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INDUSTRIAL ROBOTICS IN LOGISTICS

Possibilities to utilise collaborative robotics in 3PL operations

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Opinnäytetyön tavoitteena oli tehdä selvitystyö yhteistyörobotiikan hyödyntämisestä kittiprosessissa. Työ tehtiin DHL Supply Chain Finland Oy:n erään varaston operaatiossa, jossa kittioperaatiot ovat merkittävässä roolissa. Yrityksen strategiakaudet 2025 ja 2030 nojaavat vahvasti digitalisaatioon ja sen mahdollisuuksien hyödyntämiseen. Selvitystyön tavoitteena oli myös kerätä tietoa teollisuusrobotiikasta, oppia ymmärtämään sen tuomista mahdollisuuksista kehittää operaatioita ja tuottaa analyysi tarvittavista muutoksista ja sen vaikutuksista. Käytännön tavoitteena oli tuoda uutta teknologiaa näkyviin toimipisteelle testaamalla robotiikkaa toimipisteessä.

Työ toteutettiin monimenetelmäisenä tutkimuksena, jossa hyödynnettiin niin laadullisia tutkimusmenetelmiä kuin kehittämistutkimuksellisia menetelmiä. Työn alussa määriteltiin kolme tutkimuskysymystä, joihin haettiin vastauksia tutkimalla yhteistyö- ja teollisuusrobotiikkaa, ruuvaus- ja pakkausautomaatioita, kartoittamalla markkinoilla olevaa tarjontaa ja kititys-prosesseja sekä toteuttamalla pilot-kokeilu valituilla prosesseilla yrityksen toimitiloissa. Laadullisia aineistonkeruumenetelmiä käytettiin käymällä läpi dokumentteja ja kirjallisuutta kartoitus- ja tiedonhakuvaiheissa sekä havainnoimalla prosessien nykytilaa ja pilot-kokeiluja. Kehittämistutkimuksellisia tutkimusmenetelmiä hyödynnettiin pilot-kokeilussa käytännön testaamisen, sen arvioinnin ja ratkaisuehdotuksiin uusiksi prosesseiksi.

Tutkimuksen tuloksista selviää, että yhteistyörobotiikka soveltuu niin ruuvaus- kuin pakkaustyön automatisointiin muuttamalla hiukan manuaalisia prosesseja. Markkinoilla on tarjolla ruuvaukseen ja pakkaamiseen soveltuvia yhteistyörobotteja, työkaluja ja muita oheislaitteita prosessien toteuttamiselle. Pilot-kokeilussa havaittiin, ratkaisun soveltamiseen ja käyttöönottoon tarvitaan lisää tutkimusta ja panostusta mitkä on nostettu kehityskohteiksi.

Johtopäätöksenä voidaan todeta, että ruuvaus- ja pakkaustyövaiheiden automatisointi yhteistyörobotiikalla onnistuu, mutta tarvitaan lisätutkimusta ja panostusta niin yrityksen kuin asiakkaan puolelta. Pilot-kokeilussa testattiin PoC-lähestymistavalla yleisesti yhteistyörobotiikan soveltuvuutta eikä testiolosuhteita pysytty täysin optimoimaan kaikilta osin.

Avainsanat Robotiikka, käyttöönotto, logistiikkapalvelut,
Sivut 240 sivua ja liitteitä 3 sivua

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Transinformative Leadership and Smart Services		Abstract
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This thesis aimed to investigate the use of collaborative robotics in the kitting process within a warehouse operation at DHL Supply Chain Finland Oy, where kitting plays a crucial role in the overall operation. The company's 2025 and 2030 strategic periods emphasise digitalisation and the opportunities it presents. The study also aimed to gather information on industrial robotics, understand their potential for improving operations, and analyse the necessary changes and their impacts. The practical goal was to introduce new technology to the office by testing robotics on-site.

The research was conducted using a multi-method approach, incorporating both qualitative and intervention research methods. At the beginning of the research project, three research questions were defined and explored through the study of collaborative and industrial robotics, screwdriving and packaging automation, market offerings, and kitting processes, alongside a pilot trial conducted in the company's facilities. Qualitative data collection involved document analysis, literature review, and process observation. At the same time, interventional research methods were used in the pilot trial to test practical applications, evaluate results, and propose new process solutions.

Findings indicate that collaborative robotics is suitable for automating screwdriving and packaging tasks with minimal process changes. The market offers a range of collaborative robots, tools, and supporting equipment for these processes. The pilot trial revealed that further research and investment are needed for implementation and adoption, which were identified as key areas for development.

In conclusion, automating screwdriving and packaging with collaborative robotics is feasible, but additional research and investment are required from both the company and its customers. The Proof of Concept (PoC) approach used in the pilot trial assessed general applicability, though testing conditions were not fully optimised.

Keywords	Robotics, implementation, logistics services
Pages	240 pages and appendices 3 pages

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Appendices

Appendix 1. Assembly Kit 2
Appendix 2. Assembly Kit 1
Appendix 3. Business Unit 2 - Product Family 1 Kit

TERMS AND ABBREVIATIONS

AI	Artificial Intelligence
AGV	Automated guided vehicle
AMR	Autonomous mobile robot
AR	Augment reality. Physical world is projected through camera or video viewer and visualised to the screen.
BCE	Before Common Era
DPDHL Group	Deutsche Post DHL Group
DHL Group	Deutsche Post DHL Group
DIY	Do It Yourself
DOF	Degree Of Freedom
DSC	Supply Chain Division in DPDHL Group
DSC FI	DHL Supply Chain (Finland) Oy
EEA	European Economic Area
EOAT	End Of Arm Tool
ESD	Electrostatic discharge: a sudden and often imperceptible flow of electric current
EU	European Union
GDP	Gross domestic product
GM	General Motors
HFE	Human factors / ergonomics
IEA	International Ergonomics & Human Factors Association
IFR	International Federation of Robotics
Insourcing	The assignment of an action to a department within a company rather than to a third party. Opposite of outsourcing.
ISO	International Organisation of Standardization
MRO	Maintenance, Repair and Operations
MTO	Make to Order: The products are manufactured for the quantity required for the order or orders
MTS	Make to Stock: The products are transferred into the warehouse, from where they are collected for orders later
OEM	Original Equipment Manufacturer
Outsourcing	The assignment of an action to a party outside a company. This party is usually called a third party. Opposite of insourcing.
PL	Performance level of security system
PLC	Programmable Logic Controller or Programmable Controller
PoC	Proof of Concept

RaaS	Robot-as-a-Service. A business model in which robotics companies offer the use of their robot devices via a subscription-based contract.
SIPOC	Stands for Supplier, Input, Process, Output and Customer
SKU	Stock Keeping Unit: unit of measure in which the stock of material is managed
TCP	
Third party (3rd party)	A service provider who is not directly controlled by either the seller or the customer/buyer in business transaction.
VAL	Value Added Logistics
VAS	Value Added Services
VR	Virtual reality. Computer-generated simulation which is viewed through special equipment’s such as computer, sensors, headset and gloves.
WMS	Warehouse Management System

1 Introduction

My interest in digitalisation, automation and knowledge management was a key driver, which is why I decided to apply to study this degree program. The decision is also based on the current strategy, "Strategy 2025 - Delivering excellence in a digital world" of the DHLDP Group (hereinafter referred to as DHL). The main cornerstone is in digitalisation and its possibility to achieve long-term growth. In numbers, DHL has outlined that at the Group level, DHL will invest 2 billion EUR cumulatively through to 2025 in digitalisation. At the same time, it is expected to gain at least 1,5 billion EUR yearly benefit by FY2025. (DPDHL Strategy 2025 press release)

The DPDHL Group Strategy 2025 outlines clear guidelines for operations and directions for its development. Digitalisation and sustainability are integral to its approach. Sustainability encompasses both the Safety First and Go Green policies, which, in the context of DHL, refer to prioritising the environment and people (DPDHL Strategy 2025 press conference, p. 21).

Sustainability and sustainable development are on the agenda of both DPDHL Group and HAMK University of Applied Sciences. Thesis competition instructions by HAMK guide the student to examine their chosen topic area from the perspective of sustainable development. The new DPDHL Group Strategy 2030 is named "Accelerate sustainable growth" by taking care of the environment from a carbon neutrality perspective, not to mention striving to create and maintain a safe and healthy workplace valued by diversity and trust. Digitalisation is one of the tools used to achieve the values. (DPDHL, n.d.; HAMK, 2025)

This thesis describes a research and investigation project on the possibilities of robotics in general, with an emphasis on collaborative robotics in one of DHL Supply Chain (Finland) Oy's warehouses. The purpose is to study robotics, its accessories, tooling and implementation processes as well as warehouse processes where this technology could be utilised. As a result of the thesis, it will provide calculations and estimations of the appropriate process.

The results are outlined based on safety, efficiency, and future process needs and possibilities. The results are also viewed from the perspective of sustainable development.

1.1 Basic background info of the company and its services

DHL Supply Chain is the global leader in contract logistics, managing supply chains for customers as a third-party logistics (3PL) provider across 50+ countries with 185,000 employees (Logistics Management, 2020). The company prioritises process standardisation and leverages advanced technologies such as indoor robotic transport, collaborative picking and packing robots, and data analytics to enhance efficiency.

DHL Supply Chain (Finland) Oy (DSC FI) specialises in material storage, production material flow management, and aftermarket shipment handling. These core services are supported by value-added solutions, including preparation for dispatch via different transport modes and, when required, freight forwarding.

DSC FI operates in both warehouses and in customer facilities, renting warehouse space based on strategic needs such as location and operational suitability. Contract length also influences the warehouse role as leases are aligned with customer contracts.

DSC FI’s multi-customer warehouses support various businesses simultaneously, sharing resources and service infrastructure. Operational schedules vary: some units run 24/5, while most operate 12 hours on weekdays, with emergency service options available for maintenance-based customers.

1.2 Purpose, aim and delimitations of the thesis work

This study evaluates the feasibility of implementing a robotic arm within a DHL-operated warehouse kitting process. A pilot program will assess practicality, with recommendations guided by rough cost-benefit calculations, aligned with DHL's Business Case Application (BCA) process if necessary. One part of the thesis focuses on outsourcing logistics and the role and the possibilities for a 3PL service provider to automate in its operating environment. In addition, the possibilities for robotisation in other units are being mapped at a rough level, but their processing is outside of this work.

Inspired by a successful collaborative robotics packaging solution in Central Europe, this thesis explores its viability in Finland. The selected multi-customer warehouse plays a key role in kitting services, making it a promising candidate for automation. Kitting, however, involves predictable, repetitive tasks at sufficient volume, making automation viable, especially with Make-to-Stock (MTS) kits, which offer consistency.

The pilot phase will showcase the benefits of digitalisation for staff and customers while aligning with DHL's Strategy 2025. Beyond cost savings, automation will be assessed for its impact on safety, operational flexibility, and scalability. In-house kit manufacturing further enhances DHL's competitiveness.

This study excludes software robotics (RPA), transportation robotics, goods-to-person automation, and service robotics. Possible warehouse infrastructure and IT modifications are also out of scope. The research will be conducted in collaboration with the operational team.

2 Strategic point of view

This chapter describes the strategic decisions and reasons to outsource its processes to a 3PL service provider. There are opportunities for a 3PL service provider to expand the customer relationship from buyer-supplier to a partnership, and in doing so, provide value-added services.

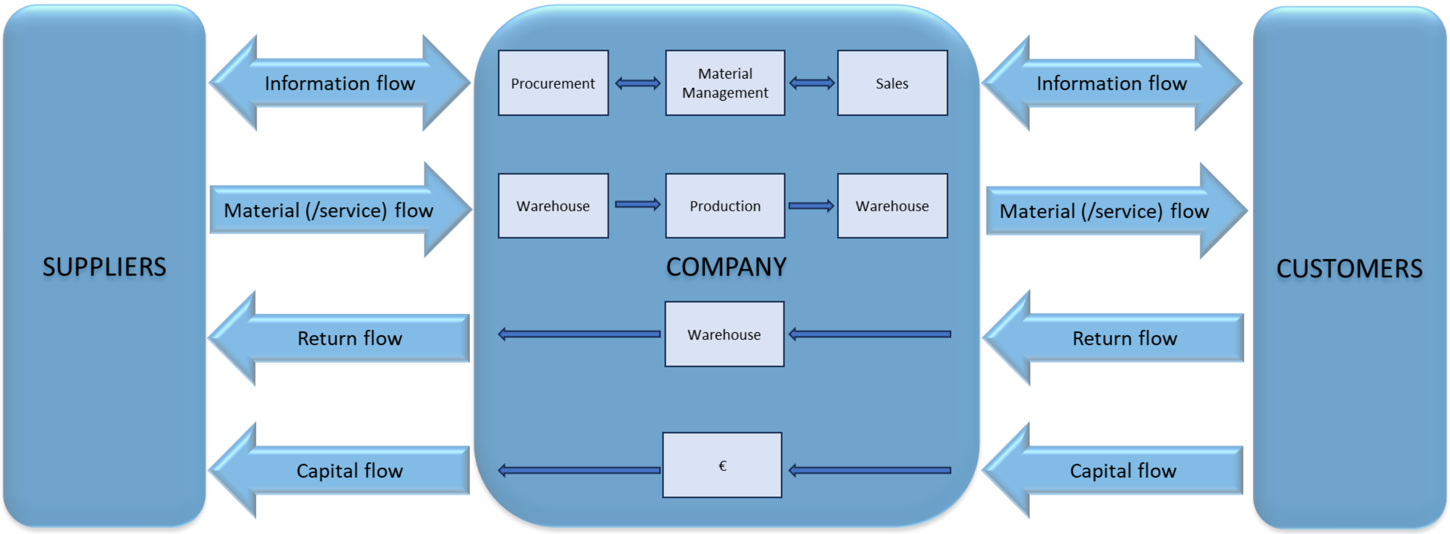
2.1 Basics of Supply Chain, its flows and networks

A supply chain is described as a network where different organisations manage and develop material and service flows, as well as related capital and information flows. The structure and size of the supply chain depend on the products and industry in which the company operates, as well as its customers. There can be many different parties in the entire supply chain, including suppliers' suppliers, wholesalers, retailers and customers' customers. The organisations belonging to the supply chain each have their role, and the company is connected to the chain. In this entity, the emphasis is on cost efficiency, customer orientation, and added value throughout the chain. (Ritvanen et al., 2011, p. 22)

Supply chain management is a newer and broader concept than logistics management. Examining the management of material and information flows within an organisation, it is referred to as logistics management. When these processes become more extensive and flows connect multiple organisations, it is called supply chain management. A supply chain within an organisation exists, but the management of the supply chain requires that the organisation plans and manages it effectively. The focus in supply chain management is relationship management, which presents challenges to operations in situations where the organisation's interests’ conflict with the benefits of the entire chain. (Christopher, 2016, pp. 2-3, 15)

Different flows of the supply chain are illustrated in Figure 1. The information flow is usually described as the initiator of the entire logistics process. However, the information is exchanged at every step of the process, including different balances, status and billing information as well as information about the materials generated for the package. Capital flow is the consideration paid for the delivered product, and capital flow is always opposite to the material (/service) flow. Return flow consists of waste or by-product flows generated during material flow. Return flow is also part of return logistics, which includes possible customer returns, service and warranty returns and recycling. One of the functional return logistics flows is the bottle return process in Finland, where consumers return up to 97% of bottles. (Ritvanen et al., 2011, p. 22)

Figure 1 - Flows in the supply chain (Adapted from Salmenkari, 2000, p. 153)

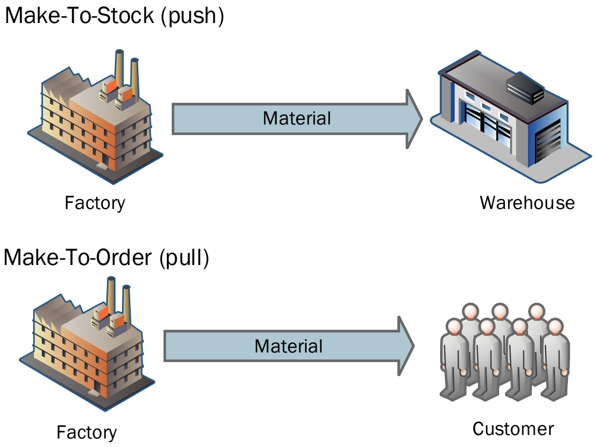


The supply chain can be pretty long, depending on the number of steps incurred by, for example, intermediate wholesalers and logistics companies. Each step adds costs, and more time is spent. The management of the supply chain refers to the comprehensive planning and management of the company's material flow, related information, and capital flow. (Ritvanen et al., 2011, p. 23)

In addition to SCM, there is also the term DCM (Demand chain management). This is used when it is wanted to emphasise the importance of demand and demand information. Unpredictable or poorly predicted demand leads to poor performance in the supply chain. (Ritvanen et al., 2011, p. 23) Toyota's production system is described as a change maker in how products are produced. The Toyota Production System (TPS) was developed based on customer demand, rather than pushing products based on forecasts into the warehouse.

Based on the customer demand, products are pulled to the market. The difference is illustrated in Figure 2.

Figure 2 - Push and Pull production strategies (Adapted from Tarantino, 2022, p. 25)



The supply chain's purpose is to improve competitiveness and ensure that it meets the customer's needs. It is not so much that individual companies compete with each other; rather, it is more a matter of competition between different supply chains. Efforts are made in the chain to minimise the costs of the entire chain and deliver products to customers in accordance with the agreed service level. (Ritvanen et al, 2011, p. 24)

2.2 Partnership in the supplier network

Hakanen et al. (2007) define a partnership as a close and established relationship between two organisations. The cooperation in this relationship is goal-oriented and is characterised by long-term commitment and trust. (p. 77) Ståhle & Laento (2000) supplement that in the supplier network, the network itself is merely an opportunity. In a business environment, the most important goal of the network is to add value. Therefore, the parties must understand how value can be increased and in which value chains it can be realised. There is nothing in the network itself which would add more value. The network can be realised as an economic value through the partnerships formed within the network and the special expertise of the partners. (p. 40)

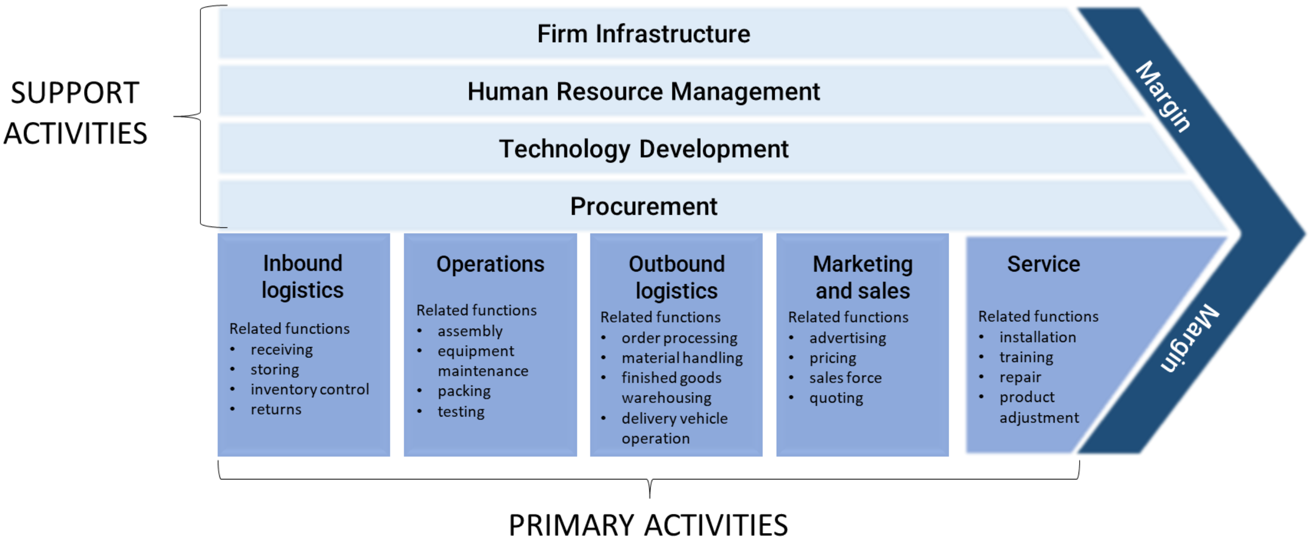
The value chain is a continuation of each other. By connecting different parts of the production or supply chain, the next step in the chain adds value to the previous part. The value between different parts of the value chain increases gradually until it reaches the final user. Each step adds value to the chain with its investment. The combination of know-how in the chain produces value that would not have been created without the combination. To achieve business benefits for all parties, win-win situations must arise between the parties in the chain. (Ståhle & Laento, 2000, p. 41)

2.3 Value creation

The examination of competitive advantage cannot be conducted at the company level or even on an industry-wide basis, as it may obscure some important sources of competitive advantage. It must be carried out function-specific, i.e. from the service packages the company offers. A single service entity can be the differentiating factor by which a company can differentiate itself from the others. The competitive advantage factor can be more decisive in terms of quality or cost than that of competitors. (Porter, 2004, pp. 33-35)

According to Figure 3, there are five primary functions and four support functions. Primary functions include activities that are all necessary for building a competitive advantage and adding value to the chain. These activities are involved in the physical creation of the product. Support functions support the primary functions, where human resource management, technology development and procurement can be associated with specific primary activities. The company's infrastructure is not related to any primary function; it only supports the entire chain. (Porter, 2004, p. 38) Each activity can promote the company's relative cost position and create the basis for differentiation. The company will gain a competitive advantage when these activities are performed better than its competitors. (Branch, 2009, p. 13)

Figure 3 - The Generic Value Chain (Adapted from Porter, 2004, p. 37)



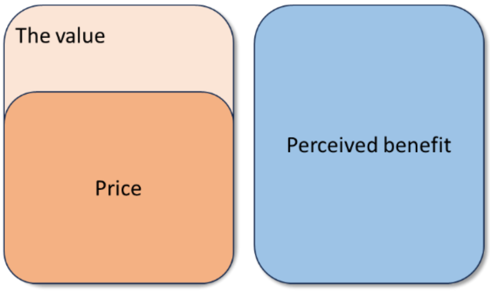
Instead of developing operations, the development of logistics services focuses on information processing, improving the conditions of movement, restructuring value chain structures, internationalising services and continuous diversification. The transfer channel is more commonly used for assembly and customisation than single transfer, which highlights the role of logistics service providers as a producer of added value rather than a mere cost driver. In the future, the ability to serve and develop sustainable solutions, measured in terms of quality and reliability, will be emphasised instead of operational costs. Companies operating throughout the entire value chain need to consider the end customer's wishes in greater detail. Ultimately, the final customer bears all the costs incurred throughout the value chain. (Haapanen et al., 2005, pp. 31, 243)

According to Harrison et al. (2014), two types of value can be created: shareholder value and customer value. Customer value is defined from the customer's perspective. It represents the perceived benefit gained from a product or service compared to its purchase cost. Shareholder value, on the other hand, refers to the financial return generated for shareholders based on their invested capital. To be considered a worthwhile investment in the eyes of shareholders, the returns must exceed those of comparable investments with similar risk profiles (p. 83). Porter (2004) defines value as the price a buyer is willing to pay, which means total revenue rather than costs. Companies strategically raise prices to differentiate themselves and increase perceived value. According to Porter, total value consists of activities and margin. The activities include both primary and supporting business processes, while margin is the difference between the total value generated and the collective cost of performing these activities (p. 38). Tuulaniemi (2011) further explains value as the ratio between sacrifice and benefit. The price paid is not always a direct monetary cost; sacrifices can also take non-financial forms. Additionally, value is relative, shaped by prior experiences. It exists only if something is perceived as valuable, making it a subjective rather than an absolute measure. (p. 30)

There is debate on which value should be considered. One perspective is that organisations are in business primarily to maximise shareholder value, which can be achieved by delivering customer value and maintaining competitiveness. Another perspective is that there is a need for balance because values can be conflicting and therefore destructive to each other. The lack of alignment between business models, practices and customer needs will harm shareholder value. All the same, customer value ensures loyalty and hence promises continuous revenue. Contributing to shareholder value entails making continuous investments that support the supply chain strategy, enabling the meeting of customer needs. (Harrison, 2014, p. 84)

