since it can operate with M2.5 x 12 Torx screws, it is intended to work in smart systems in conjunction with IR or cobot, and it is able to tighten the screws with regulated torque [54]. This smart screwdriver will be working in conjunction with SCARA robot #1.

Figure 3.3.1.1. Robotiq SD100 smart screwdriver [55]

For ease of programming, the author will stop on the products of the same EOAT manufacturer – Robotiq. For pick-and-place EOAT, the author decided to choose vacuum gripper from Robotiq EPick series. It requires no external air source, and the gripping area is also customizable with additional suction cups and extenders. This vacuum gripper will be installed to SCARA robot #2.

Figure 3.3.1.2. Robotiq Epick vacuum gripper with single suction cup [56]

As an AOI solution, the author decided to use two OnRobot Eyes vision system [Figure 3.3.1.3] due to its moderate price, high image resolution and low weight.

Figure 3.3.1.3. OnRobot Eyes camera and controller [57]

Full list of EOAT setup is available in the table below:

Table 3.3.1.1. List of components for tool changer EOAT setup, with weights and prices (incl. VAT) [58], [57], [59], [60].

EOAT	Type	Weight, kg	Quantity	Price, €	Total
Robotiq SD100	Smart screwdriver	1.5	1	8087	8087
Robotiq EPick	Vacuum gripper	0.71	1	5679.1	5679.1
OnRobot Eyes	Camera system	0.26	2	7401.74	14803,48
OM-26R26	Screw feeder	n/a	1	710.69	710.69
	Required payload	**1.5**		**Total**	**29280,27**

Now equipped with data regarding EOAT usage and product component dimensions, the author can proceed to select a specific robot model. This choice, along with already available information, will enable the author to propose an updated workstation design for the robotic assembly of the product mentioned in title of this study.

3.4 Chosing the robot model

The SCARA robot market is not that extensive, as jointed-arm robot market, but it still offers diverse models from various suppliers tailored for different applications. Prior to selecting a specific robot supplier and model, conducting thorough research and evaluation is crucial. This evaluation should encompass comparing robots based on specific technical parameters. Should the comparison based on technical aspects not yield a clear preference, other factors like cost, past performance, and accessory availability should be taken into account.

The author decided to choose following parameters for comparison:

- Footprint. Criteria: smaller - better
- Payload. Criteria: 1-1,5 kg (1 kg for „gripper+camera" setup)
- DoF. Criteria: ≥3
- Repeatability. Criteria: ≥0,05 mm
- Reach. Criteria: ≥300 mm

Within the framework of this comparison the author decided to focus on the SCARA robots from 5 different suppliers:

- EPSON
- Denso
- Dobot
- Mitsubishi
- Omron

Those companies provide small-to-medium price SCARA IR models to the market, and their product information is publically available.

A search for IR using the above criteria yielded results in the form of several robot models presented in the table below.

Table 3.4.1. Technical parameters of selected SCARA robots [61], [62], [63], [64], [65], [66]

SCARA robot models					
Parameters	Epson SCARA T3-B401S	Omron i4-350L	DOBOT M1 Pro	DENSO LPH-050A1	MITSUBISHI RH 6FH3520
Footprint, mm	180x142	240x180	230x175	180x170	-
Payload, kg	3	5	1,5	3	6
DoF	4	4	4	4	4
Repeatability, mm	±0.02	±0.01	±0.02	±0.02	±0.01
Reach, mm	400	350	400	400	350

In the pursuit of identifying the optimal robot, the author assigned a rating between „1“ and „5“ to every technical parameter in each category. A score of „5“ denoted the highest performance, while „1“ indicated the lowest. These scores were then aggregated to determine the ultimate winner. Because there wasn't enough information on power consumption, the author didn't factor it into the calculations. While low power usage is nice, it's not a vital cobot feature. However, the true payload capacity is crucial. Therefore, cobot models without this information were included in the sample. They may require a deeper investigation, possibly reaching out to the manufacturers for more details. Comparison results are presented in the table below.

Table 3.4.2. Relative comparison of selected robots

Parameters	Epson SCARA T3-B401S	Omron i4-350L	DOBOT M1 Pro	DENSO LPH-050A1	MITSUBISHI RH 6FH3520
Footprint, mm	5	2	3	4	n/a
Payload, kg	5	5	5	5	5
DoF	5	5	5	5	5
Repeatability, mm	4	5	4	4	5
Reach, mm	5	5	5	5	5
	24	**22**	**22**	**23**	**20**

In conducting a relative comparison of SCARA robots, a leader emerged from the available data. Upon examining the final comparison results, it's evident that the robots closely match each other. Given that all these robots share the same class and declared load capacity, there's a hypothetical assumption that the actual footprint of the Mitsubishi model might align with the outcomes seen in models from other manufacturers. However, in practical scenarios, engineers often lack comprehensive information, necessitating decisions based on the most complete data available.

In this study, the SCARA T3-B401S model from the manufacturer „SEIKO EPSON“ has the most suitable properties.
SCARA T3-B401S is a midrange model, which can be obtained at the price point around 9556 € (incl VAT) [67]. The robot will be shipped with a teachpanel and a control box.

Figure 3.4.1. SCARA robot T3-B401S, SEIKO EPSON [67]

With the product, assembly process, equipment set, and robot specified, the author can now initiate the planning of a robotic workspace. This entails crafting an assembly process where robot would play major role in the product manufacturing.

3.5 Optimizing product assembly: evaluating robotization with selected equipment

So, having all the input, and having determined the necessary equipment and process parameters, the author can optimize the product assembly process by robotizing it. Process will be started and supported by human, while the robots will perform all product assembly tasks. The operator will initiate the robot’s program and will not intervene while both robots execute their tasks. Operator will continue to perform tasks which require transportation of parts to the workstation and finished products to the packing area. Operator will monitor the actions of the robots and will intervene to the process in case of any discovered process imperfections. Also, operator will monitor the AOI log and will examine rejected components.

Robot #1 will perform following tasks:

- Pick the upper half of the case and take to assembly fixture;
- Place the upper half of the case into the assembly fixture;
- Pick the microcomputer board from the rack and take it to table-fixed AOI camera;
- In case of “FAIL” check, place the board to QC area;
- In case of “PASS” check, place the board into the assembly fixture, over the upper half of the case;
- Conduct AOI check of installed board with manipulator-mounted AOI camera;
- Pick the lower half of the case and take to assembly fixture;
- Place the lower half of the case into the assembly fixture, over the microcomputer board;
- Pick the finished product and place it to finished product area.