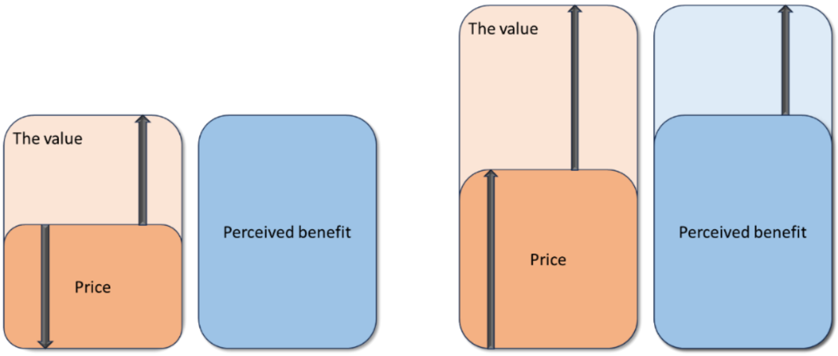
The primary task of any organisation is to create value for its customers. The created value is important to the customer, which is why they are willing to pay for it. The background of a purchase transaction is typically the need to acquire something or solve a problem. If this need is satisfied, value has been created, and the customer perceives the benefit. The perceived benefit is illustrated in Figure 4. (Tuulaniemi, 2011, p. 31)

Figure 4 - Value determination (Adapted from Tuulaniemi, 2011, p. 31)



Many companies claim that they add value for their customers. Since value is described as the ratio between the price and gained benefit, added value can be created only when the actual price decreases, the perceived benefit by the customer increases or both. As shown in Figure 5, when the price decreases, the added value increases while the perceived benefit remains constant. The value can also be added when the price increases, and at the same time, the perceived benefit also increases. In a situation where only the price increases, the generated value will decrease since the perceived benefit remains the same. (Tuulaniemi 2011, p. 33)

Figure 5 - Added value (Adapted from Tuulaniemi, 2011, p. 32)

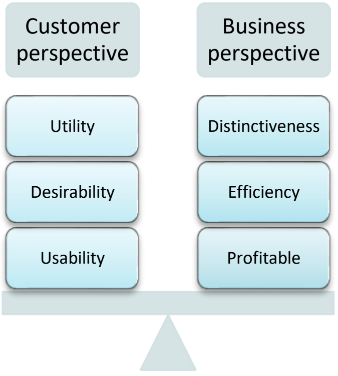


Getting value for the money no longer only means a cheap product and efficient, fast, and timely delivery. Responsibility and sustainable development are emphasised in both manufacturing materials and methods, as well as in packaging and delivery. That is why the focus of management shifts from developing the company's internal competitiveness and operations to managing its external operations. The Porter's value chain thinking supports this development, as it considers competitors, companies offering substitute products and services, and upstream and downstream actors in the value chain. (Haapanen et al., 2005, p. 32)

Megatrends present opportunities for logistics service providers to add new value to the chain by incorporating digitalisation, automation, and sustainable development. With digitalisation, the amount of data and information is growing for the entire distribution channel, and the channel wants to be more transparent. When examining emissions across the entire supply chain, a study by the University of London (Ries, 2016) found that the share in the United States was approximately 13% (p. 2). Global megatrends influence and offer opportunities for the development of logistics. Nurminen Logistics has managed to grow its container train business at a breakneck speed. The Port of Helsinki is said to be in a great location at the hub of transit traffic in Eurasia. The rail from the east ends at Helsinki's Vuosaari port, where containers can be easily transferred to ships. The operation began on a route through Russia, where the lead time of the container's journey from China to Finland was reduced from 45-60 days by ship to 12-16 days by train. This shortens the delivery time but also improves predictability with the environmentally friendly transfer method. (RailFreight.com, 2021) Nowadays, due to the war in Ukraine started by Russia, the train route through Russia has changed. The route currently takes a southern detour, which adds about a week to the journey, and has in turn brought Nurminen Logistics new customers from Central Europe. (YLE, 2022)

Ultimately, the target of the service to be produced is to strike a balance between the created experience that fulfils the customer's needs and delights them, and the need to fulfil the business goals of the organisation producing the service. The balance is illustrated in Figure 6. (Tuulaniemi, 2011)

Figure 6 - The balance of different perspectives (Adapted from Tuulaniemi, 2011)



2.4 Partnership levels in the value chain

Different partnerships require different investments in sharing and utilising information capital, maintaining and developing the trust and generating added value. Depending on the targets of the partnership, the operation and earning logic need to be understood a little. Additionally, the level of the partnership influences the various earning opportunities that can be obtained through the partnership. Generally, it can be assumed that the lower a partnership's risk, the lower its earning potential. The same generalisation also applies to the possibility of losses, if this is considered in the partnership agreement. (Ståhle, 2000, pp. 76-77)

Even in the simplest interaction between buyer and seller, it is about building a partnership; the buyer receives the item or service, and the seller receives the agreed price. This exchange benefits both parties, and the more satisfied they are with the resulting deal, the more likely it is to happen again. In a subcontracting relationship, the exchange is a significantly more complicated event. In this relationship, the entire operating process or a service unit might be bought. (Ståhle, 2000, pp. 77-78)

In a genuine partnership, the parties work together to develop their operations. The outsourced must understand that their problems cannot be transferred to be solved by the service provider, and a service provider cannot be treated as just one supplier. The deeper the partnership, the more blurred the boundary between whether an outsourcer or the service provider handles the activity becomes. (Jalanka et al., 2003, p. 12)

Relationships can be categorised as vertical and horizontal. Vertical relationships are more traditional linkages between companies in the supply chain. Examples of vertical relationships include retailers, distributors and manufacturers. These relate to each other in that individual companies achieve their objectives and contribute to the overall objectives of the supply chain. Logistics service providers are involved on a day-to-day basis. Horizontal partnerships have a parallel position in the logistics process. Two or more logistics providers have a service agreement based on trust, cooperation, mutually agreed-upon goals, as well as shared risk and investment. Each company oversees these tasks and strives to integrate its services with those of other logistics service providers. (Coyle, 2003, p. 418)

To assess an organisation's core and non-core functions, a quadrilateral framework is illustrated in Figure 7. This evaluation considers two key characteristics for each function: execution capability and importance to the business.

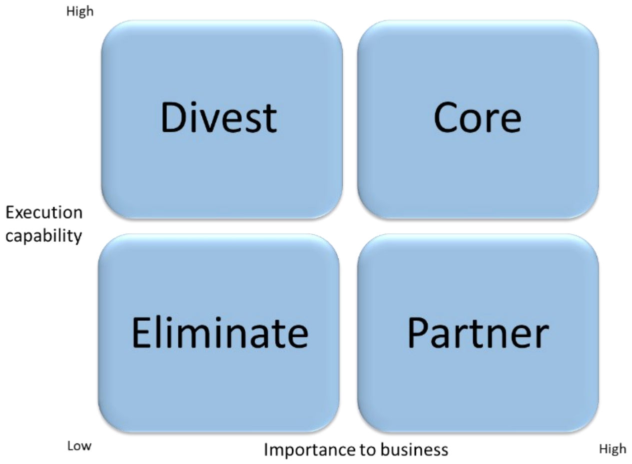
- Execution capability refers to how well the company performs the activity.
- Importance to the business describes the activity's contribution to the success of the value proposition or business objectives.

Based on this assessment, each activity is placed within the quadrilateral, which helps guide decision-making on whether outsourcing is a suitable option. If an activity is outsourced, the framework also determines the level of partnership required for the project.

(Booth, 2010, pp. 28-29)

Activities on the left-hand side of Figure 7 are not crucial to the company's business and should therefore be either eliminated or replaced with an alternative solution to perform the necessary tasks. If an alternative provider is to be selected, it should be based on quality, cost, or time. The difference between the activities in the Divest or Eliminate sections is the company's possibility to benefit financially as a lump sum. Activities in the Divest section can be considered for sale, along with their processes and systems, to another company for which the activity is core. For the needed services, the company can buy back. Activities in the elimination section either need to be eliminated or find an alternative provider to perform those with low business impact, as the company is not well-suited to perform such activities. Business risk for activities in the divest section is higher than in the eliminate section; therefore, in the selection of a possible external provider, it must be carried out with different precision. (Booth, 2010, pp. 29-30)

Figure 7 - Organisation capability evaluation matrix (Adapted from Booth, 2010, p. 28)



Activities which are located on the right-hand side of the diagram are vital to the company's business. The company itself should do all activities in the Core segment. The result of the evaluation for the selected activity is both important and where the company excels, which makes it a core activity for the company. Activities in the Partner segment should be improved either by the company itself or with a partner. To outsource these activities, the partner selection needs to be made from a strategic point of view with a service provider that excels in those activities. This is due to activities in the Partner segment being categorised as important for the business, and therefore, the chosen partner has a significant impact on success. (Booth, 2010, p. 30)

When examining the relationship types in a vertical context (Figure 8), in vendor types of relationships, there is little to no integration or collaboration between the buyer and seller. The relationship with a vendor is transactional, and collaboration is kept at a distance of "arm's length", i.e. a distant relationship. There are transactions between the parties that involve either one-time or multiple purchases of standard products and/or services. (Coye et al., 2003, p. 418)

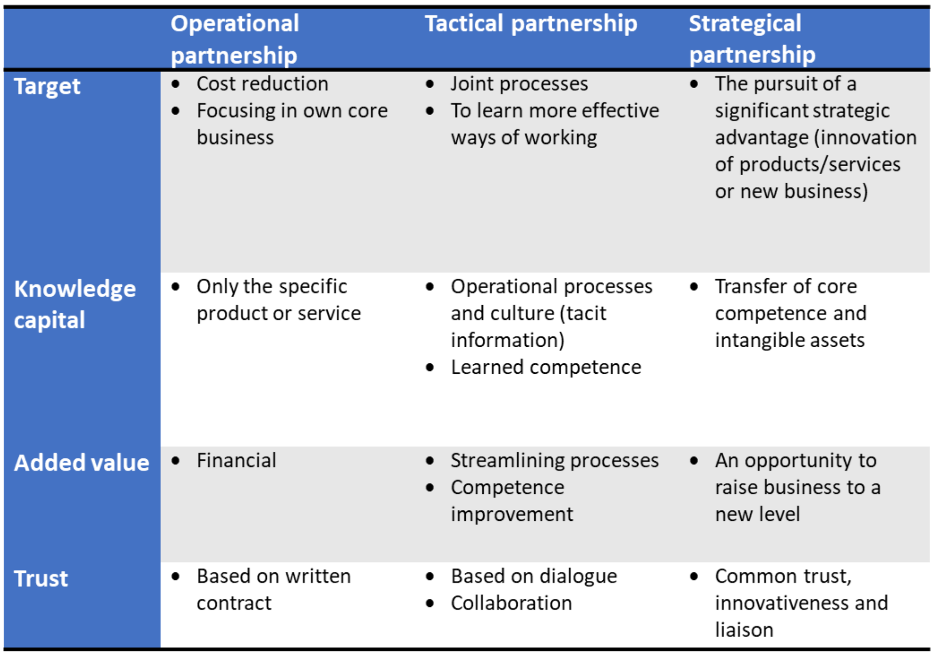
Figure 8 - Relationship perspectives (Adapted from Coyle et al., 2003, p. 419)

In contrast to a vendor-type relationship, a strategic alliance is a type of relationship in which two or more companies cooperate and modify their business to achieve long-term objectives. A partner-type relationship is a form of cooperation where better results can be achieved for each party than they would achieve individually. This type of partnership is frequently described as "collaborative", which creates a differentiating factor of ownership or joint venture. It delimits the partnership level between partner and strategic alliance types of relationships. (Coyle et al., 2003, p. 419)

Based on Ståhle's (2000) evaluation model in Table 1, in purely operational types of partnerships, the target is purely financial. Trust is based on a contract that defines the role, responsibilities, performance, and sanctions of each party. Based on the contract, typically between two companies, one has been assigned to manage a part of the other company's operations, or it involves the exchange of goods for money. For other companies, it is a core business, while for the other company, it is merely a solution to the problem. The products or services to be purchased are ready as such and can be connected directly to the partner's business, so that no actual learning or sharing of information takes place. Both buyer and seller have multiple choices, and the handled operations are tendered at regular intervals. (pp. 81-84)

To successfully outsource business-critical activities, organisations should leverage methods from both tactical and operational partnership levels. Effective partnerships, whether tactical or strategic, require trust, a shared vision of achievable strategic goals, and the realisation of financial and non-financial benefits. Strategic partnerships demand a higher degree of these attributes compared to tactical ones. To foster collaboration, organisations must move beyond traditional customer-supplier thinking and legal constraints. This shift allows for a comprehensive review of key cooperation processes and the development of a shared operational approach. Both parties must fully understand each other's value chain, extending to the paying customer. Transitioning from a structured to a more flexible operational model should ultimately serve the partnership's best interests (Ståhle, 2000, pp. 86-88).

Table 1 - Levels of Partnership (Adapted from Ståhle, 2000, p. 103)



	Operational partnership	**Tactical partnership**	**Strategical partnership**
Target	• Cost reduction • Focusing in own core business	• Joint processes • To learn more effective ways of working	• The pursuit of a significant strategic advantage (innovation of products/services or new business)
Knowledge capital	• Only the specific product or service	• Operational processes and culture (tacit information) • Learned competence	• Transfer of core competence and intangible assets
Added value	• Financial	• Streamlining processes • Competence improvement	• An opportunity to raise business to a new level
Trust	• Based on written contract	• Based on dialogue • Collaboration	• Common trust, innovativeness and liaison

The benefits of strategic outsourcing, such as the growth of knowledge capital, manifest through operational processes and organisational culture. Knowledge capital is integrated through experiential knowledge transfer, facilitated by dialogue and collaboration. The deeper and more cooperative the relationship becomes, the higher the risks and demands. As change accelerates, the implementation of competence and value chain management becomes increasingly critical. However, this dynamic also presents opportunities for increased value creation and revenue growth. Strategic partnerships aim to reach new levels of competitive advantage that would be unattainable without collaboration. The key is to identify areas where strategic advantage can be created and maintain transparency within those areas. Ultimately, mutual trust is essential for realising strategic benefits (Ståhle, 2000, pp. 89-95).

2.5 Outsourcing

Outsourcing of functions and operations is one of the most significant changes in global business. The idea in this trend focuses on functions and operations that bring benefits and are core to the outsourcer. Outsourcing is not only about procuring materials. It also applies to the outsourcing of services, transportation and storage. (Cristopher, 2016, p. 198) The first forms of outsourcing were already in use since the 1800s with the spread of mechanisation. The hydropower produced by the dam devices was enough for several different operators, which led to the growth of the engineering industry around the factories. These engineering workshops offered both new machines and the repair of these machines. Therefore, individual factories did not have to hire their machine builders or repairmen. (Schön, 2013, p. 113)

The importance of the service industry and service economy is continually growing. VTT Technical Research Centre of Finland Ltd.'s report "Palvelut muokkaavat kaikkia toimialoja" (Vähä et al., 2009) describes five trends that support the development of the service economy. In terms of the Finnish economy, the report covered, among others, all primary industries, including Healthcare, Wood and Paper, Energy, Technology, Construction, Transportation, and Logistics. The five common trends, which apply to all mentioned and numerous other industries, are (Vähä et al., 2009, p. 26):

1. Economic globalisation and the China phenomenon
2. Demographic change and the deterioration of the dependency ratio in developed countries
3. Increasing energy consumption and economic availability
4. Ecological factors and climate change
5. Digitalisation and the opportunities created by technologies

When comparing the share of GDP for services, the United States ranks in its tenth percentile (80%) compared to Western EU countries (70-75%) and Finland (66%). Using

GDP to measure the share of services is not entirely reliable, as there is no direct proportional metric for the share of services. Because of this, Finland's service sector is larger than reported due to hidden service business in industry. Companies are no longer purely production or service-oriented. (Tuulaniemi, 2011, p. 21)

In general, the outsourcing decision is evaluated by the "make or buy" decision, which is based on transactional cost theory. The idea was presented by Ronald Coase in 1937, and the theory focuses on operational costs and neglects to consider long-term strategic effects and expertise. The reasoning is based on the idea that the costs of an outsourced operation are the same regardless of where it is done. The difference in costs can be attributed to governance costs, including planning, implementation, and control. Based on the theory, activity should be done where governance costs are the lowest. (Iloranta & Pajunen-Muhonen, 2018, pp. 173-174)

There are several reasons why a company outsource part of its operations to an external partner. Cost reduction is the key decision-making criterion. Sources of savings can be categorised into two areas: an outsourced service provider achieves higher productivity when conducting the service, or the costs of production factors are lower than those of an outsourcing company. Higher productivity is the result of the ability of a company specialising in outsourced services to produce the service more efficiently with standardised tools and processes and with higher quality than a company where the service is only one support function among others. Lower cost of production factors is due to a strategic decision that logistics service operators can offer. The logistics service provider is focusing solely on its core activities, which serve as a supporting function for the outsourcing company. The economy of scale enables an operator offering services with increased flexibility and reduced overheads for other clients as well. Usually, the service operators' organisational structure is lower than that of the customer company. (Lehikoinen et al., 2013, pp. 21-22; Branch, 2009, p. 71) OEM (Original Equipment Manufacturer) companies seek opportunities to reduce manufacturing costs by making significant changes to the supply chain. Decision-making criteria, in addition to the price-quality review, include the reliability of delivery, flexibility and the ability to react to changes in demand. (Suominen, 2008, pp. 28-29)

There are also reasons for outsourcing that are not wanted to be said out loud. It may be a reason to transfer service production to countries with lower costs, or by striving to eliminate either long-term and often more expensive employment relationships or by engaging in collective labour agreement shopping. Expensive employment relationships are handled by hiring young or inexperienced people with a low starting salary. The purpose is not to keep the person in the company for a long time. The aim is to keep a steady rotation so that the effect of general increases does not become too large. Collective labour agreement shopping involves transferring employees from an expensive or complicated union agreement to another union agreement, resulting in reduced wages and other conditions. (Lehikoinen et al., 2013, pp. 22-23) Branch (2014) notes that in EU legislation (TUPE) prevents the reduction of terms and conditions of the existing workforce in short term and this cause the reason for labour agreement shopping no longer a driver for outsourcing (p. 583) Still, for example in Finland, the Government owned postal service company Posti tried to transfer personnel to the services of its subsidiary and at the same time change the collective agreement to a cheaper alternative. Ultimately, this led to the resignation of the Prime Minister and the Minister of Ownership. (YLE, 2019)

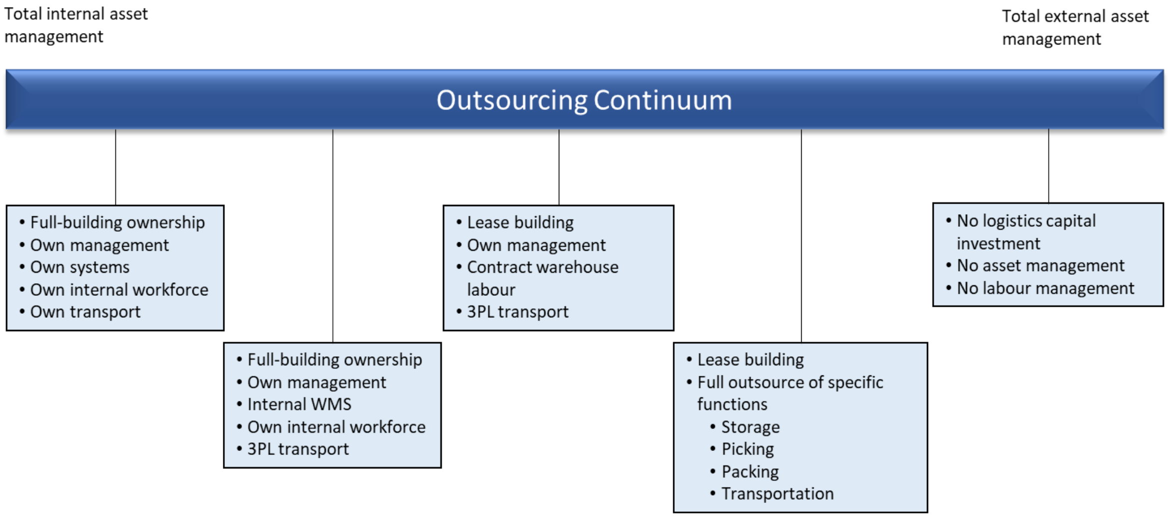
There may also be other reasons behind outsourcing. Outsourcing has been generalised as a tool for successful management, and the announcement of outsourcing usually elicits a positive reaction in the press and among analysts. Predictable publicity may be tempting to outsource even if there seems to be no basis for it. Outsourcing may occur in situations where processes have not been developed in a timely or effective manner. It may be that the organisation has lost control of costs, concentrating on core business, and its technological investments have proven to be a mistake. (Iloranta & Pajunen-Muhonen, 2018, pp. 179-180)

2.5.1 Outsourced logistics

The main reason to outsource a company's logistics operations is to focus on its own core business. Logistics has also become an increasingly important competitive factor. The efficiency of the supply chain significantly determines a company's success in the market. This means that the supply chains are competing with each other. Outsourced logistics has been utilised to enhance competitiveness by optimising functionality and efficiency in the company's logistics operations. The goals of outsourcing logistics have been stated as flexibility, improved service levels, cost savings, and the release of capital tied up in logistics. When comparing logistics investments with investments aimed at other businesses, logistics investments are not competitive in the short term. Outsourcing is seen as an attractive alternative in situations where a logistics supply chain needs to be built from scratch, or when considering investments in a warehouse construction project, or long-term renting. A logistics partner offering outsourcing services can either have these solutions ready or they can take advantage of their economies of scale. (Jalanka et al., 2003, p. 10)

Companies can outsource various logistics operations, ranging from entirely internal logistics management to total external logistics management (Figure 9). In internal setups, firms own their logistics infrastructure, workforce, and systems. At the other extreme, companies outsource all logistics without managing assets or labour. Most firms adopt a hybrid approach, balancing internal and external functions based on strategy (Rushton et al., 2014, pp. 560-561).

Figure 9 - Outsourcing Continuum (Adapted Rushton et al., 2014, p. 561)

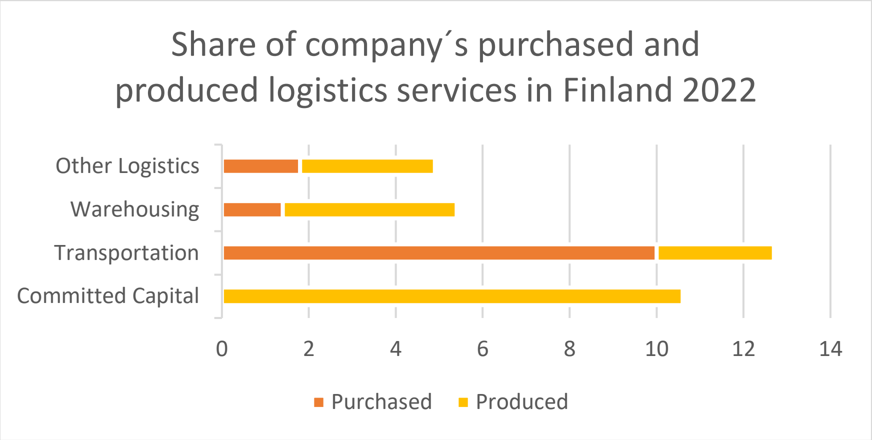


An annual worldwide study, the Third-Party Logistics Study (2024), indicates that logistics services were outsourced to a 3PL through a conducted survey. Most of the outsourced tasks involve day-to-day operations, including domestic and international transportation (62% and 51%), transportation planning and management (49%), freight forwarding (49%), warehousing (65%), and customs brokerage (53%). However, the outsourcing of more strategic and customer-facing functions tends to be less common than day-to-day operations. Activities such as order management and fulfilment (23%), cross-docking (35%), and product labelling, packaging, assembly, and kitting (23%) are more customer-oriented. (3PL Study, 2024)

According to Solakivi et al.'s Logistics Survey 2023 (Solakivi et al., 2023), the total value of purchased logistics services in Finland amounted to €13.2 billion. This figure, based on a 2022 survey, includes data from industry sectors, including construction and trade. When public sector logistics costs are factored in, the total value of purchased logistics services in Finland reaches €15 billion. Additionally, companies produced the logistics services they required internally, amounting to approximately €10 billion in the same year. The cost of committed capital, which is included in a company's total logistics costs, was reported at

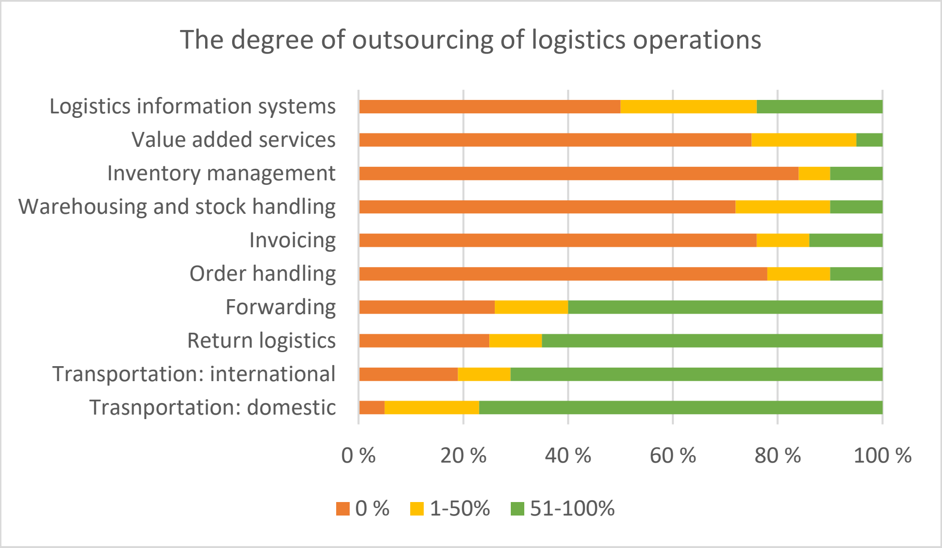
€10.6 billion in the 2022 survey. In Figure 10, the share of purchased and self-produced logistics services in terms of transportation, warehousing and other logistics functions. The value of capital committed to the warehouse is also included as self-produced logistics. (Solakivi et al., 2023, p. 65-66)

Figure 10 - Share of purchased and produced logistics (Adapted from Solakivi et al., 2023, p. 65)



When examining the extent of logistics outsourcing in Finland (Figure 11), it is evident that most companies outsource a significant portion of their transportation, return logistics, and forwarding operations. For example, domestic transportation has been outsourced fully or partially in 97% of the respondents, and 80% of the respondents have outsourced international transportation. Storage, order processing, and even invoicing are handled primarily by Finnish companies utilising their resources. However, in many companies, these services have been outsourced, either wholly or at least partially. In value-added services, more than two-thirds of the respondents produce these services independently. (Solakivi et al., 2023, p. 66)

Figure 11 - The degree of outsourced logistics (Adapted from Solakivi et al., 2023, p. 66)



The outsourcing of logistics services began with the outsourcing of transportation. Overall, sourcing logistics operations has become more common these days. In the First Party Logistics (1PL) model, the company manages all logistics-related functions. When a company purchases single logistics services from an external operator, such as transportation or forwarding, it is referred to as Two-Party Logistics (2PL). When the degree of outsourcing increases, the purchased services are more comprehensive. In the 3PL model, the ordering company outsources activities related to the supply chain, such as warehousing, transportation, forwarding and value-added services to an external company. These functions are routine for the 3PL service provider, and the control of logistics remains with the customer. Four-party logistics (4PL) offers comprehensive solutions that span industry boundaries to meet the diverse needs of customers. The Service provider takes care of the customer's entire supply chain, combining different services and technologies. The services are assembled into a network that is responsible for controlling the logistics and offers the customer a complete logistics service. (Ritvanen et al., 2011, p. 128)

A 4PL service provider acts as a single interface between all parties in the supply chain. In this way, the service provider oversees and manages the entire process, enabling a more effective and faster decision-making process, especially when it becomes crucial during disruptions. The 4PL model offers new leveraging possibilities for technologies to both predict potential disruptions and provide resilient supply chain processes. (DHL Supply Chain Insights)

Most 2PL companies aim to transition into 3PL companies to achieve higher returns. Many 2PLs have evolved into 3PLs by adding new logistics capabilities and integrating their operations. The term "3PL" is used to describe freight forwarding and contract logistics companies. 3PL performs either all or a larger portion of a client's supply chain logistics activities. The value adding is based on information and knowledge. The same phenomenon arises between 3PL and 4PL companies as between 2PL and 3PL companies; 3PLs are attempting to transition into the 4PL segment. When comparing the profitability between 3PL and 4PL services, the 4PL segment is more profitable than the 3PL segment. This is mainly due to the charging mechanism used by 4PLs, since they can charge more based on consulting fees rather than operational transactional fees. (Vasiliauskas & Jakubauskas, 2007, p. 69)

Branch (2009) states that cost is the primary driver for 3PL selection, followed by service enhancements like supply chain optimisation, new technologies, partnerships, and value-added services (p. 70). The Chairman of LOGY (Finnish Association of Purchasing and Logistics), Markku Henttinen, emphasises that outsourcing logistics is a strategic decision, not just a cost-cutting measure. Companies often hesitate to invest in fixed costs, such as real estate and automation, or struggle with personnel availability. However, outsourcing can enhance flexibility, shorten delivery times, and optimise batch sizes, especially with the rise of online shipping. A logistics provider should be viewed as a supply chain partner, adding value by managing material flow and offering more innovative, more efficient solutions. This is particularly beneficial for in-house logistics, where tailored strategies can improve operations. (Businessopas, n.d.)

Branch elaborates (2009) that prioritising low pricing in the selection of outsourcing partners ignores the service, cycle time and inventory impact of supply chain management. It leads to a situation where the 3PL service provider becomes more of a goods service operator rather than a producer of added value. It is also worth noting that competitors can lower prices, but this will affect the service image and the value that can be offered. Reducing allocated working hours and not doing any additional value-adding work may be tactically possible, but it is strategically weak. (pp. 146-147)

For future strategic logistics focus areas, several key factors should be considered. Customer needs and market environment help to determine the needed added value for both the supply chain and the overall logistics operation. The focus on technological development is about keeping pace with the latest trends, while it is also mandatory to have adequate professional resources for maintaining and developing processes. Both in supply chain and overall logistics operations, added value is crucial. It can be aligned with cost benefits, especially in terms of efficiency and return on investment. (Branch, 2009, pp. 156-157)

2.5.2 Value-added services

Value-added logistics (VAL) or value-added services (VAS) are strategic solutions offered by logistics providers to enhance supply chain efficiency and foster close collaboration with customer organisations. These services help shorten production lead times by supplying pre-assembled components and serve as an alternative to tendering for bagging or bundling complex products, tasks that material suppliers might otherwise handle.

The VAS work described above can be divided into two different types of work, which have slightly different names and meanings:

- Settlement work is described as picking and packing single or multi-SKUs into a package, creating a new SKU for storage or shipment.
- Kitting or pre-assembly, which involves tools for assembling components.

(Bluecart, n.d.; HUB Logistics, 2022)

In this study, the term kit is used to describe both settlement and kitting activities.

Both processes follow either Make-to-Order (MTO) or Make-to-Stock (MTS) principles, depending on operational needs. A kit may contain one or multiple SKUs, optimising logistics efficiency. By integrating settlement services with broader logistics strategies, companies can streamline operations, improve workflow, and enhance value throughout the supply chain. (Bluecart, n.d.; Haapanen et al., 2005, pp. 250-252)

The value-added services significantly enhance the value of the distributed product. According to Rushton et al. (2014) and Haapanen et al (2005), these kinds of value-added services are: (pp. 577-599; p. 251):

- Specialist or niche services
    - A completely operational service is specially designed for the distribution of a particular product type. An example of this type of operation is a hanging garment, where the entire distribution process from the production point to the retail store is designed to be displayed on hanging rails. The operation can be conducted either with a manual or a sophisticated automated system.

- Inbound logistics
    - The movement of goods into a manufacturing company is also seen as a suitable area for additional value-added service. Conducted service includes the coordination of collected materials, components and packing the products according to the requirements set by manufacturing. Usually, this has been supplemented with stock control and ordering services.
- Pre and post-manufacturing assembly
    - To support the just-in-time operations, logistics service providers supply pre-assembled products directly to the production line at precisely the appropriate time. An example of this type of service can be found in the automotive industry, where entire modules are supplied directly next to the production line.
    - Post-manufacturing services occur outside the manufacturing environment, typically conducted by logistics operations. The final modification to the product is made just before it is dispatched to the end-user or market. An example of this kind of modification can be found in the computer industry, where, for instance, pre-installed software is provided in the proper language, and the correct type of keyboard and power pack are included in the box.
- Repacking
    - It may be necessary for goods to be repacked before they are ready for sale. For example, it may be needed to pack two different items, which are delivered from separate manufacturers, into one single package.
- Pre-retailing
    - Service where products are prepared for shop-ready use in the retail environment. Actions performed might be, for example, labelling, unloading goods from their outer package, etc.
- Return and refurbishment
    - Due to environmental legislation, it may be necessary to un-assembly parts of the components from the returned product to be reused. For example, in the EU, it is a legal requirement to reuse parts from scrapped cars.
- Packaging returns
    - Also linked to environmental legislation, producers of packaging waste are legally responsible for the collection of the packaging waste. The waste itself can be reused or disposed of. Since reverse logistics is challenging to perform through traditional outward logistics operations, specialised operators are required to conduct this type of service.

- Product returns
    - One more issue has arisen due to environmental concerns and legislation. In Europe, this can be seen as a set of WEEE directive (Waste Electrical and Electronic Equipment) for returned consumer products that have reached the end of their working life. Organisations that manufacture, supply, and use electronic and electrical equipment are subject to this legislation, and it has a significant impact on their operations. The idea behind the directive is to encourage the reuse, recycling and recovery. The same difficulties in performing reverse material flow as in packaging returns exist.
- E-fulfilment
    - The rapid growth of internet shopping has led to an increase in the demand for the fulfilment of internet orders. Traditional channels may not be suitable since distribution is typically undertaken using postal or parcel services. While the internet has narrowed the distance between the consumer and the selling organisation, actual physical activities are still needed to be taken. The exception for physical fulfilment is digitalised products, where the internet is the distribution method.
    - There is also a change of physical distribution because traditional channels are not appropriate for the required home delivery type. For example, grocery home deliveries require a small vehicle with compartments for different types of grocery products, such as fresh, chilled, and frozen.
- Traditional home delivery
    - 3PL contractors run home delivery operations, including the possibility for installations, returns, repairs, refurbishments or disposals. Typically, the service is provided nationwide, fulfilling consumer electronic goods for manufacturers, retailers, insurance companies and service providers

Traditionally, supply chains were factory-driven, focusing on cost minimisation and departmental silos, where functions like sales, transportation, and production operated independently. This led to cost transfers between departments. Production-centred approach offered minimal customisation, pushing products to market without guaranteed buyers. VAS now enable the creation of tailored products and services based on the final user's needs, improving lead times and cost efficiency through pre- and post-manufacturing processes. The rise of external service providers has led to the development of customer-specific VAS solutions, which are now available both locally and globally. Final customisation increasingly occurs just before shipment, supported by standardisation and modular production, which enables shorter series, faster changeovers, and streamlined operations. This customisation pressures product design, requiring standardisation and modularisation for adaptability across consumption areas. This structural shift in logistics has elevated 3PL providers to key roles in the value chain. (Haapanen et al., 2005, pp. 23, 251-253)

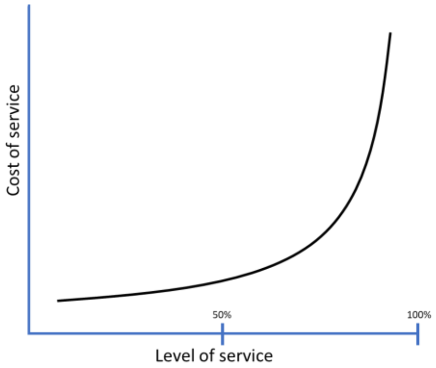
Modern supply chains prioritise customer responsiveness and agility, with competitive advantage emerging from collaborative networks rather than individual firms (Christopher, 2016, p. 296). Technological advances increasingly shape logistics operations, with flexibility and adaptability becoming key performance indicators (Christopher, 2016, p. 285).

Value-added services offered by 3PLs differ from those of contract manufacturing in terms of the network required for contract manufacturing. According to Suominen (2008), the contract manufacturing network should be capable of providing the necessary services, including product planning and procurement. At its best, contract manufacturing is a versatile form of customer service. The best-known contract manufacturing industry in Finland is the electronics manufacturing sector, where product manufacturing is often entirely outsourced to external companies. (pp. 4, 28-29) This kind of model is not a core business of 3PLs but refers closely to 4PLs, where the 4PL service provider takes care of the entire supply chain of its customer. (Ritvanen et al., 2011, p. 128)

2.5.3 Pricing models in outsourced logistics

An outsourcing company struggles with the cost of producing the services. The goal is to find an optimal level of cost which guarantees the needed service level. The company itself sets the acceptable balance between cost and service. The choice must be made between extremes, where the service objective is laid down to minimum cost or service maximisation, where the budget is fixed, and the service is supplied within this cost constraint. When reaching the perfect service level, which is 100%, the cost to produce will eventually increase with each raised percentage, as shown in Figure 12. An increase of 5% in service levels will cost way more between 90% and 95% than between 70% and 75%. It should be noted that a service level increase, for example, from 94% to 96%, may have a negligible impact from the customer's point of view, while the cost to achieve and maintain the higher level will play a crucial role in terms of cost increase. (Rushton et al., 2014, pp. 46-47)

Figure 12 - The cost curve (Adapted from Rushton et al., 2014, p. 47)



The contract's billing principle impacts the outcome of outsourced logistics for both operational and financial sides. The charging criteria must be straightforward and easily measurable, covering both the actual service and the pricing of occasional or infrequently used accessories and additional services. Also, fixed costs should be determined in the contract. There are three basic types of charging: accrual basis, cost-plus, and hourly-based. (Jalanka et al., 2003, p. 49) Rushton et al. (2014) categorise cost-plus types into two distinct categories: basic cost-plus and open-book models (p. 589).

The accrual basis is the easiest pricing model to follow, which should be used whenever the service to be performed can be defined with sufficient precision in terms of content and workload. One criterion is that the service to be performed is not subject to rapid change. This is particularly popular in transportation, event-based IT operations and the physical handling of goods. (Jalanka et al., 2003, p. 49) Price can be cost per case, drop, etc., or a combination of these. (Rushton et al., 2014, p. 598)

A cost-plus price consists of the facilities used and the services provided. The price corresponds to the actual cost, with a preset profit margin added. Such situations, which are best suited for the cost-plus method, include the start of a new operation or a rapid expansion of the current setup. (Jalanka et al., 2003, p. 49) Advantages include cost visibility for the client, which is beneficial for budgetary purposes. It is also suitable when both parties are seeking the benefits of developing methods to be done jointly. The downside of the cost-plus method is that it does not offer incentives to enhance operations through productivity improvements, as any cost trimming will result in a reduction in revenue for the contractor. To avoid this, it is possible to add either targets to reduce costs or a joint agreement to reduce costs. (Rushton et al., 2014, pp. 597-599)

Open-book is a more open charging type than cost-plus. A settled budget is agreed upon between the parties, and performance is monitored against it. The customer can see the real cost of the produced service as well as all the savings achieved through performance improvements. The drawback of this contract type is that it may compound any inefficiencies that are built into the original agreement. Therefore, it is common to include cost reduction or performance-related incentive clauses to provide a shared benefit. The responsibility of presenting performance improvements lies with the contractor. (Rushton et al., 2014, p. 599)

An hourly pricing model could be used to invoice temporary work when the scope of the work is difficult to predict. Generally, hourly based pricing should be minimised and used to supplement other work and contract types. (Jalanka et al., 2003, p. 50)

Several different pricing methods can be used in the service contract. Typically, this can occur during the start-up of a new operation, or transition costs are included either in standard service fees for an agreed-upon period or are to be agreed upon separately. Fixed costs can be agreed with tiered performance pricing or by using the fundamental part with an added operational cost. (Jalanka et al., 2003, p. 51)

2.5.4 Benefits sought from outsourcing logistics

Achieving the benefits of outsourcing is a challenge in practice, and it requires broader skills, knowledge and resources than usual. There must also be a purpose and purposeful steering towards the change. In a purpose-powered outsourcing relationship, both parties must commit to the long-term pursuit of added value. To support the achievement of the goals, objective measures and management methods need to be set. Rewards can be part of goal setting. (Iloranta & Pajunen-Muhonen, 2018, pp. 174-175) Jalanka et al. (2003) supplement the measurement and monitoring of goals with facts and not emotional generalisations. Goal setting for service providers must focus on the matters where the selected partner has influence possibilities. (p. 34)

Weele (2018) emphasises that outsourcing is not a purchase transaction; it is a decision. Weele divides the desired benefits in time according to the expected value of realising the benefit. The tactical benefits of outsourcing include short-term goals that aim to reduce management and operational costs, free up internal resources, and improve overall performance, as well as the recovery of cash resources or the outsourcing of poorly managed operations. Strategic reasons are long-term goals that focus on core activities, increasing flexibility, improving customer satisfaction and sharing risks. Expanding capacity can be seen as a strategical reasoning in situations where the company does not have it to perform the desired function or lack of expertise to perform the function at the desired quality and cost level. (pp. 192-193) Hines (2004) mentions also exemption from regulations which can be seen as part of increased flexibility (p. 177).

Organisational advantages, which focus on core business or core competence, are challenging to measure, but the side effect, organisation streamlining, can be measured by the achieved savings through reduced overheads. With a 3PL service provider, outsourcers have the opportunity to access wider knowledge and technological advantages. The 3PL operator may be utilising leading-edge technologies or providing access to them via the 3PL. With the introduction of new technologies, the possibility of upgrading operational efficiency exists. (Rushton et al., 2014, pp. 581-582)

Financial factors may occur both in the short and long term. One-off cash increase may occur in situations where the service provider pays for existing assets owned by the client at the start of the contract. Long-term financial benefits are gained from the elimination of asset ownership. Capital cost advantages are gained through a decrease in the need for investments in logistics facilities (warehouses, distribution centres), as well as resources (vehicles, personnel). The released investment capital can be guided to core business areas such as production machinery or retail stores. The transformation of fixed costs into variable costs is consistent with capital release investments. The elimination of ownership and responsibility of plant, property and equipment lightens the balance sheet. (Rushton et al., 2014, pp. 582-583) Additionally, fluctuations in demand due to seasonality can be managed without increasing fixed costs (Iloranta & Pajunen-Muhonen, 2018, p. 179).

Depending on the type of agreement and the designed solution, a third-party service provider can offer economies of scale, which are achieved when multiple functions are handled together by a third-party service provider with the same resources and overhead costs, and through better utilisation of equipment and labour. A single large distribution centre may replace three or four sites used by different smaller companies. The more action-based pricing model is used, the more precise a picture of actual operating costs is achieved. (Rushton et al., 2014, p. 583) Iloranta & Pajunen-Muhonen (2018) highlight that, compared to the situation where the operation is performed in-house, international studies have verified the achievement of cost savings through outsourcing. This has been achieved without significant degradation in quality. It is also possible that quality can be improved due to outsourcing. (p. 175)

Greater flexibility by a 3PL operator may be required when entering new markets, developing new products or services. Entering a new geographical area via a 3PL service provider is a more affordable solution than building new logistics infrastructure. The Same applies to expanding delivery methods into home-delivery services. 3PLs can offer several value-added services as a standard process, which may provide a significant added attraction to the user company. (Rushton et al., 2014, p. 584)

Market utilisation occurs in situations involving large corporations where there might be an exchange of goods and/or services between different internal business units. Due to individual profit targets of each business unit, it may be tempting to use higher prices for a company belonging to the same group than for an outsider. The internal transfer price can work in standard solutions, but in a slightly more customised solution, it is difficult to define a fixed point. With outsourcing, the function is subjected to competition. (Iloranta & Pajunen-Muhonen, 2018, p. 178) Rushton et al. (2014) point out the improvement aspect through the 3PL service provider, rather than the company driving the changes itself. This is because performance-based incentives can be written into service contracts. (p. 584)

3PLs are interested and forced to invest in automation. The operating model, where investment is made only on behalf of their customers, is becoming a competitive advantage by offering an enhanced customer experience with automation solutions already installed. Therefore, automation has become a necessity for logistics service providers to solve challenges in increased demand, volume fluctuations due to seasonality, staffing issues and rising labour costs. (GEODIS, 2023)

2.5.5 Risks and drawbacks of outsourcing logistics

Jalanka et al. (2003) compare logistics partnership to marriage; both parties must be honest with each other and invest in cooperation. In a healthy and successful relationship, both parties can achieve their set goals. However, as in marriage, outsourced activities can sometimes end up in divorce and either partner change or insourcing. Trust is the foundation of a partnership, as it is on trust that the rationale for outsourcing is built to achieve set goals, ensure the required service level, and support short- and long-term development. Furthermore, both parties exchange confidential information during both the takeover and operational phases. Additionally, during both the takeover and operational phases, both parties also exchange confidential information with each other. (pp. 11-12)

Christopher (2016) highlights the shift in decision-making that occurs when the supply chain evolves into a value chain. From a decision-making point of view, outsourcing may add complexity to the supply chain, as there will be more interfaces to manage, and a higher level of relationship management is required. The supply chain will be transformed into a value chain, and this transformation will increase the distance of the transaction point in terms of both value and cost. Both occur in the resulting network through interconnected partners rather than locally. The term' extended enterprise' becomes a tool that determines how competitive advantage is gained or lost. (pp. 10-11) The gap in decision-making culture and process may lead to problems in co-operation. It may be caused by the fear of losing the logistics expertise. If this fear rises too high, then it might be that logistics seems to be too important an operation to be outsourced. (Rushton et al., 2014, p. 582)

The complexity of the supply chain increases the risk of problems occurring in the chain. The longer and more complex the supply chain is, the greater the probability that time or quality-related failure increases. The outsourcing can create access to immaterial property and enable expertise to be transferred to another company without permission or compensation. By leveraging existing technology, it can be used to protect a competitive advantage and mitigate the harmful mobility of expertise. (Swink et al., 2014, pp. 339-340)

The selection made by the outsourcer and the outsourcing partner aims to achieve a win-win situation. A risk of increased costs exists if only one partner is used. This situation can be unintentionally drifted into, especially in customer-tailored products and services. Reliance on a single supplier or customer may cause risks for both parties. From an outsourcer's point of view, reduced knowledge of the market and other suppliers leads to unawareness of costs and cost levels within the supply chain. The lack of competition may not lead to more efficient operations, putting the partnership at risk of falling behind technological development or struggling to manage costs. From the outsourcing partner's point of view, there may be a need for investments in the operation, which can provide a competitive advantage due to better cost or operational levels achieved through the investment. However, if the need for the produced product or service discontinues, the investment payback may cause financial issues and therefore may jeopardise the partnership. (Iloranta et al., 2018, pp. 282-283)

Tanskanen & Pajala (2021) emphasise the work steps before concluding the contract. To avoid the possibility that the outsourcing partner may take advantage of the situation, select a partner in which the outsourced operation is also strategically important. This ensures the continuity and development of the operation. The more attractive the outsourced is seen in the eyes of the outsourcing partner, the more likely the partner will invest in the partnership and ensure its performance and compliance with the contract. (pp. 231-233)

The increase in the degree of processing as a result of outsourcing also increases the depth of the supplier partnership and the time required to manage the partnership. Pure raw materials are typically purchased through direct transactions, while the production of processed products requires a more partnership-like relationship. The quality of procured services is dependent on the personnel of the selected partner, where motivation and relationships are key attributes for success. (Österlund & Suomela, 2014, pp. 55-56) Huuhka (2019) also notes that evaluating the service provider in advance can be challenging. Therefore, relying too heavily on a single supplier can be seen as a risk, as outsourcing often introduces operational, financial, and legal risks. The one-time costs associated with outsourcing are often underestimated, despite the pursuit of cost savings. (pp. 170-174)

Contract lengths may be seen as a drawback for investing in automation, especially on a large scale. This can be seen as a barrier to the adoption of technologies; 56% of 3PLs' top challenge is a lack of a clear business case, while the second-highest reason is a lack of capital (46% of responders). From the 3PL point of view, the investment requires a certain payback period, which typically differs from the length of most common outsourcing contract terms. Therefore, technology suppliers offer solutions via RaaS, which allows 3PLs to shift the investment cost and associated savings to their customers using an activity-based pricing model. (3PL study, 2024) According to the blog text of GEODIS (QEODIS, 2023), one of the leading global companies offering 3PL services, investing in contracts lasting 3 to 5 years does not offer sufficient payback time for 3PLs.