Robot #2 will perform screw tightening task.

The flowchart of the optimized assembly process is available in [appendix 2]

3.5.1 Determining the robot production cycle time

To determine possible robot production cycle time, it is required to give time assumptions to all operations, based on available robot’s, and product data.
The reach distance of T3-B401S equals 400 mm, and standard cycle time equals to 0,54 sec [68]. This data allows to assume that one-direction movement within the work envelope will be done in time of 1 second, picking the object will require 1,5 seconds and placing the object will require 1,5 seconds. AOI check will require 1 second.

Pick-and-place tasks will require following steps and times:

Table 3.5.1.1. Time assumptions for pick-and-place tasks robotization

Step	**Time, sec**
Pick the upper half of the case and take to assembly fixture	5
Place the upper half of the case into the assembly fixture	1,5
Pick the microcomputer board from the rack and take it to table-fixed AOI camera	6
Place the board into the assembly fixture, over the upper half of the case	4
Conduct AOI check of installed board	1
Pick the lower half of the case and take to assembly fixture	5
Place the lower half of the case into the assembly fixture, over the microcomputer board	1,5
Pick the finished product and place it to finished product area	5
Total	**29**

Therefore, when tightening the screws, the robot will move the EOAT from the product to the screw feeder, and back, with an approximate time of 5 seconds/cycle (path from product to feeder, picking up the screw, and path from feeder to product, and placing the screw (without screwdriving).

The feeder itself has a screw supply cycle speed of 0.9 pcs/sec [60], which will allow the feeder to prepare 5 screws in a five-second cycle of the screwdriving robot, and, therefore, the feeder will not limit the speed of the system, that is, it will not be a bottleneck. The speed of screw tightening will be set to 300 rpm (maximum limit of SD100 is 500 rpm [54]), due to small size of the screw and the material of connected components.

Now, an M2.5x12 screw is a metric screw with a diameter of 2.5 mm and a length of 12mm, with the thread pitch of 0.45 millimeters [38]. This means that for each full revolution of the screw, it advances 0.45 millimeters along its axis, which will give about

27 full revolutions to tighten the screw (12 mm / 0,45 mm =26,66). However, the screw will not be tightened to full length because of the thickness of the object it requires to fasten (in this case, the microcomputer board). So, the author assumes that the number of revolutions to affix the MB will be equal to 25.

To determine the time to tighten a screw, it is required to consider the angular speed of the screwdriver and the number of revolutions required to tighten the screw fully. The angular speed can be found using the formula:

$$Angular\ speed = \frac{n\ revolutions}{60\ seconds} = \frac{300}{60} = 5\ rpm \qquad (3.1)$$

Having this result, it is possible to calculate the time for one revolution:

$$Time\ for\ 1\ rpm = \frac{1}{Angular\ speed} = \frac{1}{5} = 0{,}2\ sec \qquad (3.2)$$

Assuming that it will be required to make 25 revolutions to tighten one M2.5x12 screw, the total time (T) for screw tightening could be calculated by formula:

$$T = Time\ of\ 1\ rpm\ \times n\ revolutions = 0{,}2\,\text{sec} \times\ 25\ rev = 5\ sec \qquad (3.3)$$

Time for tightening of screws per one product is presented in the table below:

Table 3.5.1.2. Time assumptions for "screw tightening" task robotization

Step	**Time, sec**	**N of iterations**	**Total time, sec**
Cycle "Go to feeder – pick the screw – go to product – align the screw"	5	4	20
Tightening the screw	5	4	20
Total			**40**

Having all the data calculated, it is possible to calculate the total robot production cycle time, by summing up the results of all described processes. This will result in 69 seconds or 1,15 minutes of machine time. This data will complete the data from the table above [Analysis of possible human-robot collaboration], outlining the benefits of assembly process robotization.

Table 3.5.1.3. Comparison of assembly time before and after robotization

Time type	**Before robotization, min**	**After robotization, min**	**Difference, %**
Labor time	3,31	1,7	(-)48,64
Machine time	0	1,15	100
Throughput time	3,31	2,85	(-)14

Results of the robotization not only decreased the labor time, but also decreased throughput time of the assembly of one unit. Comparing the results, it is possible to conclude that robotization has a serious effect on reducing labor time, thereby positively influencing the final price of the product, and increases the efficiency of the product assembly process, allowing less time to be spent on it.

Of course, such results were obtained based on data from manufacturers of robots and EOATs, and the design of the product itself, without practical testing, during which inconsistencies between calculations and reality may be revealed, but even with a slight increase in machine time, robotization will allow achieving results similar in time, significantly increasing quality and consistency of product assembly.

3.5.2 Layout of robotized workstation

Integrating a robot into a human-centric workspace triggers its significant adjustments. Firstly, the use of a small and low-power industrial robot implies dividing the workspace into a robotic assembly zone and a process supply zone. The assembly zone will be separated from the supply zone by light barriers. Additionally, the assembly zone will be equipped with light indicators indicating the status of the robots and the presence of malfunctions and errors. The supply zone is intended for operator actions: it includes a quality assessment area where the robot will deliver parts that have not passed AOI, as well as a finished product area where the robot will deliver the completed items. This zone will allow the operator to add elements and parts of the product without entering the robots' working area.

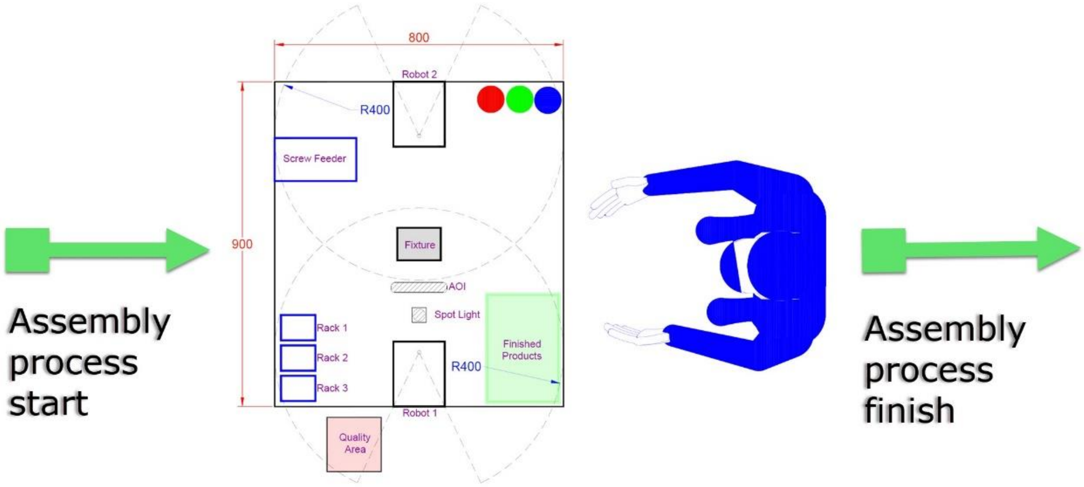


Figure 3.5.2.1. Proposed layout of robotized workstation [Author]