2.6 Measuring the network

A basic rule of thumb when choosing KPIs is to use the same KPIs that were used before the change. This ensures a basis for comparison. KPIs can and should be built over time if the operation changes or requires a new or modified KPI. (Jalanka et al., 2003, p. 12)

Supplier performance in the value chain can be evaluated using three key metrics: price, cost, and quality. As discussed in Forbes' article How to Measure Supplier Performance (Forbes, 2017), these factors provide valuable insight into supplier effectiveness. One of the most used metrics is price, which ensures that suppliers meet predefined price targets. This method is particularly effective for tracking periodic changes and can be expressed through metrics such as year-over-year percentage price variation. Another approach is measuring the percentage of savings achieved against the quoted price. However, percentage-based evaluations should be handled with care, as they can be challenging to aggregate due to variations in the volume and value of goods or services. Additionally, percentage-based savings do not represent actual monetary gains. A more powerful measurement tool is the evaluation of the cost impact on business operations. Unlike price metrics, cost directly reflects financial outflows, making it a tangible concern at all levels of an organisation. Since real money exits the business through costs, they serve as a more concrete and widely relevant performance indicator. (Forbes, 2017)

The aim of the supply chain is to produce (added) value for the end customer at the lowest possible total cost. The success of supply chain management is measured by how well it achieves competitiveness, profitability, productivity, and continuous improvement, as well as problem-solving, transparency, and effective information transmission. Each organisation of the supply chain must produce its value for the chain with its core business. Organisations in the supply chain evaluate the benefits from their own perspectives. Overall, it can be that more than 80% of the time used overall in the supply chain is non-value-adding time. Value chain thinking is based on eliminating or minimising all non-value-adding activities throughout the entire supply chain. (Ritvanen et al., 2011, pp. 23 - 25)

Understanding the value chain only of one's own industry is often not enough, because working in collaborative relationships, the value chains of these partners and their industries must also be understood. Different actors form the network of value chains, and these intersections are created through partnerships. The seam points are decisive for the functionality of both the individual value chain and the network of value chains in partnership relationships. The customer's customer controls the definition of the value chain and the criteria for the added value produced. Measuring the added value of the service is difficult when the equivalent of added value is not a physical product. For example, the added value provided by expertise should be measurable so that the customer understands the expert service they receive and is willing to pay for it. (Santalainen, 2014)

Branch (2009) highlights the importance of factors other than costs, operational efficiency, and achieving performance improvements. The first is the development of strategy. The strategy is the key factor that differentiates 3PLs in the marketplace, and it is also a unique contributing factor that separates 3PL service providers from one another. Additionally, change management is inevitable with any change. This is a factor that distinguishes 3PL service providers from one another. The leadership attributes affect processes, goals, innovation and methodology. A good 3PL operator has a built-in proactive approach rather than a reactive approach. Additionally, the ability to separate broader entities, such as supply chain processes, from individual transactions or overall services, rather than focusing on transportation or storage. (pp. 71-72)

The quality of people is found to be a key factor in the balance between service and cost, where service is seen as more important than the cost factor when selecting a 3PL operator. The real cooperation, flexibility, and problem-solving are measured out on a day-to-day basis after the start of the operation. Different people usually handle these than those who sold the solution. (Rushton et al., 2014, p. 587)

3 History and the future of robotics

3.1 Industrial revolutions

The flow of innovation has advanced the technological front and expanded the realm of human knowledge. The ability to develop new things, as well as the ability to adopt innovations, has become a crucial factor in competitiveness. Some innovations become successful because they can spread to multiple areas of society and be incorporated into many different entities. (Schön, 2013, pp. 46-47)

The Industrial Revolution is often referred to as a period of significant impact on subsequent development, and it has therefore become a revolutionary era. New possibilities offered during that time were implemented in later development, leading to the spread and utilisation in more than one industry. The significant impact of new opportunities on growth became evident, and major social changes occurred with the widespread adoption of innovations. Society adapted in different ways to new opportunities that lasted so long and extended so far that it would not have been possible to foresee them. (Schön, 2013, p. 48)

The late 18th century set the stage for the 19th century, often referred to as the First Industrial Revolution, which is widely regarded as having originated in England. One of the most significant innovations of this period was the steam engine, refined by James Watt in the 1780s. While Watt did not invent the machine from scratch, earlier versions had been developed over centuries. His modifications significantly improved its efficiency, making it more potent than a simple water pump with high fuel consumption. However, it took nearly 50 years for the steam engine to become a common feature of the English economy. (Schön, 2013, pp. 49-58) The beginning of industrialisation in England was further marked by the establishment of the first actual factory in 1771. (Dinwiddie, 2019, p. 23)

The term "Industrial Revolution" has been debated, as the impact of Watt's steam engine was initially limited to a few industries. However, the turning point came when various innovations spurred further developments, transforming industry, the economy, and social conditions. Before coal became the dominant energy source, non-fossil fuels were widely used for power generation. By the late 19th century, oil emerged as a supplementary energy source alongside coal. This shift contributed to the rise of the factory system, in which labour-intensive craftwork was relocated to production facilities, allowing a single machine to be used across multiple phases of manufacturing. (Schön, 2013, pp. 49-58)

At the end of the 19th century, the first Industrial Revolution evolved into the Second Industrial Revolution through a series of interconnected developments. Like the First Industrial Revolution, it was about new materials, new power engineering, and production management. Common to all was the increase in knowledge level due to education and research, as well as the growth of human capital. Innovations were increasingly emerging from new industrial countries such as Germany and the United States. (Schön, 2013, p. 72)

Standard production systems were innovated at that time. The inventor of the assembly line and conveyor belt is considered to be Henry Ford, who introduced them in 1913. However, there are signs in history of earlier usage of these currently widely used production methods. The first conveyor belt was introduced in a Cincinnati slaughterhouse in 1870. However, there are signs of roller conveyor usage in the British Navy as early as 1804, but the full potential was not exploited. Eli Whitney and Samuel Colt developed a new kind of work arrangement and the benefit of interchangeable parts. Whitney pioneered the cotton industry, while Colt became famous for its revolvers. Ford has admitted that it used a meat-packing line as a model when developing its production line, which reduced car assembly time from 12.5 hours to 1.5 hours. Other remarkable innovations were made in 1873 by Gramme (the first industrial electric generator), by Otto (the first internal combustion engine), and in 1893 by Diesel (the diesel engine). (Marttinen, 2018, pp. 25-26)

At the turn of the 1960s and 1970s, the third industrial revolution is considered to have begun, although the 1970s were also a time of global crises. Until the beginning of the 1970s, global economic growth ended in weakening growth and several repeated crises. The most significant crises were the oil crises in 1973 and 1979, which led to a shift in direction, including declines in industrial production, returns on investments, and a change in focus in industrialised countries from industry to services. (Schön, 2013, pp. 445-449)

The electronic industry revolutionised technology and the economy with Intel's introduction of the first microprocessor (Schön, 2013, p. 459). Early programmable controls date back to the first industrial revolution, including punch cards (1804) and stepped drums (1810), which used holes or raised areas to control equipment. (Dinwiddie, 2019, p. 24) Modern programmable logic, small industrial computers designed for automation, emerged with the first programmable logic controller (PLC) in 1969. PLCs replaced thousands of relays and timers, offering flexibility, reliability, and cost-effectiveness, securing their dominance in industrial automation. Meanwhile, the 1960s saw the rise of industrial robots, further advancing automation. (Marttinen, 2018, pp. 38-39)

During that time, there was growing concern about the effects of automation on society. Martin Luther King delivered his last Sunday sermon on March 31, 1968, about an ongoing revolution that was being supported by automation and computerisation. Parts of his speech were quoted from the Ad Hoc Committee on the Triple Revolution report, which mentioned two other revolutions: those in armaments and human rights. The report predicted that automation would lead to an economic system where unlimited production volumes could be achieved and no humans would be needed anymore. According to the report, automation was not expected to increase demand; instead, it would lead to unemployment and increased inequality, ultimately resulting in a loss of consumer purchasing power. To remedy this, a minimum income was proposed, which would replace haphazard social assistance measures. In the United States, concerns about automation were largely set aside due to the emerging economic growth between 1948 and 1969. The recession experienced in the early 1970s was primarily caused by the oil crisis, rather than computerisation or automation. (Ford, 2015, pp. 30-33)

However, as Ford mentions, those times are behind us and can be analysed in the present. Especially in the United States, changes began to occur at that time that have long-term implications and that together demonstrate the impact of advanced information technology. The near-perfect correlation between increased productivity and improved incomes began to break down. The effects were evident, among other things, in stagnant wages, unequal income distribution, and economic recovery that did not correspond to increases in employment. Although most of the changes primarily apply in the United States, many of these factors also apply to other developed nations, albeit to varying degrees. (Ford, 2015, p. 34)

Industry 4.0, the fourth industrial revolution, emerged in Germany in 2011 and was formally introduced to the government the following year. Unlike previous revolutions, it was deliberately initiated and integrates physical innovations with digital advancements, such as big data, AI, and IoT. (Marttinen, 2018, p. 57) This physical-digital-physical loop captures real-world data, analyses it, and translates insights into physical actions, impacting entire value networks beyond individual factories (Deloitte, 2017). Industry 4.0 operates on four principles: machine communication, information transparency through digital twins, technical assistance for hazardous tasks, and autonomous decision-making by cyber-physical systems. (Marttinen, 2018, pp. 58-59)

Industry 5.0, introduced by the European Commission, complements Industry 4.0 by prioritising sustainability and human-centred innovation. It promotes circular production models, efficient resource use, and workforce empowerment, shifting focus from economic gains to social well-being. (European Commission, n.d.) Unlike Industry 4.0, Industry 5.0 is not an industrial revolution but a strategic evolution toward a more balanced and ethical industrial landscape. (Forbes, 2022)

3.2 General development of Industrial robots

In past decades, logistics has not been a primary focus for manufacturing companies. This may be the consequence of the homogeneous nature of the traditional logistics model. This consists of bulk cargo movements, relatively stable pricing and a predictable service level. The COVID-19 pandemic has also shifted attention towards logistics due to global supply chain shortages of several items, including semiconductors, cars, and lumber. (Tarantino, 2022, p. 149)

Technology is influencing everyone's life. In the logistics industry, all logistics companies have some digital path. It has been argued that companies that do not allocate resources to utilise the new waves of available technologies risk obsolescence. The biggest challenge for transportation and logistics companies is the lack of digital culture and training. For logistics companies, there is no need to understand the technologies themselves, but there is a need for comprehension of where and how to apply these technologies. (Tarantino, 2022, p. 154) According to MIT (MIT Sloan, 2020), five supply chain technologies deliver a competitive advantage:

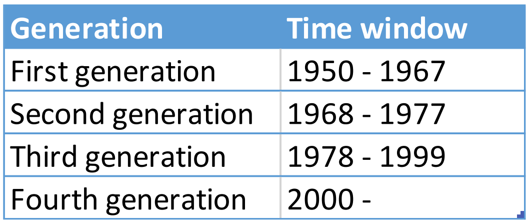
1. The Internet of Things (IoT)
2. Blockchain
3. AI, machine learning and analytics
4. Robots and automation
5. 3D printing

The definition of automation varies slightly depending on the degree of human involvement. Wilson (2019) states that an automated system is assumed to replace human labour (p. 4). In contrast, Westcott et al. (2024) define automation as requiring little to no human labour. Despite this difference, the two definitions remain broadly similar. Automation can be categorised into two main types. Discrete automation, which includes robots, involves processes executed in intermittent movements, typically applied to individual parts or components. Process automation, on the other hand, is designed for continuous operations, such as fluid handling in chemical plants or food production. In general, automation is defined as a system comprising mechanical or electronic devices that control operations automatically. It follows a predetermined sequence of actions, with sensing capabilities enabled through various components such as sensors, actuators, and specialised techniques. These devices monitor ongoing processes and make necessary adjustments to ensure smooth operation. Additionally, automation is a practice that converts manual operations into automated or mechanised processes, covering a wide range of applications, from simple pick-and-place tasks to the complex control of nuclear plants. (pp. 4-5; p. 2)

Mechanisation is a term commonly used in industry, describing the use of motor-driven machines to assist humans in performing tasks. A stem-powered lathe, which dramatically decreases the time to carry out various tasks, is mechanisation, whereas the use of a hand-powered tool is not. The mechanisms themselves can be either automated or manual, but mechanisation has not changed to automation. Mechanisation is used to save the use of human muscle, and automation saves the use of human judgment. (Westcott et al., 2024, p. 4; see also Marttinen, 2018, p. 21)

An industrial robot, defined by ISO, is an "automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or fixed to a mobile platform for use in automation applications in an industrial environment" (ISO 8373:201(en)). Hänninen (2022) categorises the development of industrial robots into four generations based on their technical capabilities. Robotics, as we know it today, began in the 1950s when industrial robots were first introduced into industry. Generations of industrial robots are presented in Table 2. (p. 57)

Table 2 - Generations of robotics development (Adapted from Hänninen, 2022, p. 57)



Generation	Time window
First generation	1950 - 1967
Second generation	1968 - 1977
Third generation	1978 - 1999
Fourth generation	2000 -

The first-generation robots were very simple devices, lacking the capability to control the implementation process and were equipped with no sensors or external environment contact. Unresponsiveness to the existing environment means that the robot will continue working according to the programming, even if there are no objects in the working area or the objects differ from the planned ones. At worst, this would mean that the robot cannot distinguish between, for example, metal and human hands. This would lead to dangerous situations or financial losses. The main characteristics of robots at that time were their loudness and the ability to perform simple tasks related to material handling or canning. (Hänninen, 2022, p. 58)

There are several references to the first robot in history. Hänninen (2022) states that the Unimate robot was the first industrial robot, developed and patented in 1954, and sold to General Motors in 1961. Before that, a robot with five arms stacking wooden boxes in a predetermined pattern was developed in 1937. The difference between these two is that the Unimate is the first digitally operated and programmable polar coordinate-type of robot. (p. 119) Dinwiddie (2019) refers to the robot built by DeVilbiss Company in 1941, which some also refer to as the first industrial robot. It was a parallel-type robot that was later directed towards spray painting applications in the automotive industry to ensure even, consistent coats of paint while minimising waste. (p. 26)

The key advancement between first- and second-generation industrial robots was their ability to perceive and adapt to environmental changes. Sensors enabled robots to monitor their surroundings and report issues, although operators still had to diagnose problems manually. Increased computational power allowed robots to switch tasks, though reprogramming and tool changes often halted operations. A breakthrough occurred in 1969 with the Stanford Arm, which featured six degrees of freedom, enabling movement in multiple directions and rotations. Unlike earlier robots that followed fixed sequences, this innovation allowed computer-controlled positioning. (Hänninen, 2022, pp. 71-74)

The microprocessor, introduced by Intel in 1971, revolutionised robotics, leading to the first commercially available microcomputer-controlled robot in 1973. This advancement reduced controller size, enhanced computational ability, and paved the way for modern robotics. (Dinwiddie, 2019, p. 27)

In Europe, robotics progressed rapidly in 1973, with ABB and Kuka introducing the first microprocessor-controlled six-armed robot. In 1979, Nachi replaced hydraulic welding robots with electric motor-driven models, further advancing the automation process. Finland saw its first industrial robot in 1971 at Strömberg's factory in Vaasa, designed to handle TV picture tubes. Though part of a larger factory project, commercial production remained minimal for unrelated reasons, and the business was later transferred to Cimcorp. (Lempiäinen, 2023, p. 23)

PLCs serve as the brains of automated operations, processing sensor inputs, executing programmed decisions, and activating outputs. Modifications, including changes to grippers or sensors, are made via the robot controller. Early open-loop controllers lacked environmental sensing, simply executing predefined tasks. The second generation introduced relay logic for motion control; however, due to its limited functionality, open-loop systems are now rarely used. The breakthrough came with the introduction of PLC innovation, which enabled input monitoring and allowed robots to verify correct operations. The fourth generation of integrated processors makes controllers more like modern computers. Initially, robots were programmed using specialised languages, later abandoned due to system incompatibility. The shift to C+ and Basic improved control, eventually evolving into self-generating code, where controllers autonomously create programs based on set action points and logic flow. (Dinwiddie, 2019, pp. 48-50)

Third-generation robots are more capable of solving individual problems when they arise. This is due to improvements in sensor technology and programming, which enable better surrounding monitoring and learning from observations and experience. The development of reasoning ability practically means, in the face of a problem, the robot's ability to decide actions based on its programming. For example, the robot could, based on its monitoring, move a defective component to one side, inform the operator, and then proceed to the next component to be worked on. The robot's programming and modifiability are designed to enable the robot to switch between tasks based on a reprogrammed schedule. The development of control technology took steps from localised central computer units (PCs) towards remote maintenance via the internet and teach pendants (handheld devices). Robot's teach pendants are nowadays more high-quality operating devices, replacing individual robot controllers, with features such as displaying error messages for the entire system or entering commands that affect peripherals. Additionally, the increasing use of robots to achieve faster production with better quality has increased the popularity of industrial robots in this era. This also applies to robot manufacturers themselves, who were also able to increase the characteristics of the robots while decreasing the cost of manufacture. (Hänninen, 2022, pp. 79, 85, 111; see also Tarantino, 2022, pp. 314-315)

Robotics research in Finland began in the 1980s, driven mainly by Nokia Mobile Phones' Salo factory. This progress led to mass production at the factory, increasing the demand for lightweight assembly robots. By the year 2000, electronics assembly automation reached its peak, a level that has not been surpassed since. One key success factor, acknowledged even by Nokia's competitors, was the ability to implement production automation projects alongside rapid and sometimes incomplete product development. While automation advancements gained traction in the 1980s, the area of most significant ongoing interest remains machine shop applications. (Lempiäinen, 2023, pp. 25-27)

During the development of third-generation robotics, there was a raised demand for more flexible solutions. Especially smaller companies were unable to compete with more aggressive larger companies. This phenomenon affected both the new robotics manufacturers and users of robotic solutions. Smaller robot manufacturers were either drained out due to a lack of market share after a couple of years of operation or acquired by larger robot manufacturing companies. Users of robot solutions have started looking for replacement solutions on the market to replace large, clunky legacy systems that operate behind closed doors. In response to market needs, the development of modern collaborative robots began. Other technological developments in robotics included accessories such as machine vision, as well as changes in the robot's transmission method from gears, pulleys, and belts to a direct-drive robotic system. The change in transmission method enabled an increase in speed and accuracy, as well as a decrease in maintenance requirements. For this reason, the majority of modern robotic systems use the direct-drive method. (Dinwiddie, 2019, pp. 28-30)

The fourth generation of robots introduced significant advancements, transforming previous models from basic mechanical devices into servo-controlled systems with enhanced computational capabilities. These improvements have greatly enhanced robots' ability to observe and react to environmental changes. Usability has also advanced, enabling small batch sizes and ensuring compatibility with high-mix, low-volume production environments. Additionally, thanks to sophisticated camera technology, robots can now collect materials from non-premade trays. (Hänninen, 2022, pp. 92, 112)

Research and development in human-robot interactions began at the Massachusetts Institute of Technology (MIT) in the early 2000s. The focus of the research was to create a system which could be operated without isolation and be placed side by side with human workers. In 2012, a company called Rethink released a robot which was able to work in an industrial environment without the need for a cage. Baxter, as it was called, was equipped with force sensors, a 360° camera system, and AI software to adjust to changes in its work environment and slow its speed to safe levels when humans were detected nearby. By 2017, robot manufacturers such as ABB, FANUC and Universal Robotics (UR) had a total of 19 different models for collaborative robotics. From robot manufacturers, UR focuses solely on collaborative robots, while other manufacturers have developed collaborative systems to ensure they do not get left behind. In 2016, the first ISO standard, ISO/TS 15066:2016, for collaborative industrial robot systems was published and serves nowadays as a basis for many regulations related to the field of collaborative robots. Before that, existing ISO guidelines on collaborative industrial robot operation were ISO 10218-1 and ISO 10218-2. (Dinwiddie, 2019, pp. 31-37)

Modern controllers utilise AI to learn from data and adjust programs autonomously. Without AI, human intervention is required in situations such as faults or system lockups. However, with AI, the system can analyse multiple options and make informed decisions. As AI technology continues to evolve, these systems will become increasingly prevalent. The latest generation of controllers is closely linked to collaborative robots. These systems monitor and calculate the amperage draw of various motors during operation, enabling robots to respond appropriately and prevent harm to people or the environment. Additionally, robots can integrate camera feeds and other detection systems to identify nearby humans, prompting them to slow down their movement to a safe speed. AI also plays a key role in adjusting programmed operations when parts are misaligned. Most collaborative robots can be programmed by switching to teaching mode, allowing users to guide the robot to desired positions physically. Without this capability, programming must be done manually via a teach pendant, a process that is often time-consuming. (Dinwiddie, 2019, p. 50)

Beyond technical development was the emergence of the robotic integrator, which usually differs from the robotic system manufacturers. Integrators are specialised in selecting, adapting, installing and programming robots for whatever applications their clients request. Typically, the setup is designed to be programmed and tested initially on-site before deployment. Most of these companies are not involved in the development or manufacture of the robotic systems they use, but they may have decided to work with only one robotics company. Some integrators might utilise any available system on the market to meet the customer's needs. Common to all is that they position themselves as a one-stop shop, which guarantees a selection until the system is up and running based on the customer's requirements. (Dinwiddie, 2019, p. 30) However, Holamo et al. (2023) emphasise that comprehensive system integrators are not familiar with this approach, and most parties involved in the project are willing to limit their responsibility to only their own restricted part of the delivered services or products. (p. 79)

Hänninen (2022) points out that it may be too early to conclude the final development of fourth-generation robotics, as today's robots will likely require artificial intelligence solutions that are considered more intelligent than those currently available. However, one feature already stands out as a new feature compared to the previous generation – a strong sense of community. Today's robots can work with humans. (p. 92)

3.3 Effects of industrialisation and robotisation

General Motors (GM) announced in 1982 that it would build a 'factory of the future' to automate production with 4000 robots. The project's vision was to increase productivity and flexibility. Due to increased productivity, a five-year production cycle would be reduced by two years, and employee productivity would increase by 300%. Increased flexibility would enable the switch between varied GM models more easily than before. Manual systems and interfaces would be eliminated, and the number of personnel would be significantly reduced compared to the current situation. It would even be possible to run the operations without turning on the lights. (Armstrong & Shah, 2023, p. 87)

Industrialisation and automation created threatening images as early as the first Industrial Revolution. During the 1800s, some factories were burnt down to protest mechanisation. The question of whether mechanisation leads to a decline in employment and unemployment due to the use of technology or whether it increases both income and the demand for labour has been relevant throughout modern economic growth since the 19th century. In the long term, the need for mechanical engineers is emerging, and at a later stage, someone will be needed to maintain and repair the machines. In the short term, it is obvious that new machines developed productivity while some workers lost their income. Getting used to and changing direction takes time, costs, and creates uncertainty. New information and new tools need to be gathered and investing in something new raises risks. (Schön, 2013, pp. 65-66)

During the Second Industrial Revolution, innovations were based on the increased level of knowledge. The importance of research and education was high, and human capital took an even more important role in economic growth. Chemistry and physics were integral to the development, which was subsequently applied to engineering sciences. Development was directed from the experience-based processing of raw materials by the staff towards a systematic study of the composition and properties of raw materials. At the same time, the information intensity of production also increased, particularly in the research laboratories of growing companies, especially during the development processes. Systematic research also extended to the organisation of production by Frederick W. Taylor, who is considered the developer of what is called scientific management or Taylorism. (Schön, 2013, pp. 72, 81)

This development action resulted in larger activities being divided into smaller patches, which were then monitored and standardised. The work performance could be measured and analysed so that the cost and efficiency per phase and activity could be measured and improved. This development also included the contract system, where an employee's salary was either fully or partially based on the number of pieces they could produce. Development was carried out using scientific methods, which prevented the employee from engaging in passive, independent learning. Notable is that this was not limited to blue-collar work; white-collar workers, such as those in marketing and accounting, were also involved. Simplifying the work steps also enabled possibilities for automation. (Marttinen 2018, pp. 27-28; Schön, 2013, p. 82)

The information economy experienced significant growth, particularly in the United States, during the 20th century, largely due to the early introduction of public educational opportunities. However, these were initially restricted by racial discrimination. During the 1950s, in the United States, 80% of 15-to 19-year-olds were involved in public secondary education; in Europe, the highest participation rate was achieved in the Scandinavian countries, at 30%. There were also differences in the education philosophy; in Europe, education was based on the possibility of working as an intern in a company and attending vocational school simultaneously, while in the United States, education was based on publicly funded programs that did not offer specialisation opportunities. The mobility was intended to happen later in the career, both through university studies and the labour market. In Europe, the American model was seen more as a waste of public funds. In Europe, the focus was on educating the elite. (Schön, 2013, pp. 288-289)

Ford (2013) raises a moral question, especially regarding the development of the IT sector and its distribution of income. Although new inventions, such as Henry Ford's Model T, are often based on earlier inventions, the IT sector is an exception. It can create machine intelligence as a substitute for workers and cover a significant portion of a company's activities. The IT sector also tends to create monopoly situations. This has significant consequences for both the economy and society. Technical capital accumulates only for a small number of people, which in turn fuels the excessive growth of income inequality and, thereby, the weakening of purchasing power for most people. Additionally, public funds have been utilised to finance research projects aimed at developing new technologies. For example, in the United States, the internet was created and funded by DAPRA (Defence Advanced Research Projects Agency), which later also funded Apple's digital assistant called Siri (Speech Interpretation and Recognition Interface). (pp. 82-83)

By investing in education, the overall growth will increase due to increased knowledge. In history, this has led to the more efficient utilisation of existing technology, as well as the creation of entirely new technology, even faster. New technology will enhance the knowledge and skills of workers, enabling them to utilise new technology effectively. This interaction has strengthened modern economic growth, and it is now commonly referred to as lifelong learning. The timespan for embracing new information and technology is shortened, as is its adoption time. (Schön, 2013, pp. 83, 124, 290-293)

Ford (2013) presents the opposite view, predicting that providing training as a solution will continue to be the primary option, but its actual impact will be minimal. In Ford's view, machines also pose a threat to high-skill jobs, both for blue- and white-collar workers. Algorithms will eventually overcome human thinking, primarily if speed is used as the criterion. Another problem is that companies are reluctant to hire new employees, or if they do, it is likely to be for routine, lower-skill tasks, for which, in the worst case, a human will need to teach the algorithm to perform it correctly. (pp. 134-136)

In Finland, changing careers through education has been either partially or entirely the responsibility of companies. The Finnish government's actions in 2024 resulted in the Adult Education Grant not being available for studies commencing in autumn 2024 or later. The Adult Education Grant provided financial support to employees and entrepreneurs for studies that supported their professional development. The Adult Education Grant enabled them to pursue a degree or shorter courses at several educational institutions throughout Finland. The government justified the decision with savings and employment growth. However, it is essential to note that the support is funded by unemployment insurance contributions, which both employers and employees pay. The collection of the contribution is required by law. (Aikuiskoulutustuki, n.d.; see also YLE, 2024a, YLE, 2024b)

What happened to General Motors 'factory of the future’? It turned out to be a mess. Production costs exceeded those of the factories employing thousands of workers. Distinguishing between different car models was unsuccessful, and the robots were spray-painting each other rather than the cars on the line. The factory was closed in 1992. Later, it was shown that with automation, a company will gain productivity but lose process flexibility. The use of robots is interrupted for routine maintenance, and inflexible programming causes a flow of consultants to production, which discourages line employees from continuous improvement efforts. (Armstrong & Shah, 2023, p. 87) This was also discovered by Tesla, which rapidly scaled up its car factories using automated processes. This led to difficulties due to overestimating the capability of the robots and failure, as well as not optimising processes before applying the automation. This resulted in numerous production delays, and subsequently, cars were recalled to the factories for new installations. (Augmentus, 2021)

What happened to the company that sold the robots to GM's project? Japan's Fanuc Ltd has managed to build the factory that GM dreamed of. At Fanuc's Japanese factory, robots make other robots. In addition to the lighting, the air conditioning and heating have also been turned off. In 2003, 50 robots were built in 24-hour shifts, and production was able to operate autonomously for 30 days at a time. (CNN, 2003)

3.4 Development of programming and software development

One trend in programming is the rise of no-code and low-code programming solutions. The names of the terms refine the level of how much actual coding is required to build a program. Low-code software development is a straightforward approach that enables non-technical users to build applications without requiring extensive programming knowledge. No-code software development refers to the method where practically anyone from the organisation, no matter the level of expertise, can build an application that works with the current infrastructure. There is no coding knowledge required at all. (Microsoft, n.d.) This is becoming a tool to program industrial robots, as robot manufacturers seek easier ways to develop robot solutions (ABB, 2023). Forbes describes in the article: How Will the No-Code Market Grow In 2023? (Forbes, 2023) the future trend of no-code solutions. Forbes predicts that the emergence and the rise of AI will affect the development of no-code/low-code solutions. Companies are seeking to streamline their development processes and increase the speed of creating digital solutions. No-code solutions provide possibilities for low-cost development, a wide range of capabilities and ease of use, which will accelerate the trend of no-code/low-code development.

The trend towards no-code/low-code programming is exemplified by Scratch, the world's largest coding community for children aged 8 to 16. It is a coding language used with a web browser, and everything is created using a visual interface. (Scratch, n.d.) Westcott et al. (2024) note that as robots transition from controlled industrial environments to uncontrolled environments, such as homes, hospitals, and workplaces, an increasing number of unskilled individuals are exposed to the influence of robots. This requires more flexibility from robot systems. The flexibility of a robot system is measured by its ability to be programmed. (p. 477)

Considering the history of computing, it can be stated that if the operating system that has become a standard is inexpensive and has easy-to-use programming tools, the number of application programs will grow exponentially. This claim is supported by iPhone, iPad and Android applications. ROS (Robot Operating System) was initially developed at the Stanford University Artificial Intelligence Institute, from which it was later developed into a complete software platform at a company called Willow Garage Inc. This company designed and built programmable robots mainly for use by university researchers. ROS is a free and open-source software platform that is quickly becoming the most common platform used in robot development. In 2013, thousands of software components were running on the ROS platform. Standardised software and external hardware form the foundation, making it relatively easy to develop new models without having to reinvent the wheel. (Ford, 2013, pp. 6-7)

The ongoing industrial revolution is made possible by the dizzying development of information technology. Ford (2015) states that Moore's Law is currently the best-known metric for measuring the increase in computer performance. According to Moore's Law, the number of transistors in an integrated circuit doubles approximately every two years. Information technology, however, accelerates in many ways, which is developed at a rate much higher than Moore's law alone would predict. For example, the capacity of computer memory and digital information carried on fibre-optic lines have both experienced continued exponential growth. The power of computers has taken even more dramatic steps. For example, the size of transistors has shrunk to about 5 nanometres by the early 2020s. Most likely, they cannot get much smaller. However, there are alternative development directions, such as 3D microcircuits and carbon-based materials, that can maintain the development process. Bits move in an abstract environment where the pace of development is dictated by algorithms and applied mathematics. In some cases, algorithms have developed faster than hardware. An example of a complex production planning problem that would have taken 82 years to solve with computers and software in 1982 was solved in about a minute in 2003.

Examining the development of both software and hardware during this period, it can be observed that the speed of computer hardware improved by approximately 1000 times, while the development of algorithms improved by about 43000 times. (Ford, 2015, pp. 65-66, 72-73)

4 Robotics and its implementation

The word robot was first introduced in a play called 'Rossum's Universal Robots' in 1920 by Karel Čapek. The word did not appear in a good light in the play. The robots descended into a killing spree, which could impact public attitudes towards robots. (Marr, 2020, p. 139) In 1942, Isaac Asimov introduced three basic rules of robotics that are still valid and complied with today:

1. The robot must not harm a person, either in motion or stationary.
2. The robot must follow human instructions, except if they are against the law.
3. The robot must protect itself if the behaviour follows the rules 1 and 2.

(Westcott et al., 2024, pp. 398, 400)

Asimov added in 1985 rule number 0: The robot must not offend humanity and must protect humanity to the best of its ability. With this new law and revised order, Asimov prioritises humanity over the person. (Blomsjö, 2023, p. 3)

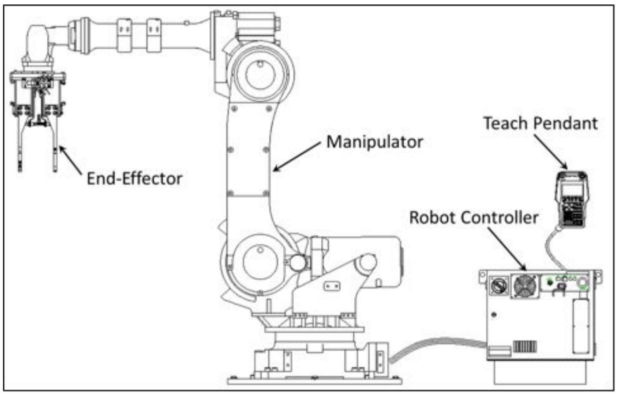
The general definition of industrial robotics is that devices are reprogrammable part processing devices, shared multipurpose manipulators and have at least three freely programmable degrees of freedom and a tool. IFR and ISO have created definitions for the field, which limit, for example, automatic shelf lifts used in warehouses out of the scope of robotics. (Lempiäinen, 2023, p. 17) It is worth noting that dedicated, general-purpose industrial robots are also excluded from this scope, as they do not meet the ISO standard definition of reprogramming, which requires multipurpose capabilities and the ability to move axes. These general-purpose robots are dedicated to a specific task and are not multipurpose as a consequence. (Wilson, 2015, p. 20)

4.1 Robot structure and characteristics

The robot is a collection of subsystems that are managed. As a rule, the complexity increases as the number of components and systems increases as well. The major components of the industrial robot system can be seen in the Figure 13: (OTM, n.d.; Dinwiddie, 2019, p. 41)

- Manipulator: degrees of freedom and number of axes
    - Includes base type and power supply
- Control system or robot controller
- Teach pendant (/interface)
- End-Effector

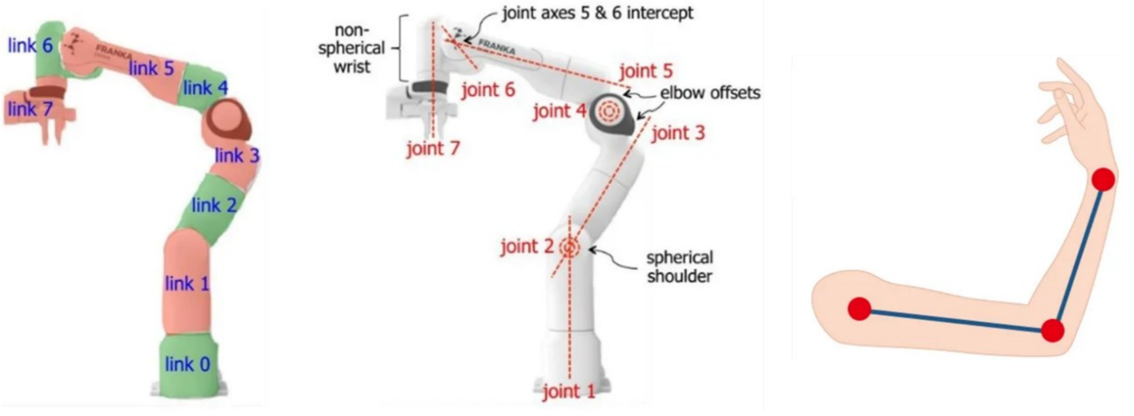
Figure 13 - Industrial Robot System (OTM, n.d.)



Manipulators consist of various parts, such as motors, linkages, cables, and other components needed to complete the desired task of the robot. The manipulator is formed from joints connected by large links. Each part of the robot that controls movement is referred to as an axis. By axes, the robot is given a degree of freedom (DOF), and the categorisation of the manipulators is done by the two-axis manipulator, three-axis manipulator and so on, depending on the number of axes (links). Each axis is equipped with a drive unit (motor, gear, angle encoder), which allows the robot to conduct its individual movements. (Dinwiddie, 2019, p. 54; see also Tarantino, 2022, p. 312)

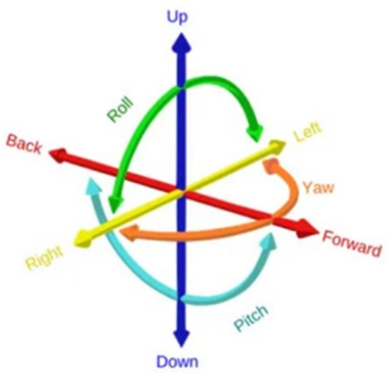
The structure of a typical robot manipulator, compared to that of a human arm, is illustrated in Figure 14. The axes are divided into primary and secondary axes. The primary axes are used to produce larger movements in the workspace, and the secondary axis is used for the orientation of the end-effector, which is the device that allows the robot to perform the desired task. The indication of primary and secondary axes might be misleading, although all of them are involved in completing the desired task. Moreover, in some cases, external axes, such as positioners, are also used in task complementation. The last axis is usually called the wrist, which, like in the human hand, orients the end-effector in an orientation required to align the end-effector to the proper position. (Blomsjö, 2023, pp. 35-36, 73)

Figure 14 - Structure of a typical robot manipulator compared to the human arm (Adapted from Roboacademy, 2020)



The number of links is calculated from the base, where the robot is mounted, towards the end-effector. The exception is made if the base is mounted on a mobile base; in this case, the base is referred to as the last axis of the system. The number of DOFs increases the complexity while enabling the mimicking of most human motions. For example, many gantry-style robots have three axes, while robot arms typically have five or six axes, creating more flexibility for the system with an increased number of DOFs. (Dinwiddie, 2019, pp. 54-55) The maximum amount of DOFs can be six, regardless of the number of joints. Degrees of freedom, or movements, can be seen from Figure 15. The movements can be forward, backwards, up, down, to the side and rotational movements around these directions. Six degrees of freedom means that the robot is practically capable of moving the workpiece in all six directions. (Billing, 2023a, p. 118)

Figure 15 - Degrees Of Freedom (Roboacademy, 2020)



Through the links and degrees of freedom (DOFs), a robot's reach and workspace are defined. **Reach** refers to the maximum distance the centre point of the robot's wrist can extend, often measured from the penultimate joint. It determines how far the robot can stretch, but does not indicate all possible positions within that range. The **workspace**, on the other hand, represents the entire space in which the robot can position its tool at various locations and orientations. The final achievable workspace is heavily dependent on the tool used and its dimensions. (Billing, 2023a, pp. 118-119) The TCP (Tool Centre Point) is a technical definition crucial for executing most robotic tasks. It is typically the mechanical interface at the end of the manipulator, often located at the wrist's end flange. Each tool attached to the end-effector requires a precisely determined TCP, as its accuracy directly impacts the quality of the intended solution. While TCP-related functions vary between manufacturers, their core principles remain consistent. There are multiple methods to define TCP, ranging from manual adjustments and refinements to sensor-based and software-driven solutions. Depending on the method used, periodic verification and adjustments may be necessary to maintain accuracy. (Blomsjö, 2023, pp. 51-52)

The robot is attached to the desired structure through its base. Generally, the base can be either a solid mount or a mobile one. In solid mount bases, the robot is fastened to the floor or other structures using bolts or other fastening systems. The solid base may be anchored to concrete floors, secured to building walls, mounted on overhead structures or secured inside the machine system. The mobile base serves as an enabler, enabling the manipulator to be moved to various locations. The mobile base can be linear rails, which allows the manipulator to move back and forth over a limited area. Another base type is a wheeled base, which consists of wheels that drive and navigate the robot between desired points, while also avoiding obstacles along the way. A standard solution is a material handling system that moves materials in warehouses for tasks previously accomplished by humans and forklifts. A newer idea is to use mobile bases with a mobile robotic arm, for example, in machine tending applications, to cover a larger area compared to traditional gantry-based robots. Regardless of the base type, it is mandatory to secure the robot in place regarding the amount of force it can withstand, whatever load it will be manoeuvring. (Dinwiddie, 2019, pp. 57-59)

The robot must get its power somehow. The three most common power supply sources are hydraulics, pneumatics and electricity. Any other power supply method can be used; usually, the one that is already available. Hydraulic power is generated with a non-compressible liquid given velocity and piped to perform the work. A hydraulic-powered solution is used when there is a need for a large amount of power with precise control. This allows, for example, a robot to lift car bodies, moving them with ease and stopping & holding precise positions whenever and wherever needed. Other advantages include easy manoeuvrability, precision and quietness compared to a pneumatic power source. The downside, or at least a point of concern, is the system's maintenance. The used liquid, often oil, needs to be filtered, monitored and usually changed yearly as filters and tank cleaning are conducted. Some leakages do exist, and even though leakages are easy to spot, they can be in the range from a minor annoyance to a disastrous failure, causing both environmental and component damage. Hydraulic-powered robots are also more expensive compared to pneumatic or electric models of the same capacity. (Dinwiddie, 2019, pp. 41, 45-46; see also Tarantino, 2022, pp. 313-314; Asfahl, 1992, p. 144)

Pneumatic power corresponds to hydraulic power but uses compressible gas instead of non-compressible liquid. The pneumatic benefit is the ability to vent the used air back into the atmosphere. With electricity, electrons need to be returned to some paths, and with hydraulics, liquid needs to be returned to the tank. In most production environments, the needed air with continuous sufficient pressure is readily available. Another benefit of good availability is their modular construction and their use of standard commercially available components. The latter benefit also applies to other power sources, but is particularly beneficial for pneumatic models. Other advantages include a low price, a safe, clean, and easy-to-use power source, and the production of less pollution compared to hydraulic. The downside of pneumatic power is its loudness, lack of precise control, and vulnerability to vibrations. (Asfahl, 1993, pp. 144-145)

Today's pneumatic robots rely heavily on electrical controls, which makes them more electrical solutions rather than pneumatic ones. This is due to the rise of electrically powered robotics, which has become the most commonly used power supply format because it is also readily available, plentiful, easy to store and inexpensive. Additionally, electrically powered robots offer the highest precision and ease of connectivity to networks and programming. The development of servo motors has made electrical power robots, in terms of load capacity, fully compatible with hydraulic power robots without the noise, cost and mess. The disadvantages of electro-powered robots include higher initial costs compared to pneumatics and hydraulics, as well as the potential for overheating in specific environments. Robot manufacturers in the United States have invested in hydraulic models, primarily due to their focus on automotive manufacturing. Japanese robot manufacturers emphasise automatic assembly and, therefore, electric-driven models. Still, situations in which a purely hydraulic or pneumatic-powered robot is used are applications in which electricity cannot or should not be used. (Dinwiddie, 2019, pp. 41, 47-48; see also Tarantino, 2022, p. 314)

Robot controllers' main task is to control the system. Without some way to control the actions of the robot, the timing of the actions and the sequence, the robot is a useless machine taking up some space. These tasks include motion control, communication and safety system functions. The controller calculates and performs the movements of the axes based on the pre-programmed program or commands given via the teach pendant. It also includes information communication with other interfaces, such as sensors or a gripper. Based on the received information, the controller makes decisions based on a system of logic filters and commands. A group of commands is called a program, which the robot executes under its control to perform an action. (Billing, 2023a, p. 120; Dinwiddie, 2019, pp. 48-49)

The teach pendant is used to communicate desired changes to the robot's program without the need for using any other software. Each robot manufacturer has its pedant, while the process of programming the robot is the same for everyone. The interface of the pendant might differ; for example, how the robot is moved, joystick or push buttons are widely used. The trend is that most of the desired functions, if not all, can be controlled through the pendant. Many collaborative robots allow direct manipulation of the robot for programming, removing the need to use the pendant. Some safety features can be found in every pendant, such as an emergency stop and a dead man's switch. The first is for emergencies, which, when pressed, stops the robot and several of its backend systems. The latter enables the robot to move freely. Anyone who is in the danger zone of the robot must carry a teach pendant. Teach pendant development is expected to evolve, as well as general robot development. (Dinwiddie, 2019, p. 52-54)

4.2 Robots' performance characteristics

The best robot to perform a desired function must be tailored to the specific needs and requirements of that function. Several needs or requirements may counteract one another, and the selection of robots and other system equipment, such as tooling or material feeding, will affect the collection of subsystems. Different characteristics of how robots are evaluated are standardised in the ISO 9283:1998 standard. The standard describes the testing methods for robot properties, which are used to specify the technical data of robots, allowing for a comparison of robot properties. Selecting a robot for the desired purpose will be a compromise between the robot's characteristics and its accessories. In most cases, the document of the robot's technical documentation and described performance includes characteristics listed below:

- Robot type
- motion capability
- speed
- payload
- accuracy and repeatability
- workspace
- environmental conditions
- other specific requirements

(Blomsjö, 2023, p. 81-84)

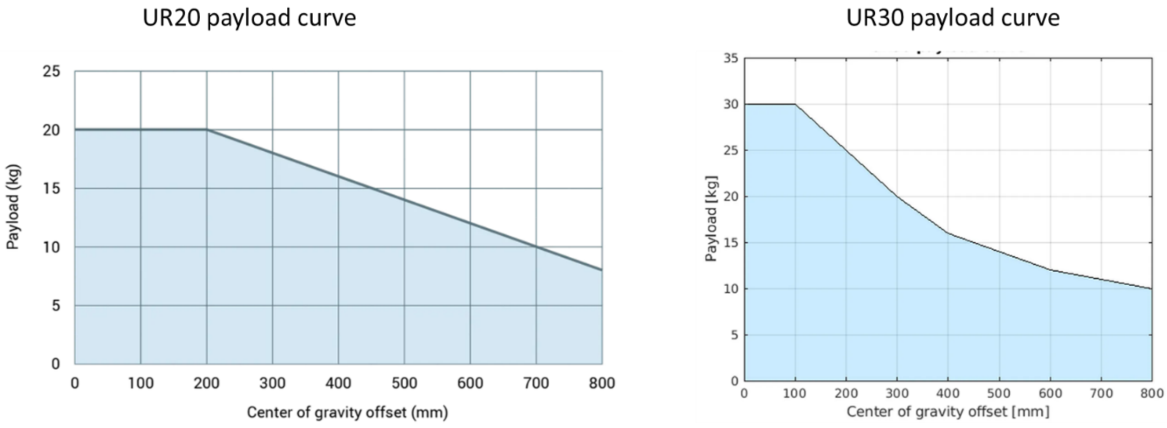
Lempiäinen (2023) states that most end users are interested in payload, reach, accuracy, repeatability, layout possibilities and speed of the work cycle. (p. 17) Wilson (2015) shortens the list into four main performance parameters: payload, repeatability, speed, reach and working envelope. However, he highlights that, ultimately, the most crucial starting point is the cost and simplicity of the entire solution (pp. 29, 32)

The type of robot structure affects the desired performance. Depending on the planned application, different robot types with a suitable EOT ultimately fit the application in various ways. A specialised robot, tailored in terms of its mechanical design, tools, and programming, might be more effective than a general-purpose robot for specific applications. There are options to choose from the leading robot manufacturers, depending on the required capabilities. Some robot models may be specialised for certain types of applications, as mentioned in their technical specifications. This kind of example is the SCARA robot, which is usually addressed as the solution for high-speed and standard cycle operations. (Blomsjö, 2023, pp. 84-85) Wilson (2019) observes that some manufacturers tend to focus excessively on the main configuration, even though their catalogues may offer robots with alternative structures that can meet the exact requirements. A wide range of robots is available, allowing for diverse options to suit any specific application. (pp. 28-29)

Motion capability is described as the range in degrees, maximum speed per axis in degrees per second and allowable moment of inertia. The moment of inertia concerns the handled payload related to the weakest part of the robot, which is usually the wrist. Additional data may be added related to the allowed moment for each axis. (Blomsjö, 2023, p. 86)

Payload is a vital characteristic in selecting a robot, but at the same time, it is not straightforward to determine. Most robots can carry heavier loads than they can move at maximum speed. The shape of the carried object and its surface influence the ability to carry the payload. (Asfahl, 1993, p. 164) The distance of the tool's centre of gravity from the robot's flange also limits the achievable payload. The torque of the tool and the object attached to it is applied to the robot's wrist. (Wilson, 2015, p. 29) Figure 16 is an example of payload curves of Universal Robotics' models UR20 and UR30 and the effect of centre of gravity offset distance on reaching the maximum payload. For example, the UR30 can carry its maximum load (30kg) when its centre of gravity offset is 10cm or less, while the UR20 can perform its maximum load (20kg) when its centre of gravity offset is 20cm or less. If the centre of gravity offset is 40cm for both, the maximum load capacity for both robots is just above 15kg. (UR) The payload may also differ from the robot's mounting direction. A wall-mounted robot may have a different rated payload than an inverted-mounted robot. (Blomsjö, 2023, p. 87)

Figure 16 - Payload curve comparison of UR20 and UR30 (Adapted from Universal Robotics, n.d.)