The workstation is a table enclosed by light barriers (not presented on layout). Along the sides of the table, service areas are formed where the operator delivers new components and retrieves both finished products and parts that did not pass AOI inspection. In this configuration, when products are assembled in small batches, it is practical to transport components and finished goods using carts. However, if demand increases, conveyor belts can be used for this purpose. In the center of the table, an assembly fixture is placed. Next to it, there is an AOI camera eyepiece directed upwards, inspecting the microcomputer boards before their installation into the fixture, and a spotlight.

The workstation is connected to the electrical network, compressed air supply, and LAN. Workstation will be equipped with emergency stop button.

Both robots will be situated on their own pedestals positioned opposite sides of the assembly table. Inside this pedestal, there will be a controller box, and a teach pendant for configuring the robot will be affixed to the pedestal’s side.

Pick-and-place components will be stored in the racks on the left side of the Robot#1. Automatic screw feeder will be situated on the right side of the Robot#2. This proximity between the feeder, racks, and EOATs reduces the manipulator's travel distance from the pedestal to the product and back, thereby guaranteeing a swift operational cycle. However, the approbation period will point out the most optimum positions for these parts of equipment.

Finished products will be delivered to “Finished products” zone, on the right side from the Robot#1. Quality area will be situated outside the workstation perimeter, on the stand-alone shelf.

3.6 Performance criteria selection

Processes within a company can either get better or worse. When there's a lack of control, processes tend to deteriorate and might even come to a standstill. To steer processes in the right direction aligned with the company's goals, it's essential to assess them using key performance indicators (KPIs). These KPIs serve as guiding metrics for the desired progression of processes. To evaluate this project, the author selected the following KPIs:

Table 3.6.1. KPI's for new workstation

KPI	**Description**	**Unit of measurement**	**Goal**
Yield	Ratio of good products to total number of products	Percentage	Maximization
Cycle time	Time required to execute the program	Minutes	Minimise
Utilization	Ratio of actual usage time to total time	Percentage	Maximization
Idle time	Time between the end of one program and the beginning of the next	Minutes	Minimise
Time of equipment faults	Time for solving cobot equipment or code issues	Minutes	Minimise

The criteria outlined facilitate an analysis of the effectiveness of the assembly process from various perspectives (productivity, quality, work organization). If any criterion does not meet the defined value, it is essential to analyze the bottlenecks that arise and immediately explore ways to eliminate them.

3.7. Workstation performance improvement

The author's description of the proposed workstation reveals the installation of two robots with varied tasks assigned to them. These robots already constitute a production system, where its actors interact sequentially within the workspace alongside objects such as fixtures and screw feeders, assembling various parts into a cohesive unit—the finished product. The aim is to ensure that the robots do not obstruct each other's movements or idle excessively. To ensure the workstation system operates efficiently, the author will examine opportunities for improvement.

For this task, the author chose to assess and balance the cycle times of robots as an example. A system of two robots with its equipment, assembling one product from start to finish, can be observed as a small assembly line with a set of various tasks. Process of line balancing involves evenly distributing tasks across workstations to ensure they bear similar workloads [69]. Assembly Line Balancing (ALB) represents a foundational challenge in operations research. Ever since Salveson's pioneering mathematical formalization in 1955, scholarly attention has primarily concentrated on the fundamental issue of configuration, namely the allocation of tasks to stations. The bulk of research in assembly line balancing has centered on modeling and resolving the simpler variants of the problem, known as the Simple Assembly Line Balancing Problem (SALBP) [69].

A single-model assembly line is characterized by assemblers working on a single product. In this study, the author analyzes such a system of two robotic assemblers with the aim of enhancing its efficiency. The goal of assembly line balancing is to streamline demand on upstream work centers, manufacturing cells, or suppliers, consequently reducing inventory, eliminating changeovers, and enhancing kanban operation [69].

Since the product is assembled by two different robots, each responsible for specific assembly tasks, the author decided to present the assembly process of one device in the form of a table. Cycle times for each robot were calculated previously in [3.5.1]. In the table below, the task flow is arranged from top to bottom and divided between two SCARA robots: SCARA#1 (pick-and-place, AOI), and SCARA#2 (screwdriving).

Table 3.7.1 Order of tasks and their times of robots before balancing

Tasks of SCARA#1	**Times of SCARA#1**	**Times of SCARA#2**	**Tasks of SCARA#2**
Pick-and-place the upper half of the case to assembly fixture	6,5		
Pick the microcomputer board from the rack and take it to table-fixed AOI camera	6		
Place the board into the assembly fixture, over the upper half of the case	4		
Conduct AOI check of installed board	1		
Pick-and-place the lower half of the case to assembly fixture	6,5		
		20	"Go to feeder – pick the screw – go to product – align the screw"
		20	Tightening the screws
Pick the finished product and place it to finished product area	5		

When the table results are depicted graphically, it becomes evident that the workload of the robots significantly differs.