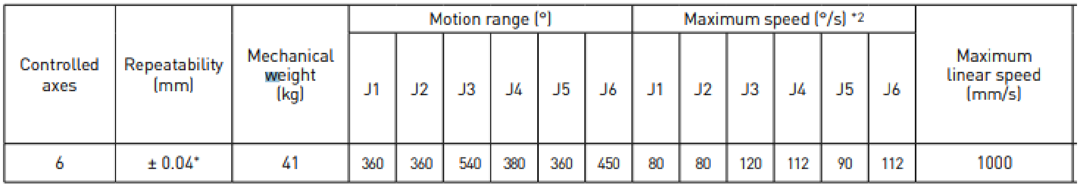


Robots are designed for repeatable work, but they are not accurate by nature. Repeatability is the robot's ability to return to the exact desired spot time after time, continuing to perform the task without slipping off the target. The repeatability of the robot can be determined by either point repeatability or path repeatability. Due to the robot's structure, some of them are unable to move to a commanded position accurately. Instead, they will consistently repeat a taught position within a given tolerance range. Point repeatability is useful for spot welding, handling, assembly, and other similar types of applications. For process applications such as welding and dispensing, path repeatability is more useful. (Wilson, 2015, p. 29; see also Asfahl, 1993, p. 164)

The repeatability feature is specified as repeatability [mm], as shown in Figure 17. The number ±0,04mm indicates the precision with which the robot returns to its starting point.

Practically, the returning point is inside a 0,04mm radius ball. Some robots may have repeatability as tight as ±0,0025mm or even more accurate. In the automotive industry, standard big hydraulic robots usually have a repeatability of ±1,275mm, while robots used in spray painting applications tolerance that can be as high as ±3,175mm (Asfahl, 1993, p. 164; Billing, 2023a, p. 133)

Figure 17 - Example of specification sheet of Fanuc CRX-series robots (Fanuc)



Controlled axes	Repeatability (mm)	Mechanical weight (kg)	Motion range (°)						Maximum speed (°/s) *2						Maximum linear speed (mm/s)
			J1	J2	J3	J4	J5	J6	J1	J2	J3	J4	J5	J6	
6	± 0.04*	41	360	360	540	380	360	450	80	80	120	112	90	112	1000

For applications where repeatability accuracy is crucial, it is possible to add an absolute accuracy calibration functionality that enables reliable offline programming, simulation, and switching programs between robots. With this feature, it is also possible to change the robots during maintenance procedures or even during the installation of a new robot. Some robot manufacturers have calibration procedures for recalibration after repair or maintenance. (Blomsjö, 2023, p. 83)

The speed of the robot is usually shown as the maximum speed for each axis. The maximum speed of individual axes, which is also shown in the example in Figure 17, is misleading since, in many applications, the movement performed by the robot is often short, and axes are not operating independently. Cycle time is used when evaluating the objective of a robot-performed task in comparison to the existing solution. To support the comparison, the so-called goalpost test, especially needed for assembly applications, provides a reliable speed comparison between robot models and manufacturers. The purpose of the test is to simulate a typical move conducted in an assembly application, which is assumed to be a 25 mm vertical move upward, a 300 mm horizontal move and a 25 mm vertical move down. (Wilson, 2015, pp. 25, 30, 106)

The robot's workspace indicates the volume which the robot can cover with its wrist's intersecting point. In practice, the end effector is mounted to the wrist, and TCP is determined and moved around the robot's workspace. Some limits may occur due to possible collisions or other safety-related concerns. To avoid the issues, a simulation is recommended to avoid unwanted situations and to verify the combination of robot placement and the attached robot. (Blomsjö, 2023, p. 88)

Based on the requirements set by the operating environment, the selection of the robot and its accessories needed to be taken into consideration. Environmental conditions can be found in various industries, such as the food and medical industries, where clean-room applications, as well as washing capabilities, need to be taken into consideration. In some solutions, robot arms and tooling might need to be covered, for example, from dust. Operating conditions may also affect the robot and its performance. These conditions include temperature, humidity, and externally induced forces, as well as varying payloads or required motions with high acceleration. Surrounding conditions may affect the interfacing with sensors, PLC or external signalling to control the robot. In these situations, verification tests should be performed. (Blomsjö, 2023, p. 89)

The robot's capabilities and performance requirements drive the selection of the robot based on the application. Still, the selection of a robot is just one part. The entire solution developed is required to meet the set targets. It is always a combination of how the application is addressed, beginning with the selection of the approach and how the process is conducted: a robot carrying the part to a fixed tool or a robot carrying the tool to a fixed part. Depending on the choice made, different requirements are established for the robot's characteristics. The choice made above can affect both the carrying capacity of the robot and the handling of the product, both when bringing the piece to the work area and when removing it from the work area. The process of robot selection is often iterative, meaning that several different approaches must be evaluated before the most optimal option is identified. (Wilson, 2019, p. 31)

4.3 Type of robots

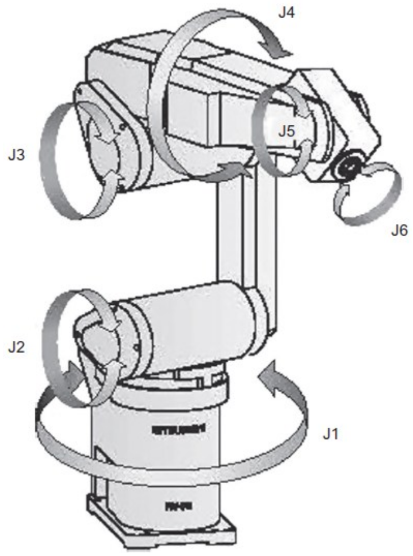
According to the ISO-8373 (ISO 8373:2021(en)), robots are generally classified as industrial robots and service robots. From the ISO determination, this excludes software robotics out of scope. Robots are classified according to their stationary mechanical structure. There are also mobile robots on the market, which are equipped with industrial robots. The mobile robot is a platform for integrated manipulators. According to the standard, the manipulator may be either fixed or mobile. (ISO 8373:2021(en), p. 1) Another classification method is used, as classified by Blomsjö (2023), depending on how their links are arranged. Industrial robots are either serially linked or in parallel. (pp. 65-72)

4.3.1 Articulated

The most common robot type is the articulated robot, which is often referred to as an articulated arm robot due to its structure resembling a human arm. It typically consists of six degrees of freedom, allowing all links to rotate. The robot covers a large workspace in relation to the required floor space of the base. Articulated robot rigidity is relatively low, which can cause problems in applications that require controlled contact forces, such as precision grinding or deburring. This type of robot is typically found in applications such as machine tending and welding, where the robot's extensive workspace can be utilised, ranging from less than 1 kg to more than 1000 kg. (Blomsjö, 2023, p. 65; Wilson, 2015, p. 123)

The robot's wrist can make the same circular motions as a human wrist. However, the robot's rotating wrist movement is considerably more comprehensive. Whereas a human's wrist can rotate 60°, the robot can produce a 270° rotational movement. This can be compared to installing a light bulb; even a person can attach a light bulb, but must do several repetitions. (Asfahl, 1993, p. 135) Due to the construction of the robot arm, each joint must carry the weight of all the following joints. In the example in Figure 18, starting from joint 3 (J3) carries J4, J5 and J6. This has an impact on carrying capacity, repeatability, and accuracy. (Wilson, 2019, p. 24)

Figure 18 - Jointed arm configuration (Wilson, 2019, p. 23)

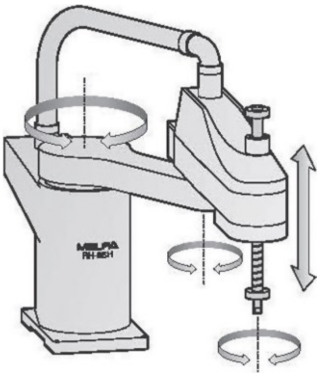


Some artificial robot hand designers have considered that the human arm has 7 degrees of freedom, and the human hand has 27 degrees of freedom, making a total of 34 degrees of freedom. Building a replica of a human hand may be too complex and expensive to build. To be able to reach that, a large variety of EOAT can be found, which are combined with the flexibility of articulated robots. A tool to fit all applications has not yet been invented. Therefore, for every type of work, such as pick and place, welding, machine tending and material handling applications, can be found a work type specific tooling. With a large variety of tooling, articulated robot arms can perform almost any task needed. (HowToRobot, 2024)

4.3.2 SCARA

SCARA stands for Selective Compliance Assembly Robot Arm. This configuration, originally developed in Japan in 1981 for assembly and manufacturing tasks, was revolutionary at the time. As illustrated in Figure 19, SCARA robots share similarities with Cartesian robots in joint movement, as both operate with three links. However, SCARA robots feature two rotational links, enabling more complex movements compared to Cartesian robots. While SCARA robots are not as flexible as articulated robots, nor as accurate as Cartesian robots, nor as fast as Delta robots, they are a cost-effective choice for applications that require a balance of speed and accuracy. They typically offer higher speed and a smaller working area than Cartesian robots, though often at a higher cost. The typical carrying capacity of a SCARA robot is 2 kg with a 1-meter reach (Wilson, 2019, pp. 24, 121; HowToRobot, 2024)

Figure 19 - Scara configuration (Wilson, 2019, p. 25)



Assembly tasks performed by SCARA robots often follow this sequence, as outlined by Asfahl (1993, p. 135):

- Picking up a part vertically from a table
- Moving the part horizontally to another point on the table
- Lowering the part at the designated point to accomplish assembly, including rotation to insert the part.

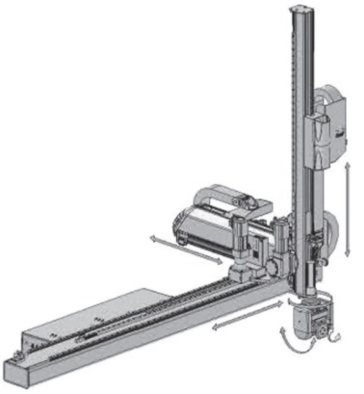
Asfahl (1993) also elaborates on the term 'selective compliance,' explaining that 'compliance' in robotics refers to the ability to accommodate misalignment, a useful feature for cases where mating parts are not perfectly aligned (p. 135)

SCARA robot is used nowadays in applications that require precise handling of small components for assembly, fastening, soldering and tasks with a large amount of downward force requirement. SCARA robots can also be used for packing, small press tending, and adhesive dispensing. Especially electronics companies have widely used the robot in question for placing small components on circuit boards. Installation and integration costs are relatively high. Articulated robots have emerged as the main competitor of SCARA robots, and SCARA robots are being replaced by articulated robots, especially in the automotive industry. Additionally, integrations with articulated arm robots and AI solutions are driving the demand for articulated arms and collaborative robots (cobots). (Wilson, 2019, p. 24; see also Dinwiddie, 2019, p. 28)

4.3.3 Cartesian

As the name Cartesian indicates, this type of robot produces motions aligned in a Cartesian coordinate system. Directions of motions are aligned with rectangular x, y, and z, meaning the moves are forward and backwards, up and down and side to side. This makes the robot's workspace simpler than other robotic models. The Cartesian robot workspace is in the format of a cube. The Cartesian robot configuration can be seen in Figure 20. (Blomsjö, 2023, p. 66; see also HowToRobot, 2024)

Figure 20 - Cartesian configuration (Wilson, 2019, p. 26)



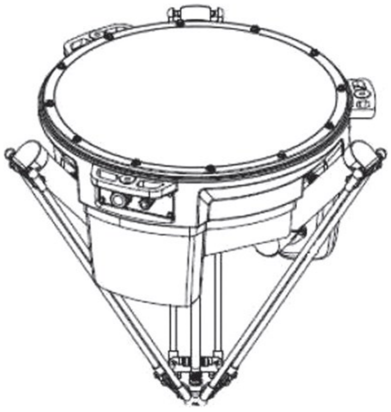
Typically, Cartesian robots are found in various material handling and logistics applications where a large area needs to be covered, and a heavy lifting capacity is required, while still maintaining accuracy and stiffness. A Cartesian robot, also known as a gantry robot, can be customised for a specific purpose, such as covering the entire floor space of a facility to function as an overhead robot. On a smaller scale, the Cartesian robot can be useful for pick-and-place and other applications which require high accuracy. (Hänninen, 2022, p. 115; see also HowToRobot, 2024) The main axis length range can vary from 1m to many tens of metres. Lifting capacity can be as high as 3000kg. (Wilson, 2019, p. 27)

Cartesian robots are also simpler from a software control point of view. They are also cheaper compared to articulated robots. From an installation perspective, Cartesian robots can make highly cost-effective solutions for many automation tasks. The downside is that Cartesian or gantry robots cannot perform rotational movements. (HowToRobot, 2024)

4.3.4 Parallel

Parallel robots, also known as delta robots, are among the most recent developments in robot configurations. It was developed in Switzerland in the 1980s and commercially introduced in 1992. The robot features three robotic arms, each equipped with concurrent prismatic or rotary joints. The development purpose of this type of settlement is to utilise overhead-head mounted machines with motors contained in the base structure, driving linked arms below. The benefit of this approach is reduced weight within the arms, which can provide very high acceleration and speed capabilities, allowing for the performance of light and fast tasks. Parallel robots have a low payload capacity, typically under 8 kg, and can achieve the exact cycle times as SCARA robots. Delta robots have become common in the packaging, pharma and assembly industries. The parallel robot configuration is illustrated in Figure 21. (Wilson, 2019, pp. 27-28; Hänninen, 2022, pp. 80-84)

Figure 21 - Parallel configuration (Wilson, 2019, p. 27)



Parallel robots, also called hexapods, can have six DOFs, and the early developments of this type of robot arose in the 1950s as a universal tire-testing machine. The first operational hexapod was used in the mid-1960s in a helicopter flight simulator at Sikorsky. Today's typical application environment can be found in the industry for pick-and-place operations in packaging operations. The development of Delta robots occurred in a chocolate manufacturing line, where the need was to pack chocolates into boxes. Within lightweight operations, a picking ratio of 700 pieces per minute can be achieved. Disadvantages can be found in limited reach and payload, and in non-suitability for vertical plane operations. (Blomsjö, 2023, pp. 70-72; HowToRobot, 2024)

4.3.5 Cylindrical

Cylindrical robots have a combination of rotary and linear axes, which create up-and-down vertical motion and a motion from the centre in and out. The cylindrical robot's structure is rigid with good access into cavities, but requires clearance at the rear of the arm. This type of robot is easy to program and visualise and is suited to machine tending and general pick-and-place applications. These types of robots are particularly popular in Asia, and especially in the electronics sector and cleanroom applications. The total market share is relatively low, at about 2%, with Asia accounting for 90% of its market share. (Wilson, 2019, p. 28)

The arm requires a small floor space compared to its reach, making it suitable for applications that require circular geometry, such as wires and pipes. Despite the simplicity of operation and installation, the technology is old with limited movement flexibility. (Blomsjö, 2023, p. 67; HowToRobot, 2024)

4.3.6 Collaborative robots

The IFR defines two types of robots which are designed for collaborative use. One group covers robots designed for collaborative use, as specified in the ISO 10218-1 standard, which fulfils the requirements for inherent safe design, proactive measures, and information. The other group covers robots which do not comply with the ISO 10218-1 standard. They may follow different safety standards, making them still safe to use. This makes collaborative robot devices, which are designed for direct interaction with humans. (IFR) Lempiäinen (2023) points out that a collaborative robot is merely a trade name that differs from everyday industrial robots in terms of design and safety solutions. (p. 28)

Collaborative robots, usually called as cobots, are industrial robots which are designed for direct interaction with humans. These robots are offered in a wide range of sizes, payloads, and capabilities, similar to other industrial robots; however, they are specifically defined as collaborative. The robot's inner and outer structure allows for a human to work alongside a robot without needing to guard it. Cobots are equipped with power- and force-limiting technologies, as well as outer design features such as rounded edges and softer materials. Built-in sensors detect the contact and automatically slow or stop the robot's movement to avoid injuries and minimise the harm caused by the contact between a human and a cobot. Practically, this means that collaborative robots and humans can bump into each other by not forgetting Asimov's laws. (Tarantino, 2022, p. 323)

Marr (2020) depicts cobots as colleagues alongside humans. They enhance the work done by humans by interacting safely and efficiently with the human workforce. Collaborative robots are capable of being adapted to various tasks of the collaborative design feature. The average price of 24000 \$ (~23000 €) cobots is an option not only for larger organisations. (p. 141) Dinwiddie (2019) points out the role of collaborative robots. With the ability of the cobot to work alongside humans with a vision system, the cobot became a cheap workforce instead of a piece of industrial equipment. Moreover, the robot can be equipped with alternative devices, for example, to detect leaks and perform other quality-related tasks continuously, rather than through random or periodic inspections. (p. 36)

Tarantino (2022) examines the role of robots in collaborative applications from a safety perspective. Whether the robot is collaborative, the robot does not complete any task without tooling. Therefore, a safety aspect still needs to be taken into account when designing an application with the use of a collaborative robot. A robot operating with heavy objects or with a welding torch can still injure people nearby. (p. 324)

4.4 Safety

Pre- and post-deployment safety actions are related to reducing risks and understanding the hazards associated with activities in and around the robot cell. Compliance with safety-related activities and standards, as specified in regulatory legislation, requires measures concerning the design, implementation, and operation of the complete robot system. One should not make the mistake of thinking that only robot manufacturers or integrators should have knowledge and experience in securing the robot cell. The two mentioned above are responsible for safety when the robot is designed to suit the application. However, after implementation, the target company and its employees become users of the robot cell. Key aspects of safety knowledge should be acquired to implement post-implementation safety-related procedures for the operation, program adjustment, and maintenance of the robot system. (Blomsjö, 2023, pp. 90-91)

The role of safety in robotics is to ensure that personnel will not put themselves in danger during the operation or the maintenance of an automated system. There are several standards explaining the requirements to provide such an environment for automated operations. Additionally, there may be country-specific standards as well as standards established by the company itself. Notable is that these standards are often guidelines rather than strict requirements, and ultimately, a risk assessment is required on behalf of the automation entity supplier. (Wilson, 2019, p. 69)

Asfahl (1992) notes that the number of accidents in robotic systems has been relatively low, but the consequences can be fatal. A certain tolerance for risks is acceptable for humans to perform a particular task, but when a robot injures people, tolerance toward that is zero. (p. 240)

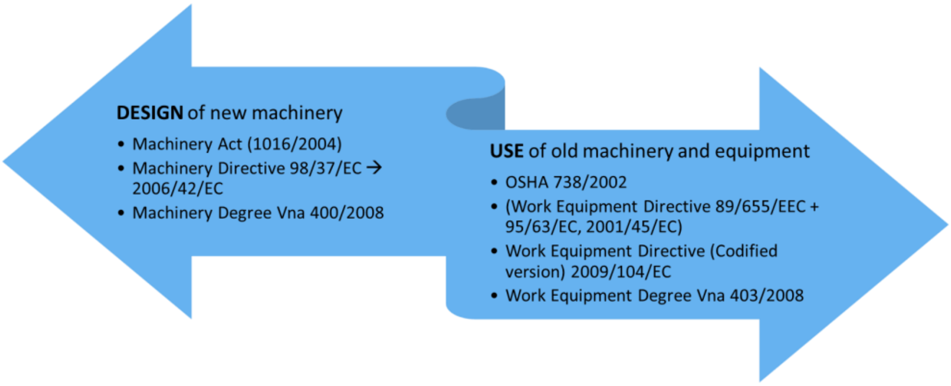
4.4.1 Laws, standards and regulations

A robot alone cannot fulfil the requirements set by the Machinery Directive, classifying it as a semi-finished product. However, when equipped with tools and peripherals, it becomes a robot cell or entity, transforming into a complete machine, as defined by the directive, capable of performing specialised functions. Safety requirements outlined in Annex I of the Machinery Directive are broad and generalised, as they apply to a diverse range of machinery, from chainsaws to welding robot cells. The responsibility for interpreting the directive lies with the manufacturer. To support compliance, the EU has published a guideline (Guide to Application of the Machinery Directive 2006/42/EC), which provides clarification. The latest version is always available for download from the EU's website (Latokartano, 2023, pp. 93–94)

There are several rules and regulations, some of which are mandatory, while others are voluntary or general guidelines, that guide robotics. In Finland, the OHSA (738/2002) governs the use of machinery, work equipment, and other devices. The law stipulates the maintenance and cleaning, as well as access control to the restricted areas and emergency situations. The basic idea is to prepare in a way that does not endanger employee health and ensures safety at all stages. Machinery Directive (2006/42/EC) defines the responsibilities of the machine manufacturer in relation to design and construction, as well as demonstrating the machine's conformity and bringing it to market. The Machinery Directive sets the minimum requirements for, among other things, the markings of the machines and the accompanying documents. A standard is a document that contains recommendations, instructions or requirements on a specific topic. Their use is voluntary, but in some cases, it is recommended by some authorities based on their usefulness. Standards can be global, European, or local, where international standards are recognised by the ISO prefix, European standards by the EN prefix, and Finnish standards by the SFS prefix. The content of European and global standards confirmed in different countries is the same, even if the prefixes differ from each other. Organisations can also require the use of some standards, for example, in tendering or the operation of the subcontracting chain. (Machinery Directive 2006/42/EC, 2006; Finlex 738/2002. 2002; SFS, n.d.

The relation of legislation before and after implementation can be seen in Figure 22. Depending on where the robotisation project is in the timeline, the legislation to be followed and who is responsible for it will be determined accordingly. On a general level, it can be stated that the Machinery Act governs all measures in the planning phase, while OSHA measures take effect after commissioning. (Malm, 2017, p. 8) Noteworthy is what Latokartano (2023) stresses: that the safety requirements apply to design rather than equipment transportation, installation, maintenance, programming, and even decommissioning. In addition to safety, the usability and ergonomics of the device must be considered in the design phase. (p. 112)

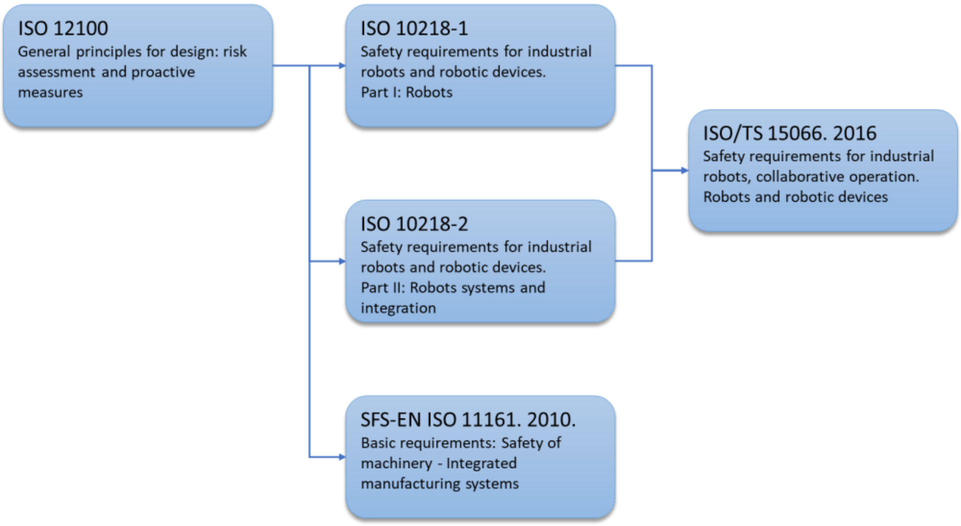
Figure 22 - Legislation of machinery in Finland (Adapted from Malm, 2017, 8)



In Finland, the Machinery Act gives the basis for machinery legislation. The purpose of the law is to ensure that a machine, work tool or other technical device, like a robot, complies with the requirements. The aim is to minimise the risk of accidents or other harm to human workers' health. Additionally, the goal is to ensure that the robot or other technical device is designed, manufactured, and appropriately equipped so that it can be handed over for use without hindrance. The technical requirements come directly from the Machinery Directive. This harmonises the technical specifications for all the introductions of machines that are put on the market for the first time in the EU/EEA area. In practice, this means the free movement of devices in accordance with the directive in the EEA area, which enables the sale of used machines both in Finland and abroad. (Latokartano, 2023, p. 92) The law applies to the manufacturer, the importer, the seller and other persons or entities who make the device available for use (Finlex 2004/1016).