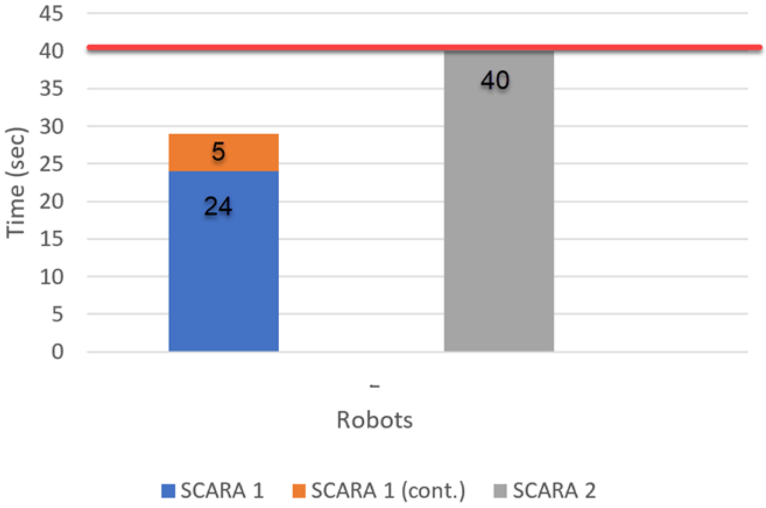


Figure 3.7.1. Robots cycle times comparison before balancing

The graph above illustrates that the cycle time for SCARA#1 robot is shorter than that of SCARA#2 robot, by 11 seconds. Consequently, SCARA#1 robot is idle 28% of the time, resulting in lower utilization compared to SCARA#2 robot.

In the graph [Figure 3.7.1.], the author highlighted with a red line the level of the longest cycle - 40 seconds. The cycle time of SCARA#2 robot represents a classical "bottleneck," and therefore, the author will examine this cycle time to assess the potential for its improvement.

The red line on the graph does not necessarily have to be a "target" that the lower column of the graph should reach. On the contrary, the author believes that with sufficient power reserves both in the robots and in the smart screwdriver, balancing should be achieved by a two-way convergence of indicators.

Since in the section devoted to calculating cycle times [48], the author identified the design features of the product as a restraining factor for a significant increase in the screwdriver's operating speed, the author will not increase the screw tightening speed by more than 20% from the specified value of 300 rpm. On the other hand, the author will allocate additional time for the AOI function, so that imaging can be performed with a smaller aperture and a longer exposure. Such imaging method will improve image sharpness and enable deeper image control by the AOI camera software.

Additionally, the author will reduce the operating speed of SCARA#1 robot at each "pick-and-place" stage to add smoothness to the operation and prevent potential component slippage, which may occur with sharper accelerations.

The initial inputs and results of cycle times of SCARA#1 [Table 3.7.2.] and SCARA#2 [Table 3.7.3.] robots are available below:

Table 3.7.2. SCARA#1 result cycle time after the balancing process

Step	**Time, sec**	**Improved time, sec**	**Change, %**
Pick the upper half of the case and take to assembly fixture	5	6	17%
Place the upper half of the case into the assembly fixture	1,5	1,5	0%
Pick the microcomputer board from the rack and take it to table-fixed AOI camera	6	9	33%
Place the board into the assembly fixture, over the upper half of the case	4	4	0%
Conduct AOI check of installed board	1	3	67%
Pick the lower half of the case and take to assembly fixture	5	6	17%
Place the lower half of the case into the assembly fixture, over the microcomputer board	1,5	1,5	0%
Pick the finished product and place it to finished product area	5	6	17%
Total	**29**	**37**	

Table 3.7.3. SCARA#2 result cycle time after the balancing process

Step	**Time, sec**	**Improved time, sec**	**Change, %**
Cycle "Go to feeder – pick the screw – go to product – align the screw"	20	20	0%
Tightening the screw	20	16,8	-19%
Total	**40**	**36,8**	

The data from both tables indicate changes in cycle time for both robots. In the case of SCARA#1, the execution speed of its program was slowed down by 22%, while the screw tightening program execution speed of SCARA#2 was accelerated by almost 9%. Such adjustments to the robots allowed for almost equalizing the cycle times of both robots, balancing their workload. The cycle times of both robots after optimization can be observed on the graph below.

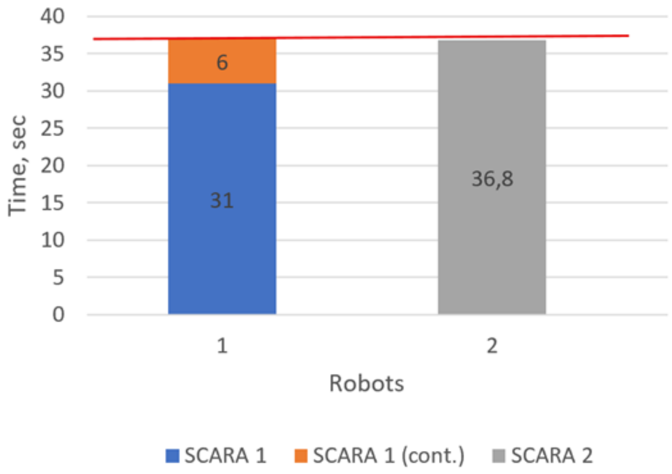


Figure 3.7.2. Robots cycle times comparison after the balancing

Thus, the system consisting of two robots has become balanced, and their cycle times are nearly equal [Figure 3.7.2.]. Consequently, the assembly cell is capable of assembling devices in batches without idling time: by using a pair of fixtures in the center of the table, the robots will work with each fixture sequentially - when SCARA#2 finishes tightening the screws on the first device, SCARA#1 will assemble and inspect the second device on AOI, which SCARA#2 will immediately begin screwing together. If necessary, further optimization of the robotic cell operation can be continued, based on the physical properties and qualities of real products and other factors.

4. IMPLEMENTATION IN THE COMPANY

4.1 Implementation of robot-cell

Introducing robots into production involves more than just buying equipment and changing layouts. It triggers extensive changes across the entire production process and related areas: quality control methods, production planning, and logistics within the production chain. This transition also encompasses tasks like maintaining the robots, programming them, keeping their EOATs in good condition, and training staff to operate them.

Having a robot in an area where people used to work prompts a reevaluation of safety measures. Industrial robot is essentially an electrical manipulator with sturdy parts and impressive speed capabilities. As a result, the Health and Safety department needs to ensure the new workstation adheres to safety standards. Any breaches will require additional steps like more training, extra sensors, or protective curtains to maintain safety standards.

Implementing a robot involves solving complex challenges across different organizational levels. At the enterprise level, the engineering team handles tasks like determining the robot's placement, redesigning layouts, adjusting processes to accommodate the robot, and acquiring necessary additional equipment and furniture. Meanwhile, the factory management secures project funding and offers vital support.

Certified professionals are crucial for installing the equipment and providing initial staff training. To ensure this, the author plans to engage a specialized company, an official dealer of EPSON. The selected EOATs are specifically designed to match the IR specifications, making setup relatively straightforward for the specialists experienced in installing industrial robots.