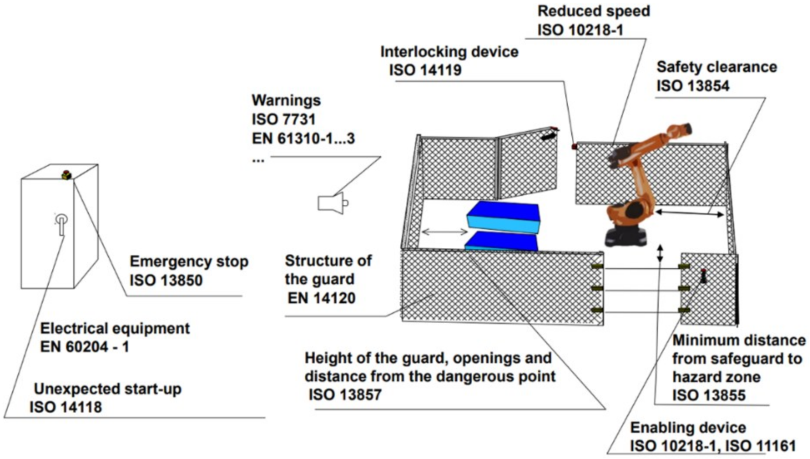
The basis of international standards related to robot safety can be seen in Figure 23. ISO 12100 includes general principles for design, risk assessment and proactive measures. ISO 10218 addresses the requirements for both robots (Part 1) and integrated robot cells and their integration (Part 2). ISO 11161 standard presents safety requirements for designing security measures and operational information for complete machine combinations of manufacturing systems. Some systems have two or more machines connected into a single unit for a specific purpose. ISO/TS 15066:2016 describes safety requirements for industrial robots in collaborative operation. A collaborative robot is designed for direct interaction with a human within a defined collaborative workspace. A collaborative workspace means a safeguarded space where a human and a robot can perform tasks simultaneously during operation. (Malm, 2022, p. 11; see also Blomsjö, 2023, pp. 90-91)

Figure 23 - Robot standards (Adapted from Malm, 2022, p. 11)



The most common standards mentioned above and other related standards to designing a robot cell or a system can be seen from Figure 24. (Malm, 2022, p. 12)

Figure 24 - Common standards related to robots (Malm, 2022, p. 12)

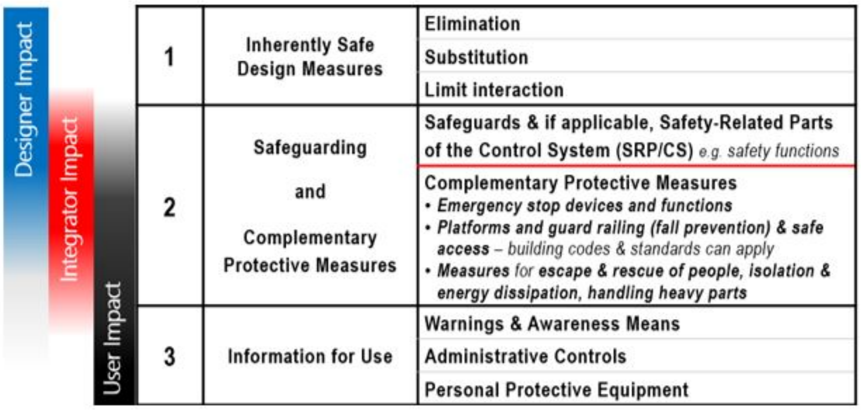


The Occupational Safety and Health Act establishes foundational guidelines for workplace machines and devices. Its primary aim is to safeguard and sustain employees' work capacity by improving both the working environment and conditions. Additionally, the Act aims to prevent accidents, occupational illnesses, and other risks to employees' physical and mental health that arise from work or the working environment (Malm, 2017, p. 8; see also Finlex 2004/1016). Blömsjö (2023) emphasises the critical role of users after the commissioning of a robot system. Once operational, the company is typically responsible for training new personnel to work with the robot system (p. 92)

From a safety perspective, one of the first tasks is to define the manufacturer of the robot cell or system, which will be the signer of the Declaration of Conformity. From the robot manufacturer's point of view, a single robot is considered a partly completed machine which cannot perform any designed task, such as welding or grinding. When a tool (like welding equipment or a grinder), protective devices and other machines and devices are added, the partly completed machine becomes a whole robot system or cell. The robot manufacturer makes the documentation and declaration of incorporation in compliance with Machinery Directive Annex II section B. Usually, the integrator, who adds tooling, protective and other devices, makes the documentation and declaration of incorporation in compliance with Machinery Directive Annex II section A and therefore, the integrator becomes the manufacturer of the robot system or cell. According to the basic definition, a wider robotic system is counted as one machine which is secured as a single entity. (Malm, 2017, p. 9)

In practice, when building an entity consisting of different machines or machine parts, a representative located in the EEA area, such as an importer or retailer, is the manufacturer of the entity. Following the same principle, if the entity is built by the company itself, the company then becomes the manufacturer of the entity. The most important thing is to find a party that is responsible for the entity and gives a certificate of conformity. If other parties involved in the project fail to do so, the buyer is responsible. The verified manufacturer's responsibility concerns, for example, risk assessment, which must cover all health and safety risks related to the entity during its life cycle. In addition to everyday use, the design must consider reasonably foreseeable possible cases of abuse. (Latokartano, 2023, p. 93) The 3-step process outlined by OSHA in Figure 25 primarily assigns safeguarding responsibilities to the machine manufacturer, followed by the robot application integrator and, finally, the user. (OSHA, n.d.)

Figure 25 - 3-Step method (OSHA, n.d.)



1	**Inherently Safe Design Measures**	**Elimination**
		Substitution
		Limit interaction
2	**Safeguarding and Complementary Protective Measures**	**Safeguards & if applicable, Safety-Related Parts of the Control System (SRP/CS)** *e.g. safety functions*
		Complementary Protective Measures • ***Emergency stop devices and functions*** • ***Platforms and guard railing (fall prevention) & safe access*** – *building codes & standards can apply* • ***Measures*** *for* ***escape & rescue of people, isolation & energy dissipation, handling heavy parts***
3	**Information for Use**	**Warnings & Awareness Means**
		Administrative Controls
		Personal Protective Equipment

Actions that need to be conducted to make machines safe can be found in the Machinery Directive:

- Risk assessment
- All safety requirements and related directives
- Design the machine according to the Machinery Directive, annex I
- Write manuals for use, construction, maintenance and safety if necessary
- Compile and maintain the technical file of the entity
- Declaration of Conformation must be drawn up
- CE-marking and other markings on the machine

(Malm, 2017, p. 9)

In Finland, the employer's responsibility is governed by the Occupational Safety and Health Act (738/2002) and the Government Decree on the Safe Use and Inspection of Work Equipment (403/2008). The purpose of these laws is to ensure that employers understand their role and that the machines and equipment in use are suitable for their intended purpose and safe to operate. In practice, the employer must make sure that the entity has a CE mark and ensure that, before commissioning, the correct installation and functionality of the entity are ensured. This is an important step because, with the approved commissioning, the responsibility for the entity's safety is transferred from its manufacturer to its buyer and user. (Latokartano, 2023, p. 96)

By using harmonised standards, the manufacturer of the robot cell not only creates a safe operation for the cell but also ensures compliance with international standards. The manufacturer saves time and money. When applying the standards to the entity, it is assumed to fulfil the main safety requirements. This does not eliminate the need for risk assessment and documentation, which will also be faster to conduct when the design is completed in accordance with harmonised standards. If the manufacturer needs to deviate from the requirements of harmonised standards, the manufacturer is forced to prove the achieved safety level in a way other than that indicated in the standard. This can result in large test sets, measurements, and documentation, which prolong deployment and increase costs. (Latokartano, 2023, p. 95)

4.4.2 Securing the industrial robot cell

According to safety standards, the robot entity must be designed to avoid danger to humans. The starting point for the securing process is always the elimination of hazards. With traditional industrial robots, this means that a robot and a human are isolated from each other. This is done due to the impossibility of controlling the impact force with sufficient speed and precision. The isolation consists of the entity, such as tooling, power sources and other accessories, even if the robot itself is safe for humans. (Latokartano, 2023, p. 105)

Following the principle that 'an ignored rule is worse than no rule at all' is essential when securing a solution. This is particularly important in the context of guarding, alarm routines, and emergency power-offs. While most of a robot's operational life is spent in the production phase, most hazards occur during programming, setup, and maintenance routines. For planned maintenance and abnormal situations, trained personnel and emergency power-offs are the most effective measures to ensure safety. When entering a robot cell, a teach pendant equipped with the ability to control the system's power should be available. Access to the robot's work envelope should be restricted to personnel actively engaged with the system. (Asfahl, 1992, pp. 240-241)

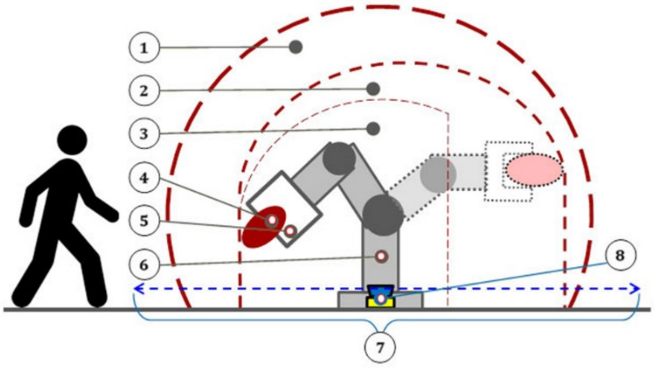
The service life of a robot and the robot cell can be over tens of years in Finland. Depending on the application, some repairs or modifications are required in addition to regular maintenance routines. Depending on the extent of the modifications, a new risk assessment needs to be conducted. In some cases, the entity is considered a new machine, causing the requirement to update all safety devices in accordance with the requirements in force at any given time. (Latokartano, 2023, pp. 105-106)

One of the simplest methods to secure a robot's work area is by using fixed perimeters or guards. These guards are typically composed of panels made from sheet metal, weld mesh, or plastic sheets. Surrounding the automation system with guards requires providing controlled access points. Doors integrated into the system enable controlled entry and can interrupt the robot's actions when necessary. These doors are interlocked with the control system, cutting power to the machinery upon access. To further secure entry, padlocks with individual keys are allocated to personnel entering the system. Each person attaches their padlock, ensuring that the system cannot be reactivated or returned to an automatic state until all personnel have exited and removed their locks (Wilson, 2019, pp. 69-70)

In some cases, fixed guards are necessary to mitigate potential hazards, such as deflecting welding sparks away from human contact while the robot performs its tasks. The placement and design of fixed guards involve compromises among factors such as cost, usability, and space availability. However, safety must never be compromised. For instance, the height of the fence should be determined by the personnel's location level rather than the floor level. (Latokartano, 2023, p. 107; see also Dinwiddie, 2019, p. 6)

Notably, the safeguarded space exceeds the robot's operational space, as illustrated conceptually in Figure 26. This ensures an added layer of safety for all involved.

Figure 26 - Robot application space (OSHA, n.d.)



Key:	**1**	maximum space	**5**	end-effector
	2	restricted space	**6**	manipulator
	3	operating space	**7**	safeguarded space
	4	workpiece	**8**	protective device or barrier (safety scanner shown)

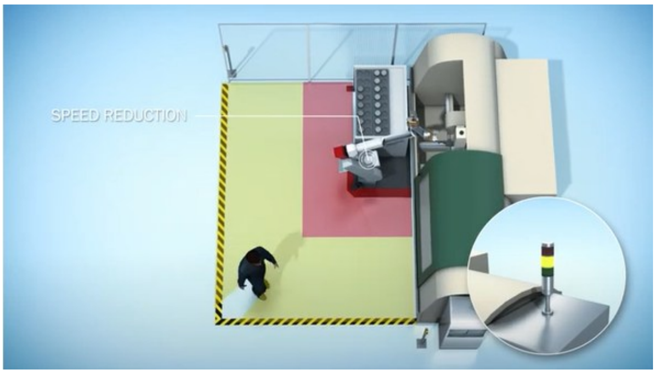
There may be a need to enter the robot work area other than for maintenance or programming purposes. In some applications, humans and robots share the same work area during the operation. This kind of process would be where the human operator presents the piece parts for a robot for pickup. Typically, a sliding feed mechanism would be utilised, which can serve to transfer parts between humans and robots. This allows the parts to be moved without the possibility of the human and the robot coming into physical contact, even though both are required to access the same physical location. This type of solution is common in punch presses; the human operator can perform the unload, load, and slide operations while the robot performs its work cycle. (Asfahl, 1993, p. 241)

According to the standards, the robot's access to areas other than those required by the movement program must be prevented either mechanically, with safety equipment, or through software. If the safety system allows, for example, the size of the robot's stopping area can be dynamically changed according to the program. At a higher speed, the stopping area is larger than when moving at a lower speed. (Latokartano, 2023, p. 109) Light guards are often used to control access to larger areas or in cases when doors are an unworkable solution. The operating principle of these solutions is simple. At one end of the aperture is a light source, and at the other end is a receiver to 'accept' the beam of the light source. If there is a deviation from this, the interruption of the beam causes the system to stop. (Wilson, 2019, p. 71)

In practice, two key considerations must be taken into account to eliminate the danger. The standard ISO 13855 guides the selection. First, the distance of the light curtain to the cause of the danger, for example, the robot, must be defined. This is affected by the time the robot, with or without the load, needs to come to a complete stop. Another thing to consider is that staying in a protected area prevents the system from restarting, not just entering the area. Ways to eliminate a hazard are to either place the light curtain often at an angle of 45° to enable wider coverage or to place separate horizontal and vertical light curtains to control the robot's work area. The method described above is illustrated in Figure 27. For loading/unloading areas where a person needs to enter randomly, the danger can also be mitigated by building a physical barrier after the loading/unloading area to prevent entrance into the hazardous area. The need for protection affects the chosen method. Whether to observe the whole body, hands, or fingers, as well as the budget, affects the selection and placement of safety devices. (Wilson, 2019, p. 72; see also Latokartano, 2023, pp. 108-109)

Photoelectric sensors or light guards can also be used to control the robot's workspace, preventing collisions with the ceiling or other structures. This can cause the robot's movement to be choppy and inefficient if it must deviate from its natural path. This can and should be removed by changing the physical positioning of the robot if possible. (Asfahl, 1993, p. 242)

Figure 27 - Implementation example of workspace monitoring (SICK, 2022)



Securing does not apply only to the robot itself. The entire robot system, including tools, machinery, equipment, and sensors, falls within the scope of the Machinery Directive and the ISO 10218-2 Standard. This is emphasised in robot systems based on collaborative robots. Securing the movement of the robot arm is relatively straightforward, but, for example, tooling in the situation of an emergency stop can be much more complex. The question is to ensure that the object carried by the tool does not come off due to a sudden stop of the robot. The solution can be found in a fixed fence or in ensuring the functional safety of the tool. An example of this kind of situation is using a pneumatic tool and securing the pressure in case of an emergency stop and possible power loss. Technical report ISO/TR 20218-1 has been prepared to clarify the standard, and the example is also described. (Latokartano, 2023, p. 111)

4.4.3 Human-robot collaboration

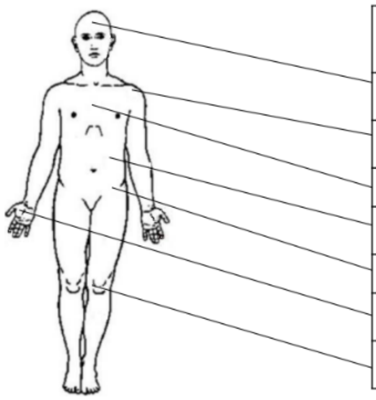
The form of human-robot collaboration is defined in ISO 10218-1 and ISO/TS 15066 standards. The basic idea still exists: robots do not hurt a person. This is achieved through controlled range, force, and speed, as well as separation monitoring and safety-rated monitored stopping. This makes restarting easier and can be automated if the assessment allows it. The practical difference between collaborative and non-collaborative systems is evident in situations involving emergency stops. In the traditional model, the servo power is cut off, whereas in collaborative mode, the servo power is on. (Malm, 2017, 14)

When referring to applications where a human and a robot share a common workspace, the term collaborative robotics is often used. In technical specifications and standards, there are no specific terms for collaborative robots or collaborative robotics. Collaboration describes more the nature of the action performed by a human and a robot. From a safety point of view, there is no need for actual cooperation in the robot cell. The fact that human has access to the cell makes the application cooperative. Usually, the actual collaboration does not exist in the applications. It is more the nature of the action. (Latokartano, 2023, p. 112)

Suppose the robot application is conducted without separate safety devices. In that case, a difference exists in the basis when securing the robot cell, depending on whether a naturally safe robot is used or not. A robot designed to be naturally safe is often referred to as a collaborative robot. The basis of a collaborative robot risk assessment is that a collision between a human and a robot can occur. The risk assessment focuses on the severity of the damage caused by the collision made by the collaborative robot. In situations where the collaborative robot is not used, the basis of risk assessment is the evaluation of the probability of a collision, meaning that a collision is not acceptable. (Latokartano, 2023, p. 112)

According to Malm (2022), robots can make two types of contact: transient contact and quasi-static contact. Transient contact is brief, occurring so quickly that the robot's control system cannot react. The force exerted during such contact is influenced by factors such as relative speed, the effective masses of the moving robot, and the body region involved. In contrast, quasi-static contact lasts longer, allowing the robot's control system to reduce speed and force. The hazard posed by this type of contact arises from the combination of pressure (N/cm^2) and force (N). ISO/TS 15066:2016 provides guidelines on safe force limits, as illustrated in Figure 28. For sensitive body regions such as the skull, eyes, ears, or face, contact should be avoided whenever reasonably practicable. Specifically, the force applied to the face must not exceed a maximum of 65N. (pp. 27, 31)

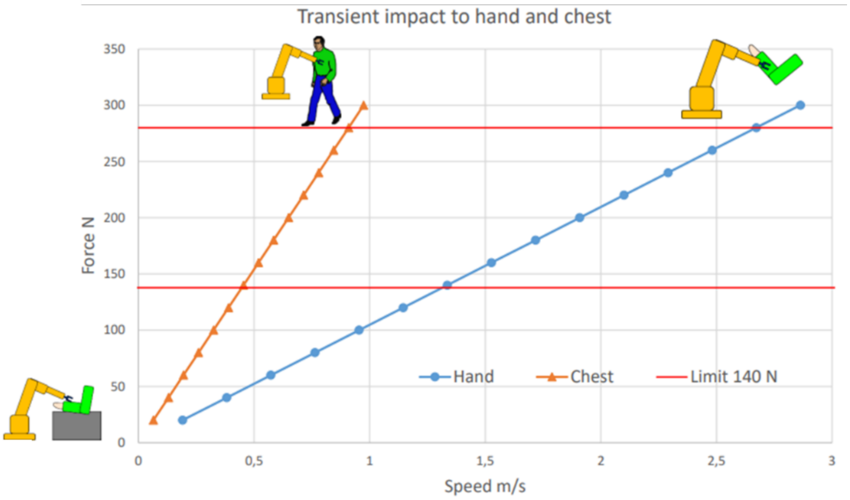
Figure 28 - Safe forces (Malm, 2022, p. 29)



Examples of pressures and forces		Quasi-static contact	
Body region	Specific body area	Maximum permissible pressure (N/cm²)	Maximum permissible force (N)
Skull and forehead	Middle forehead	130	130
Back and shoulders	Shoulder joint	160	210
Chest	Sternum	120	140
Abdomen	Abdomen muscle	140	110
Pelvis	Pelvis bone	210	180
Hands and fingers	Palm	260	140
Thighs and knees	Kneecap	220	220

Figure 29 illustrates the impact forces for a cobot as a function of speed, focusing on the chest and hand. For both cases, the quasi-static contact force limit is 140 N, while the transient contact force limit is 280 N in the example case, where the robot's weight is 28.9 kg and the load capacity is 10 kg. If the robot makes transient contact with the chest, its speed should not exceed 0.9 m/s, whereas for the hand, the speed limit is 2.6 m/s. For quasi-static contact, the upper-speed limit is approximately 0.4 m/s for the chest and 1.3 m/s for the hand. While transient impact to the hand is generally less critical, impacts to other body parts can pose greater risks. (Malm, 2022, p. 30) Bauer et al. (2016) highlight a key point from ISO 12100: designing the contact area to minimise injury risk by addressing sharp edges or small surfaces. Preventative measures, such as the use of rounded corners or padding, can significantly reduce the risk of injury. (p. 21)

Figure 29 - Transient impact forces for cobot as a function of speed (Malm, 2022)



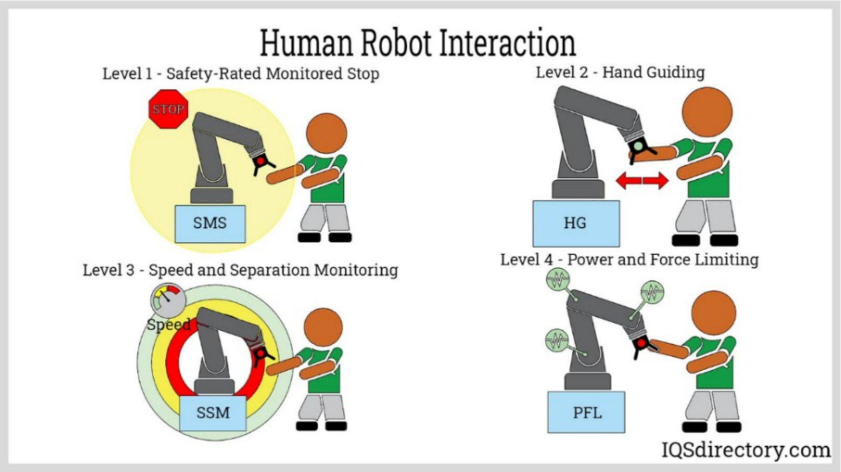
Co-operated applications do not need to be implemented only with collaborative robots. Implementing a regular industrial robot is possible as long as the control system of the robot cell accomplishes the required safety requirements. In this case, the basic principle of safety is to prevent the robot from colliding with a human in all possible situations. Access to the robot's workspace is controlled by safety devices, allowing the robot to be stopped before a human enters the workspace. (Latokatano, 2023, s. 113)

There are four methods for implementing human-robot cooperation, and one must be selected. The levels of cooperation are illustrated in Figure 30.