4.2 Risk analysis

The author pointed out the risks tied to outdated production methods [see Paragraph 2.4], which had adverse effects on both the product and personnel. By reexamining these risks constructively, the author identified new opportunities for development, leading to the adoption of robotization in the assembly process. However, because the robotization process is interconnected with other factors, conducting a thorough risk analysis remains essential.

The introduction of innovations into the production process is always a step into the unknown. The project in the author’s thoughts is often surrounded by an aura of infallibility, which prevents one from looking soberly at the circumstances of the surrounding reality and assessing possible threats to the project. These risks encompass both external and internal factors, offering the potential for complete avoidance or partial mitigation. Some threats lie beyond one's control, necessitating acknowledgment and consideration of their influence on the project's outcome. And if there is a threat, there might be a risk.

The ISO 31001:2018 Risk management standard defines risk as an „‟effect of uncertainty on objectives”, which focuses on the effect of incomplete knowledge of events or circumstances on an organization’s decision making‟ [70].

When integrating a new solution in the production process, it's crucial to thoroughly analyze it from all angles. This involves upskilling team members to identify potential risks during the planning phase. While aiming to eliminate risks upfront is ideal, some may persist due to cost constraints or other factors. Therefore, these risks should be incorporated into risk analysis in a form of the risk matrix, assessing their severity and possibility, and developing strategies to reduce their impact.

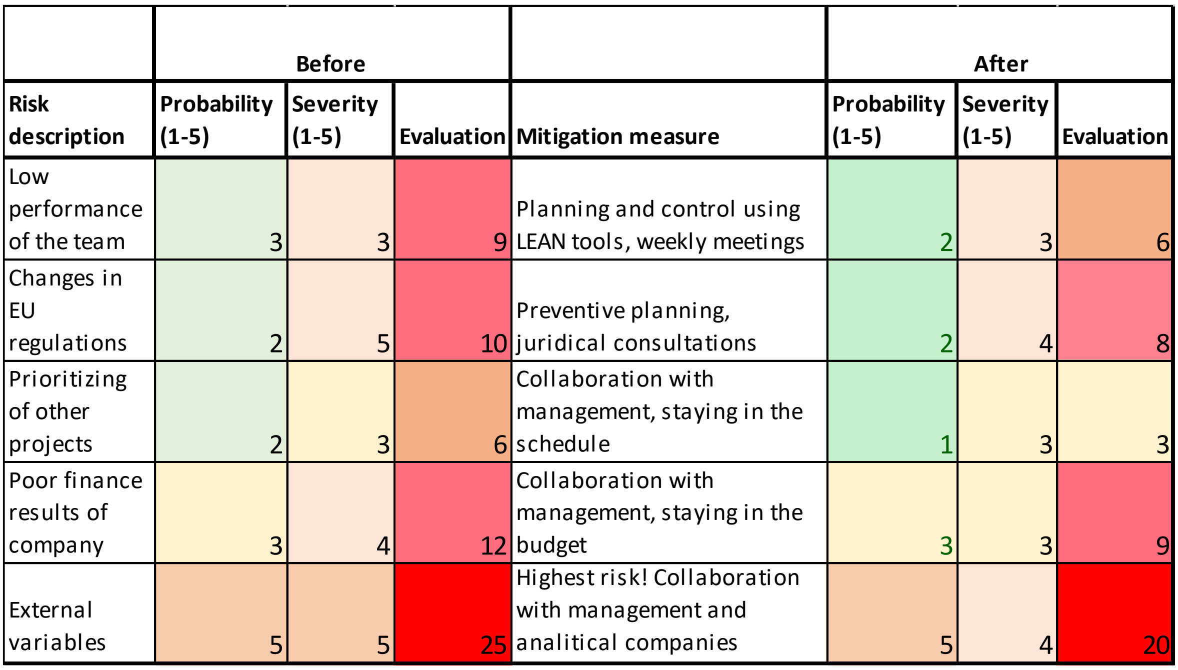
Risks can be devided into operational, and non-operational. The first group deals with the practical implementation and operational aspects of the project. The second group focuses on broader processes such as finance, strategy, and regulatory considerations.

The risk matrices indicate that certain risks, particularly those linked to external factors, may not be adequately mitigated, necessitating the company's acknowledgment and acceptance of these inherent risks. However, many operational risks can be lessened through the implementation of additional preventive measures.

Table 4.2.1. Risk matrix of operational risks

	Before				After		
Risk description	**Probability (1-5)**	**Severity (1-5)**	**Evaluation**	**Mitigation measure**	**Probability (1-5)**	**Severity (1-5)**	**Evaluation**
Robot malfunction	2	4	8	Preventive maintenance, personnel training	1	4	4
EOAT malfunction	2	4	8	Preventive maintenance, personnel training	1	4	4
Safety equipment failure	2	5	10	Preventive maintenance, personnel training	1	5	5
Lack of programmers	3	4	12	Hiring/training of personnel	1	4	4
Wrong location in layout	3	3	9	Simulations, solution's approbation period	2	3	6
Vandalism	2	5	10	Explaining the role of cobot, video control. Registration of emergency stops	1	5	5
Power loss	2	5	10	External UPS, preventive maintenance	1	5	5
Connection loss	3	4	12	External flash drive, preventive maintenance	1	4	4

Table 4.2.2. Risk matrix of non-operational risks



	Before				After		
Risk description	**Probability (1-5)**	**Severity (1-5)**	**Evaluation**	**Mitigation measure**	**Probability (1-5)**	**Severity (1-5)**	**Evaluation**
Low performance of the team	3	3	9	Planning and control using LEAN tools, weekly meetings	2	3	6
Changes in EU regulations	2	5	10	Preventive planning, juridical consultations	2	4	8
Prioritizing of other projects	2	3	6	Collaboration with management, staying in the schedule	1	3	3
Poor finance results of company	3	4	12	Collaboration with management, staying in the budget	3	3	9
External variables	5	5	25	Highest risk! Collaboration with management and analitical companies	5	4	20

5. PERFORMANCE ANALYSIS

5.1 Performance measurement

Overall Equipment Effectiveness (OEE) is a pivotal metric in evaluating the efficiency of a robotic cell in manufacturing [71]. It assesses the utilization of equipment, focusing on three primary factors:

1. Availability: OEE measures the actual uptime of the robotic cell against its planned operational time. Any instances of downtime, including maintenance, changeovers, or breakdowns, impact availability. Availability can be calculated using formula:

$$Availability = \frac{Operating\ time}{Planned\ production\ time} \tag{5.1}$$

2. Performance: This factor evaluates how effectively the robotic cell performs during its operational periods. It considers factors like cycle time, speed losses, and any slowdowns affecting production. The formula for performance calculations is following:

$$Performance = \frac{Cycle\ time \times Product\ quantity}{Operating\ time} \tag{5.2}$$

3. Quality: OEE also accounts for the quality of output. It tracks defects, errors, or rework needed, indicating the proportion of good-quality output against the total produced. Quality is calculated as follows:

$$Quality = \frac{Good\ count}{Total\ count} \tag{5.3}$$

By combining these elements, OEE provides a comprehensive view of how efficiently the robotic cell operates, highlighting areas for improvement. Availability, performance and quality coefficients should be multiplied to each other to recieve the OEE coefficient.

$$OEE = A \times P \times Q, \tag{5.4}$$

where: A – *Availability;*

P – *Performance;*

Q – *quality.*

A high OEE score signifies that the robotic cell is operating at maximum capacity, with minimal downtime, optimal performance, and high-quality output. The closer the result to 1, the better is the OEE. Analyzing OEE helps in identifying opportunities to enhance productivity, reduce inefficiencies, and optimize the performance of the robotic cell in manufacturing processes. Despite the large number of additional performance indicators, OEE is a complex indicator, containing inputs from the sides of equipment utilization, production quality, product delivery and the technical state of equipment. This data is usually monitored live by using the performance monitoring software such as „MachineMetrics‟ [72] or „FactoryFour‟ [73]. The author is emphasizing that choosing not to invest in software for monitoring the efficiency of robotic production is a pivotal point where the meaningful advantages of robotization might be lost.

5.2 Payback period calculation

The payback period refers to the time it takes for an investment to generate enough income or cost savings to cover the initial investment cost. It's a financial metric used to evaluate the time required to recoup the investment in a project or asset. Typically, a shorter payback period is preferred as it indicates a quicker return on investment. For the case of this study, the robotized workstation will reduce the required labor time by almost 49% and will reduce throughput time by 14% [see Paragraph 3.5.1]. This data will help to determine the payback period.

The product assembly process involves two essential operators: one for assembly and another for managing support and transportation tasks.

Reducing manual assembly time by 49 percent shows the opportunity to switch the assembly operator from assembling to observation, support and transportation task, reducing one position. This optimization significantly enhances efficiency, especially during periods of decreased product demand.

Before computing the payback period, it's essential to ascertain the project's cost. The investment figures for the project are outlined in the table provided below [Table 5.2.1]:

Table 5.2.1. List of items and services needed for implementation of robot cell.

Equipment	**Type**	**Quantity**	**Price, €**	**Total**
Robotiq SD100	Smart screwdriver	1	8087	8087
Robotiq EPick	Vacuum gripper	1	5679,1	5679,1
OnRobot Eyes	Camera system	2	7401,74	14803,5
OM-26R26	Screw feeder	1	710,69	710,7
SCARA T3-B401S	SCARA robot	2	9556	19112
Robots pedestals	Furniture	2	3500	7000
Installation	Works	1	5000	5000
Training	Training package	1	5000	5000
Overhead	Unexpected expenses	10%	65392,27	6539,2
			Total	**71931,5**

Now it is essential to compare two workstation setups: manned only (2 operators) and robotized workstation (1 operator and 1 industrial robot). The Department of Statictics of Estonia provides information on employers total labour cost, for 4.quarter of 2023, in electronics production sector [74]. According to provided data, it equals 2437€ per month, or 29244€ per year for one employee.

Eurostat data on labor cost shows positive growth of labor cost by 5,7% in EU per year [75]. This input was used to estimate the growth of labor cost in Estonia for next four years. The inflation rate in Estonia in February of 2024 was 4,4% according to Eurostat [76], and starting from 1.January of 2024, Estonia increased its VAT by 2% [77].

So for operating cost estimation the author uses coefficient of 6,4% to simulate yearly growth of operating costs. Operating cost for collaborative robotized workstation is higher than operating cost of manned workstation due to cobot's electricity consumption.

The final payback period calculation table is available below.

Table 5.2.2. Expenses comparison and payback period calculation

Years	**2024**	**2025**	**2026**	**2027**
Manned workstation expenses, €				
Yearly salary of 2 operators	58488	61821,82	65345,66	69070,36
Operating cost	3000	3192	3396,29	3613,65
Total cost	61488	65013,82	68741,95	72684,01
Cost cumulatively	61488	126501,82	195243,76	267927,78
Robotized workstation expenses, €				
Project initial investment	71931,50			
Yearly salary of 1 operator	29244,00	30910,91	32672,83	34535,18
Operating cost	4000,00	4256,00	4528,38	4818,20
Robot maintenance	7000,00	7448,00	7924,67	8431,85
Total cost	112175,50	42614,91	45125,89	47785,23
Cost cumulatively	112175,50	154790,41	199916,29	247701,52
Profitability calculation results, €				
Profitability difference by year	-50687,50	22398,908	23616,06	24898,78
Profitability cumulatively	-50687,50	-28288,59	-4672,53	20226,25

The conclusive payback table for the project suggests a substantial yet not the lengthiest payback period, approximately around 3.2 years. However, successful design iterations often yield subsequent product generations, matching earlier models in weight and size but featuring more intricate electrical components. This suggests potential suitability for utilizing this equipment setup in assembling future devices sharing a similar constriuction.

Furthermore, the ability to incorporate additional tools into the EOAT fleet enables the workstation's versatility in assembling diverse products. Consequently, from the perspective of a manufacturing engineer, this concept of a robotic workstation undoubtedly holds promise within the company. Nevertheless, the decision to greenlight the project and allocate funding rests with the company's board of directors, possibly involving a shareholder vote in the process.

SUMMARY

The main objective of this work was to analyse the possibilities of robotizing an assembly process of the product, which consists of microcomputer and protective case enclosure. To achieve this goal, the author needed to determine the capabilities of robots in production, their features, advantages and disadvantages.

Convinced of the primary potential of robotization of the assembly process, the author examined the device itself, its composition, structure, as well as the assembly process, and the workstation. Having assessed the current situation with the product assembly and identified the current risks, the author carried out the process of justifying the robotization of the process, which showed a positive result. According to this result, as well as the previously described features of the robots, product and work process, the author identified a type of robot suitable for these inputs – SCARA industrial robot.

Having data on the product, its assembly process and its features, as well as knowing the type of robot, the author began to create a robotic workplace and optimize the product assembly process. The author determined which assembly steps will be robotized and which will be left to the operator. Further, the author defined the level of interaction between the robot and the operator as sequential collaboration. In order to estimate the time required to assemble one product, the author conducted full-scale experiments simulating assembly conditions with 3D-printed parts and actual components of the examined product.
Using this data, the author compiled a calculation of the assembly labor time required for one device. Having defined these times as a benchmark, the author examined in detail the manual assembly steps that the author planned to robotize. Based on these descriptions, the author derived a list of EOATs that would be required for the robot to perform these tasks.

Based on the data of the selected setup, as well as the features of the product, the author began to select a specific model of a collaborative robot. After comparing and analyzing cobots with similar parameters, the author settled on one model – EPSON T3-B401S.

Using the specifications of the robot and its EOAT, as well as knowledge about the structure of the product, the author calculated the expected parameters of cycle time, throughput time, and based on them, the author calculated the possible benefits of robotization of the product assembly process. Following this, a set of criteria to evaluate

project effectiveness was established, along with the optimization process conducting a thorough risk analysis, and computing the project's payback period.

The thesis successfully achieved its primary objective. Consequently, the author developed a comprehensive solution for the automated assembly process using setup of two SCARA robots along with modern EOAT solutions. Additionally, with slight modifications, this same workplace setup could be adapted for various other assembly tasks.

The emergence of automating manual production processes is becoming increasingly prevalent. Previously, robotization necessitated uninterrupted production to justify its cost. However, with the advent of affordable industrial and collaborative robots, small businesses can now engage in robotizing routine tasks and cost optimization. Through this research, the author effectively demonstrated how implementing production automation through robotics can substantially cut costs while elevating overall quality. The approach employed by the author holds practical applicability in real-world scenarios.

KOKKUVÕTE

Käesoleva töö peamine eesmärk oli analüüsida robotiseerimisvõimalusi toote koosteprotsessis, mis koosneb mikroarvutist ja kaitsekorpusest. Selle eesmärgi saavutamiseks pidi autor kindlaks määrama robotite võimalused tootmises, nende omadused, eelised ja puudused.

Veendunud robotiseerimise koosteprotsessi peamises potentsiaalis, uuris autor seadet ennast, selle koostist, struktuuri, samuti montaažiprotsessi ja tööjaama. Hindanud praegust olukorda toote montaažiga ning tuvastanud praegused riskid, viis autor läbi robotiseerimise protsessi õigustamise, mis näitas positiivset tulemust. Selle tulemuse põhjal, samuti eelnevalt kirjeldatud robotite, toote ja tööprotsessi omaduste põhjal, määras autor sobiva robotitüübi – SCARA tööstusrobot.

Omades andmeid toote, selle montaažiprotsessi ja omaduste kohta ning teades robotitüüpi, hakkas autor looma robotiseeritud töökohta ja optimeerima toote montaažiprotsessi. Autor määras, millised montaaži etapid robotiseeritakse ja millised jäävad operaatori kanda. Edasi defineeris autor roboti ja operaatori vahelist suhtlustasandit kui järjestikust koostööd. Ühe toote monteerimiseks vajaliku aja hindamiseks viis autor läbi täismahus eksperimente, simuleerides montaažitingimusi 3D-prinditud osadega ja uuritava toote tegelike komponentidega.

Kasutades neid andmeid, koostas autor arvutuse ühe seadme koostetöö aja kohta. Määratledes need ajad lähtepunktina, uuris autor põhjalikult manuaalsed montaaži etapid, mida autor kavatses robotiseerida. Nende kirjelduste põhjal koostas autor nimekirja EOAT-idest, mida roboti ülesannete täitmiseks vajatakse.

Valitud seadistuse andmete ja toote omaduste põhjal hakkas autor valima konkreetset roboti mudelit. Pärast võrdlemist ja analüüsimist sarnaste parameetritega robotitega, valis autor ühe mudeli – EPSON SCARA T3-B401S.

Kasutades roboti ja selle EOAT-i tehnilisi näitajaid ning teadmisi toote struktuurist, arvutas autor oodatava tsükliaja, tootmise aja ja põhjal nende põhjal robotiseerimise võimalikke eeliseid. Järgnes projekti tõhususe hindamiseks kriteeriumide komplekti koostamine, süsteemi tootluse optimeerimine, põhjalik riskianalüüs ja projekti tasuvusperioodi arvutamine.

Magistritöö saavutas edukalt oma peamise eesmärgi. Seega arendas autor tervikliku lahenduse automatiseeritud montaažiprotsessi jaoks, kasutades kahte SCARA robotit koos kaasaegsete EOAT lahendustega. Lisaks võiks seda töökohta kohandada erinevateks muudeks montaažiülesanneteks.

Käsitsi tootmisprotsesside automatiseerimine muutub üha enam levinuks. Varem nõudis robotiseerimine katkematut tootmist, et õigustada selle kulusid. Kuid odavate tööstuslike ja koostöörobotite saabumisega saavad väikeettevõtted nüüd robotiseerida rutiinseid ülesandeid ja kulude optimeerimist. Selle uurimistöö kaudu näitas autor tõhusalt, kuidas tootmise automatiseerimine robotite abil võib märkimisväärselt vähendada kulusid, samal ajal tõstes üldist kvaliteeti. Autori poolt kasutatud lähenemine on praktiliselt rakendatav reaalmaailma olukordades.

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APPENDICES

APPENDIX 1

Table 2.4.8. Feasibility analysis of assembly process robotization

Technology	Handling of assembly components		
	[✓ No experience (1 point)]	solution is developed (3 points)	Solution is used for assembly automatization (5 points)
	Feeding of assembly components		
	[✓ No solution (1 point)]	Solution exists and is implemented to some extend (3 points)	Different types of feeding mechanisms are used (5 points)
	Is it possible to use group or standard technology solutions?		
	No (1 point)	[✓ For some extend (3 points)]	Possibilities for optimizing the assembly process have been analyzed (5 points)
	Is there a need for takt time synchronization?		
	No (1 point)	[✓ For some extend (3 points)]	It is needed (5 points)
	Is there a demand for decreasing cycle time?		
	No (1 point)	For some extend (3 points)	[✓ Yes (5 points)]
TOTAL	**13**	**Conclusion**	**Moderate expediency**

Product	Formation level of product families		
	Weak (1 point)	[✓ Average (3 points)]	Large (5 points)
	Design for cost-effective assembly is part of product development process?		
	No (1 point)	[✓ Conditionally possible to add (3 points)]	Yes, it already works (5 points)
	Number of products in assembly process		
	Small (individual production) (1 point)	[✓ Medium (Batch production) (3 points)]	Large (large series or mass production) (5 points)
	Nomenclature of products		
	Large (individual production) (1 point)	[✓ Medium (batch production) (3 points)]	Small (large series or mass production) (5 points)
	Robotization will disturb production rhythm?		
	Yes (1 point)	For some extend (3 points)	[✓ No (5 points)]
Total	**17**	**Conclusion**	**Moderate expediency**

Objectives and situation in the company	Is there a need for new labour?		
	No need for new labour (1 point)	[✓ Need exists (3 points)]	Need exists (3 points)
	Improvement of product quality is needed?		
	No (1 point)	[✓ Need exists (3 points)]	Urgently needed (5 points)
	Assembly operation is a bottleneck?		
	No (1 point)	[✓ Occasionally (3 points)]	Constant bottleneck (5 points)
	Increase of production output		
	Not needed (1 point)	[✓ Need exists (3 points)]	Urgently needed (5 points)
	Current assembly equipment and process are amortized or outdated?		
	No (1 point)	There is a need for upgrade(3 points)	[✓ Upgrade is required (5 points)]
Total	**17**	**Conclusion**	**Moderate expediency**

Experiences and opportunities of the company	Experience in digitalization		
	Slight (1 point)	Some experience (3 points)	[✓ Several solutions are implemented (ERP, MES, CAD, etc.) (5 points)]
	Experience in robotization		
	[✓ No experience (1 point)]	Company uses 1-2 robots (3 points)	Company has broad knowledge and experience (5 points)
	Financing opportunities		
	Few, state support is needed (1 point)	[✓ Average (3 points)]	Sufficient to implement even large-scale projects (5 points)
	Experiences in the implementation of investment projects		
	Slight (1 point)	[✓ Average (3 points)]	Large (5 points)
	Experience and competence of robot operators and technicians		
	[✓ Few (1 point)]	Average (3 points)	Great skills and knowledge (5 points)
Total	**13**	**Conclusion**	**Moderate expediency**

APPENDIX 2

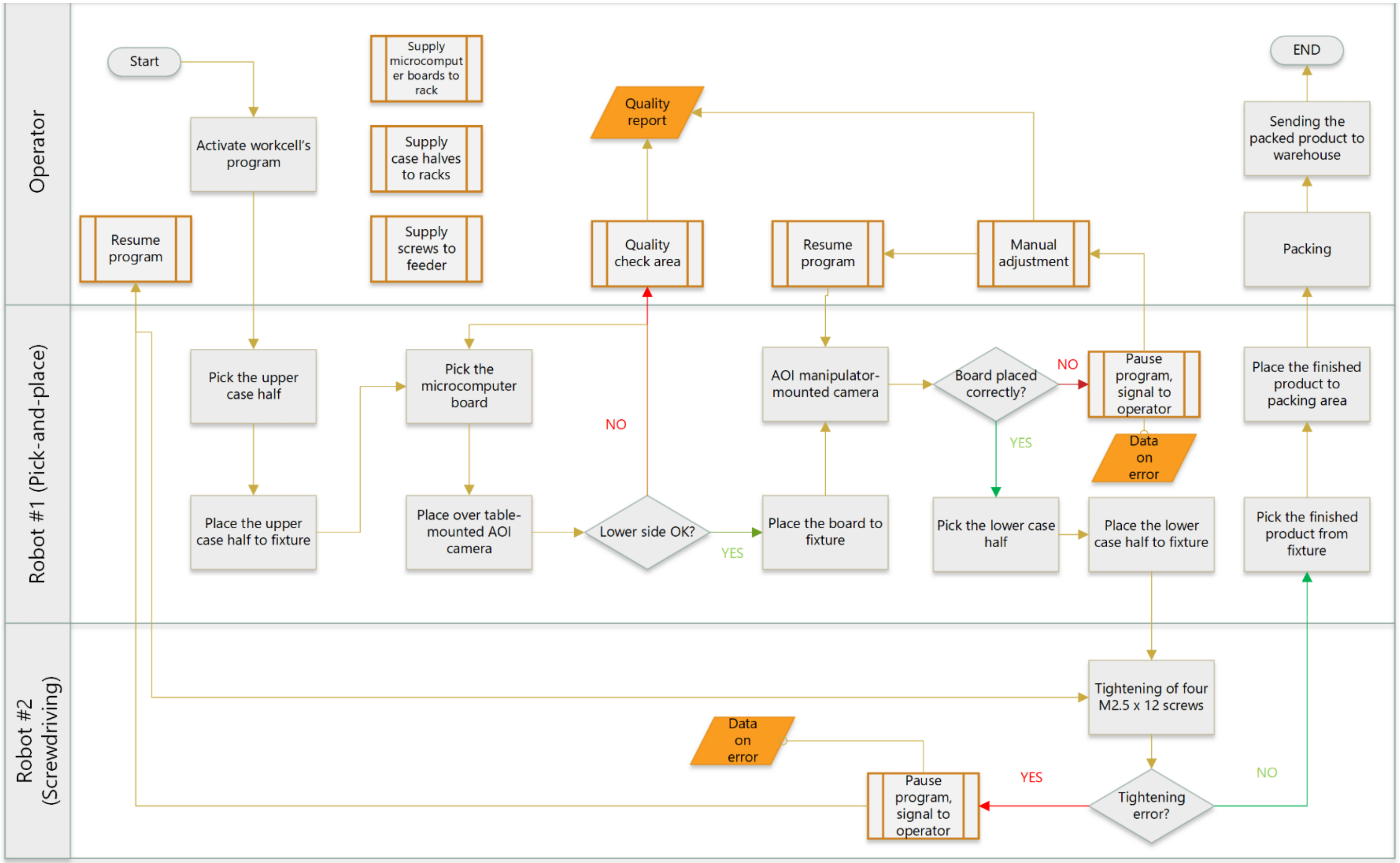

Figure 3.4.1. Product robotized assembly flowchart