1. Safety-Rated Monitored Stop (Level 1): This is the simplest method for collaborative operations in a robot cell. Shared workspace control is achieved using tools like laser safety scanners or light curtains. Standards require the robot to stop before a human enters the shared workspace, achieved by cutting power to the servo motors. When the human exits the workspace, the robot automatically resumes its program, enabling faster operation without the need for additional acknowledgement of the person's departure. (Latokartano, 2023, pp. 113-114; Malm, 2022, p. 35)
2. Hand-Guided Robots (Level 2): This method involves controlling the robot near its end effector, including features like an emergency stop and, where necessary, an enabling device. This approach is ideal for tasks requiring frequent programming, especially when the robot moves between different stations. Manual control during production involves guiding the robot's tool to position a load accurately, with force recognition enabling hand guidance without the need for additional devices. Larger industrial robots typically require separate manual control equipment, including emergency stop and enabling devices. (Latokartano, 2023, p. 114; Malm, 2022, p. 35; IQS Directory, n.d.)
3. Speed and Separation Monitoring (Level 3): This method closely resembles the safety-rated monitored stop but emphasises easy, fenceless access for humans. It relies on measuring the distance between the robot and the human and adjusting the robot's speed accordingly. Safety zones, defined by devices like laser scanners, allow the robot to operate at higher speeds when the human is farther away, while reducing its speed or stopping completely as the distance decreases. These values must be determined during the design phase and documented in the operation instructions. (Latokartano, 2023, p. 115; Malm, 2022, p. 35; IQS Directory, n.d.)
4. Force- and Power-Limited Robots (Level 4): These collaborative robots are designed to be lightweight or meet standards for limiting power and force, as defined by ISO 10218-2 and ISO/TS 15066. They are built to allow safe collisions without causing injuries. However, if collision forces exceed

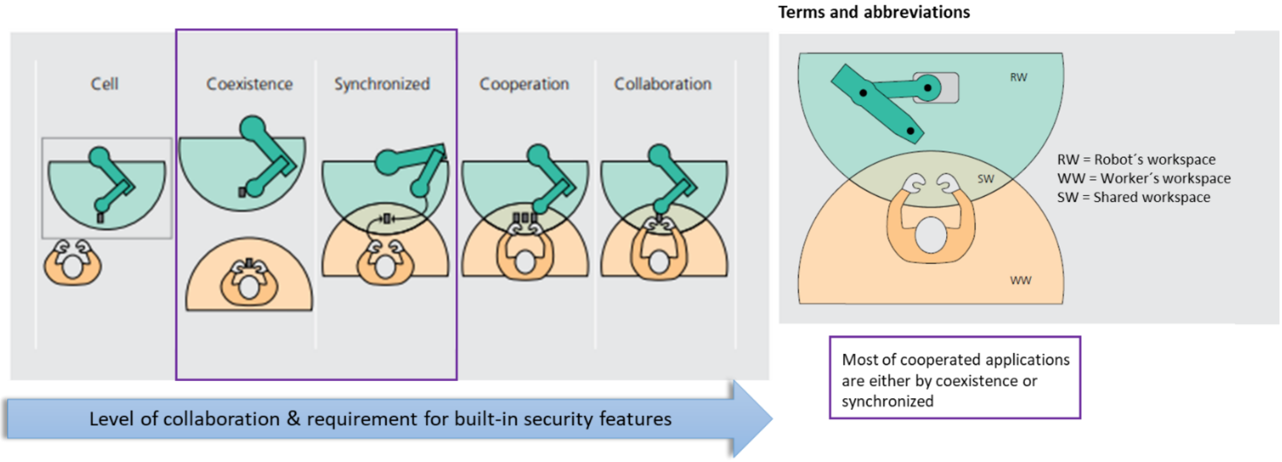
permissible limits, additional safety measures must be implemented. Force and speed limitations are monitored and controlled independently from the robot's program execution. These values are documented in the user manual, with editing restricted to authorized personnel using a password. (Latokartano, 2023, p. 115; Malm, 2022, p. 35; IQS Directory, n.d.)

Figure 30 – Human-Robot Interaction (IQS Directory, n.d.)



In history, robots have been used to perform tasks that they can do independently. In the last decades, there has been a shift from keeping workers and robots separate towards cooperation. Notable is that the cooperation levels, as presented in Figure 31, differ from the collaborative operation requirements, as presented in Figure 30. (Latokartano et al, 2023, p. 73)

Figure 31 - Levels of cooperation (Adapted from Zamboni & Valente, 2020, p. 175)



Usually, human-robot cooperation refers to the use of robots without physical barriers, i.e. cage-free robots. The tasks are carried out in a single, combined working environment, which eliminates the strict partition between human manual work and robot-automated work. Their work zones overlap, creating a shared workspace. (Bauer et al., 2016, p. 8)

Human-robot cooperation can be achieved on several levels. The most common approach is the cell-type collaboration, which practically means that a physical barrier separates the robot and the human. The material flow to and from the cell is solved with separate standard locations, where the robot picks up the material and where it leaves the finished part. The selection of the cooperation level is guided by the task conducted by the robot and the human. Typically, the complexity and cost of the application increase as the level of collaboration is chosen or required. Reasons to allow higher levels of cooperation between humans and robots during the robot's work cycle may be:

- The smoothness and speed of material flow
- Size and shape variations of the materials to be processed
- The complexity of assembly requires sequential action by a human and a robot
- Large changes in assembly that require simultaneous tasks from a human and a robot

(Latokartano et al., 2023, pp. 73-74)

Table 3 presents the types of collaboration and their associated safety measures in today's industrial applications. Based on the research conducted by Bauer et al. (2016), the primary level of cooperation between humans and robots is coexistence, facilitated by the new technology applied, which is highly reliable in this form. The suggestion is to start simply by processing from coexistence to collaboration. (p. 9)

Table 3 - Human-robot interaction types (adapted from Malm, 2022, p. 33; see also Latokartano et al., 2023, pp. 74-75; Bauer et al., 2016, pp. 8-9)

Level of collaboration	**Characteristics of collaboration**	**Related safety measures**	**Examples of applications**
Cell	• Isolated robot cells have been common in the industry since the 1960s. • No cooperation, safety measures are easy to implement.	• Separating guards	• Welding • Machine tending • Painting • Assembly
Coexistence	• Robot is cage-free • Humans and robots work alongside each other	• Safety-rated monitored stop • Speed and separation monitoring	•

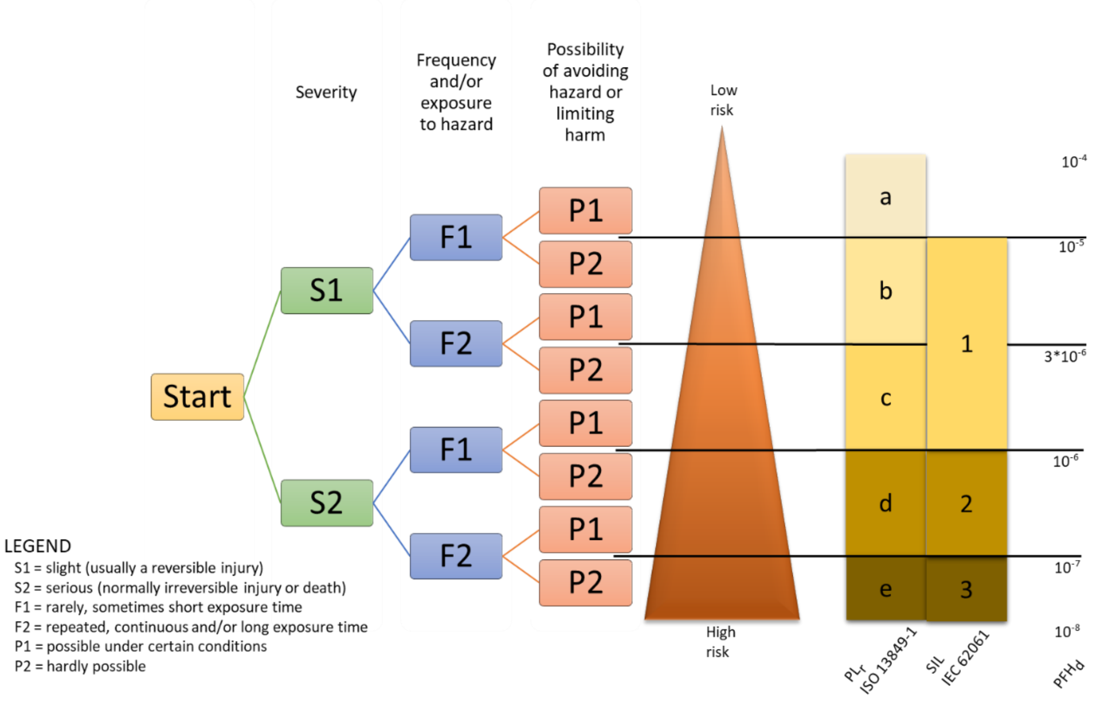
	• Identical from a collaboration point of view because of not sharing the workspace	• Power and force limiting	
Synchronised (sequential cooperation)	• Humans and robots work sequentially on the same workpiece • No simultaneous activity inside the shared workspace • Need to control the arrival and departure of humans from the workplace	• Safety-rated monitored stop • Speed and separation monitoring • Power and force limiting	• Palletising
Cooperation (Parallel operation)	• Humans and robots work simultaneously in the same workspace, but not on the same workpiece • Simultaneous activity inside the shared workspace • Collisions are not expected	• Speed and separation monitoring • Power and force limiting	•
Collaboration	• Human and robot work simultaneously on the identical product to produce something together • Simultaneous activity inside the shared workspace • Collisions are allowed • Only collaborative robots are allowed	• Power and force limiting • Hand guiding	• Assembly

4.4.4 Functional safety

Functional safety is related to the safe performance of actuators in cases when the safety-related control system initiates a safety function. Standards related to functional safety are ISO 13849-1 and IEC 62061, where the former is more closely related to machine builders, while the latter is more closely related to control system builders. The difference is not relatively big. (Malm, 2017, p. 15)

A performance level (PL) needs to be assigned for each security system in the robot cell. The safety system consists of the required performance level of safety-related control systems, such as relays, programmable logic controllers, and motor control units. The purpose is to require a certain level of performance from all individual components related to the safety system of the robotic cell, ensuring the reliable operation of the cell without posing additional dangers. The standard ISO 13849-1 defines the principles of design and integration of these components. Based on the diagram presented in Figure 32, if the ISO standard marking method is used, the performance level of functional safety is expressed with the marking PLr (Performance Level required). (Latokartano, 2023, p. 101) The higher the risk a machine poses, the higher the performance level it needs. The performance levels range from PLa to PLe, with PLa being the lowest and PLe being the highest. If the IEC standard marking method is used, functional safety is expressed with the marking SILx (Safety Integrity Level), where SIL1 is the lowest and SIL3 is the highest level. (SICK) From Figure 32, it can be seen that there is no equivalence for Pla between PL and SIL. SIL1 is divided into PLb and PLc because, in machinery, many safety functions are associated with SIL1, and the cost difference between PLb and PLc systems can be considerable. (Malm, 2017, p. 16)

Figure 32 - Performance level assignment (Adapted from SICK)



Performance level analysis begins by assessing the severity of the injury, i.e. parameter S. Slight injury (S1) can be a bruise or a small healing wound. S2 level injury can be more fatal, such as broken bone, amputation or death. The frequency or exposure to the hazard (parameter F) depends much on the nature and use of the machine being evaluated. The standard ISO 13849-1 employs the 15-minute rule, which involves determining whether the operator is exposed to the hazard more than once every 15 minutes. The possibility of avoiding danger and the probability of occurrence of a hazard are combined with the parameter P. In practical evaluation, level P1 can only be used if avoiding the danger is possible, for example, when the robot is moving very slowly. The user's training can also be considered in the evaluation. (Latokartano, 2023, pp. 101-102)

Both large industrial robots as well as collaborative robots' safety functions are needed to fulfil the requirements presented in ISO 10218-2 standard. The required performance level for safety devices is PLd or lower. Since collaborative robots and humans do not need to be isolated and there is contact allowed, the starting point for the safety design process is different. Safety is based on the characteristics of robots and robot cells instead of separate safety devices. Technical specification ISO/TS 15066 deals with safety requirements set for cells where a human and a robot work in the same area. However, Technical Specification differs from the ISO standard in that Technical Specification does not set binding requirements for safety. Technical Specification only gives instructions and examples for interpreting the standards ISO 10218-1 and -2. (Latokartano, 2023, p. 105; see also Malm, 2022, p. 18)

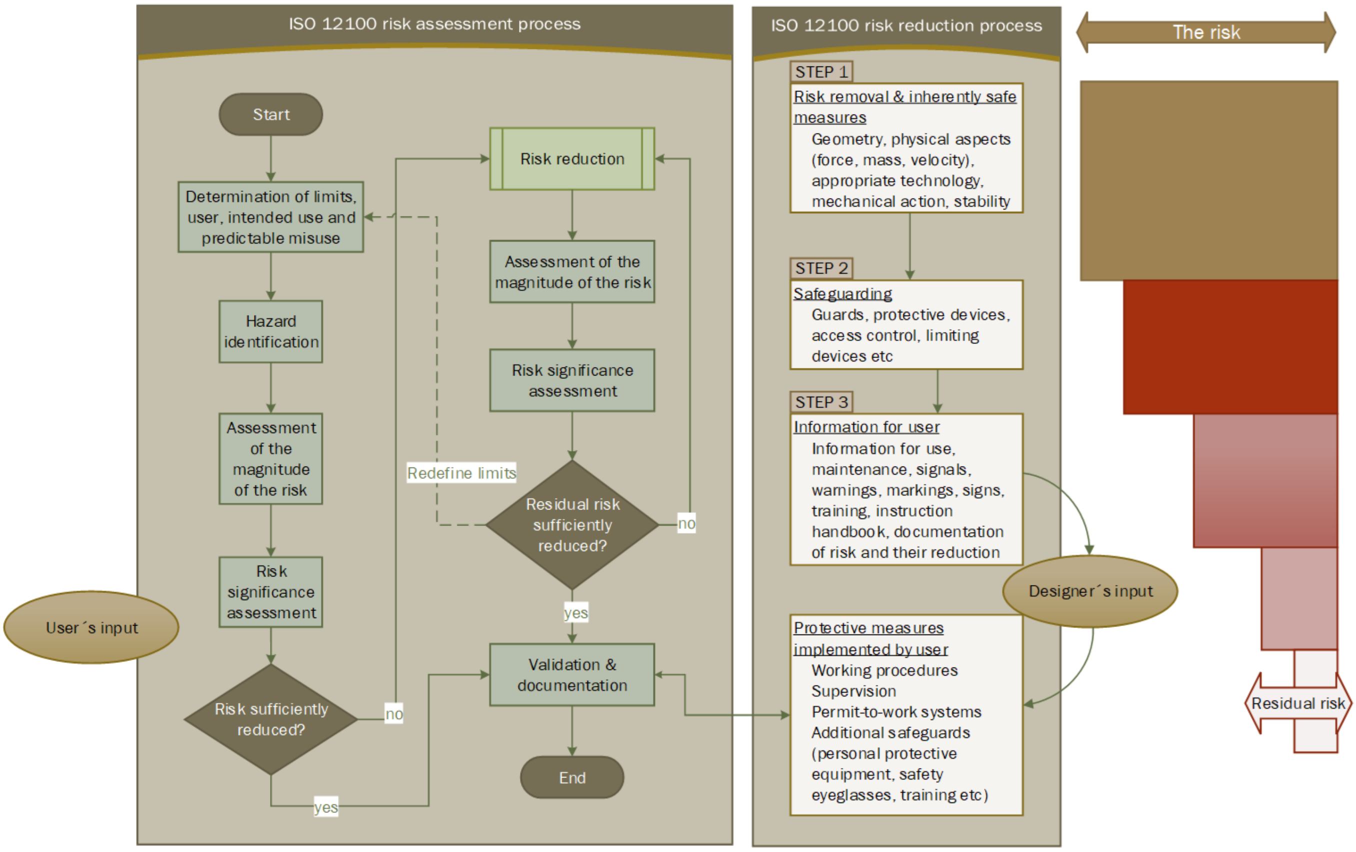
As a practical example, SICK (2023) mentions that a slow-moving mobile robot generally requires a lower performance level (close to PLa), while a large, fast-moving mobile robot most likely requires the highest performance level (close to PLe). Latokartano (2023) gives an example of a large palletising robot cell with a safety light curtain failure. If a human entered the robot cell due to the breakdown of the safety light curtain, there would be no possibility of avoiding a collision with a moving robot and a human. An impact to the head or compression in the chest area would most probably cause serious injury or death. In this example, the path to be followed would be S2 – F1 – P2, with the system still fulfilling the required performance level (PLd) of the safety devices. (p. 103)

For each performance level, the probability of dangerous failure per hour (PFHd) can be determined, as shown in Figure 36. As for the required Performance Level (PLd) probability of dangerous failure per hour, between 10^{-7} and 10^{-6}. This means that one dangerous failure is probable every 1 million to 10 million hours of operation. If the robot ran 24 hours a day, 365 days a year, it would be mathematically guaranteed that the system would run for 114 to 1141 years before the first fatal accident would occur. (Malm, 2017, p. 16)

4.4.5 Risk assessment and reduction processes for industrial robots

The Machinery Directive and the Machinery Regulation apply to all machines put into use in the EU. For machine safety, the standard ISO 12100 establishes general principles for design, risk assessment, and proactive measures. The standard provides principles and guidance for risk assessment and risk reduction, which are illustrated in Figure 33. The goal is to achieve the required safety of the robotic cell by identifying hazards and assessing the magnitude and significance of the observed risks. During the design, all detected hazards must be eliminated or at least reduced to an acceptable level, concentrating on covering the entire life cycle stages of the robot cell. The standard itself gives guidance to observation as well as to documentation. Further instructions on the application of the standard are available in the technical report ISO/TS 14121-2, as well as in METSTA (Mechanical Engineering and Metals Industry Standardisation) in Finland. (Latokartano, 2023, pp. 97-98)

Figure 33 - Risk assessment and reduction processes (Adapted from Malm, 2022, pp. 14-16; Latokartano, 2023, pp. 98-99)



Regarding the designer's and user's input loop presented in Figure 33, it is the designer's contribution to producing appropriate information to reduce the end risk. This contribution is only visible when the user implements it. Therefore, it is the user's contribution to provide the designer with information about the intended use of the machine. (Latokartano, 2023, p. 98)

Risk is analysed by determining the boundaries of the environment, the user's behaviour and capabilities, and the machine's limits. This, as with the entire risk assessment and mitigation process, must consider all stages of the machine's life cycle, including where the machine can and cannot be used and how and when appropriate use occurs. (Latokartano, 2023, p. 100)

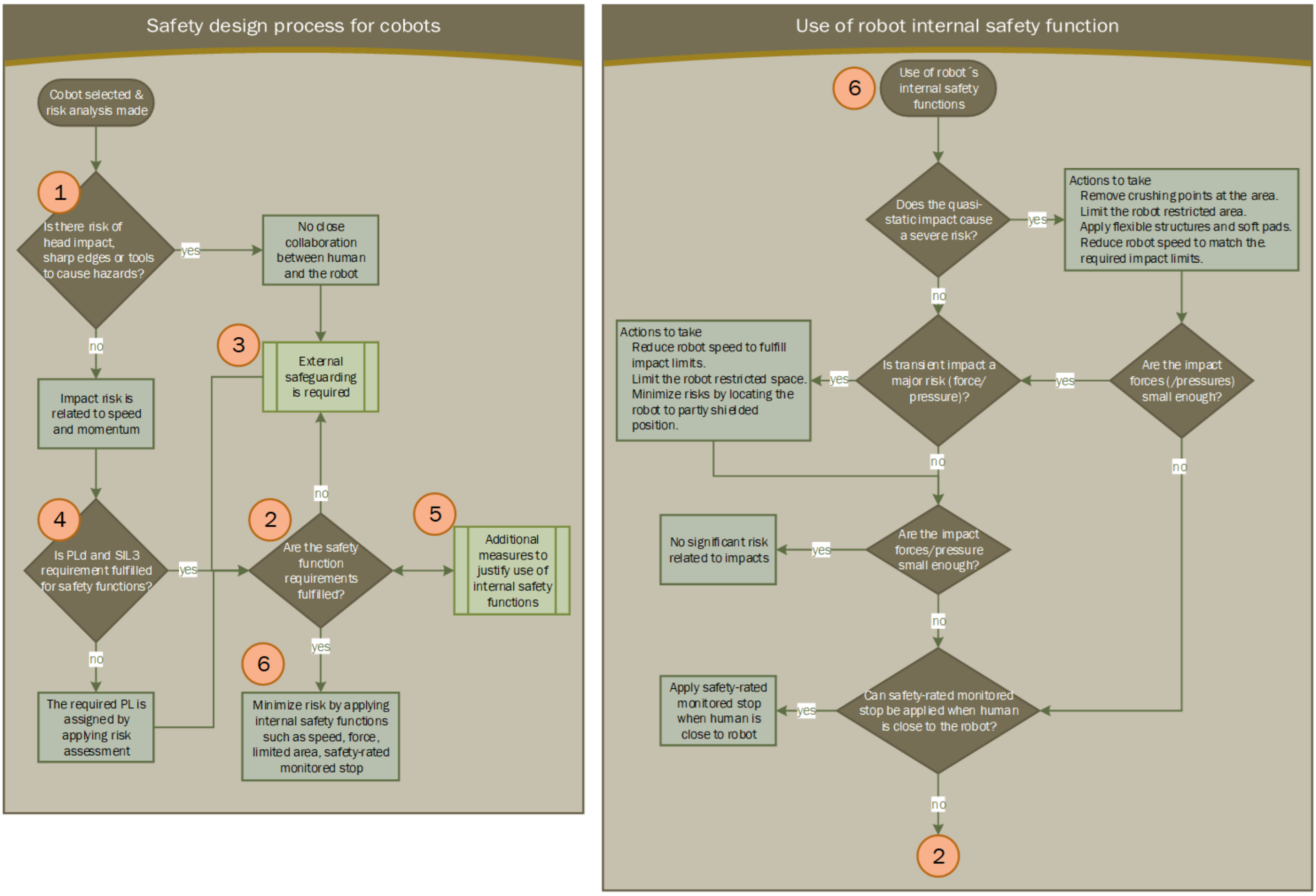
The next step is to identify hazards for each state of the machine, including human interaction, for both intended and unintended behaviour. After each hazard has been identified, actions can be taken to remove the hazard or mitigate the risk. (Malm, 2022, p. 14) Removing and mitigating is done by evaluating the magnitude and significance of the risk. The magnitude of the risk is assessed as a function of the severity of the damage and the probability of occurrence. The risk significance assessment, conducted after the magnitude evaluation, provides the output for determining the need for a risk reduction process. After each step in the risk reduction process, the result of the mitigation process can be sufficient, i.e. the goal of the risk reduction has been achieved. It should be noted that the measures in Step 3 cannot replace the mitigation measures presented in the previous steps. In practice, this means that the signs and instructions for use are the last option to reduce the risk, and all necessary measures to reduce the risk must be taken before that. (Lampinen, 2023, p. 101)

4.4.6 Risk assessment and reduction processes for collaborative robots

The safety design process for collaborative robots differs from that of industrial robots. The safety design for cobots consists of phases, which are numbered in Figure 34. The starting point (1) involves estimating the risk of head impact and determining whether sharp edges or tools pose hazards when a person enters the robot's work area. If the possibility exists, there cannot be close collaboration between humans and the robot, and external safety devices need to be applied (3). Secondly, it is needed to ensure that the safety functions fulfil the ISO 10218-2 requirements regarding functional safety (2). If not, PL assignment needs to be used for the application to see whether it gives a lower requirement than PLd (4). If safety function requirements are still not fulfilled and additional measures do not justify PLd / SIL2, external safeguarding is required (5). Internal safety functions can be applied if they meet the safety requirements (6). (Malm, 2022, pp. 19-20)

External safety measures are needed when internal safety functions alone are not sufficiently secure. For conducting external safeguarding, the approach performed with industrial robots can also be utilised here. In this case, safety functions aimed at isolating the human and the robot come into question, such as sensors used for tactile monitoring or distance detection, or a safety-rated monitored stop. For isolating the restricted space, light curtains or fixed fences can be used. On the other hand, for collaborative robots, risk reduction can be done with smaller steps. These kinds of actions may be, for example, separation distance, which enables only hand contact with the robot, use of obligatory personal protective equipment such as eyeglasses, robot movement and possible sharp edges kept away from the human workstation or use of warnings (e.g. signs, lights, voice), education or augmented reality. Regardless of the chosen approach, the residual risk is assessed after protective measures are applied. (Malm, 2022, pp. 22-23)

Figure 34 - Safety design process for cobots (Adapted from Malm, 2022, pp. 20-24)



Collaborative robots have internal safety functions that can be activated if they meet safety requirements. These robots' built-in safety functions are related to impact forces, restricted areas, speed or safety-rated monitored stops. To adapt the collaboration mode with the cobot, it is necessary to evaluate the impacts of quasi-static contact and transient contact. Based on the evaluation, the required protective measures can be adjusted by adjusting the force and speed to the permitted limits, following the standard ISO TS 15066, without having to isolate the human and the robot. (Malm, 2022, p. 24)

4.5 Industrial robot applications

Industrial robots cannot manufacture anything by themselves. A robot system must be built around the robot, which consists of the robot, its tools, the control and safety system and other various peripheral devices, such as those related to material movement, if necessary. This build entity is the machine intended by the Machinery Directive, and where the requirements of the directive are applied. (Lempiäinen, 2023, p. 19)

The largest application area for robots is handling and machine tending. These applications can be used in diverse environments and across various industry sectors, ranging from electronics to foundries. (Wilson, 2019, p. 90)

4.5.1 Material dispensing

Material dispensing applications cover all kinds of applications where the material is added, usually in the form of a liquid, onto the part to be processed. The robot is often equipped with dispensing equipment, and it moves along the edges of the piece, placing the fluid on the surface of the part or at the joints. It can also be done in a reverse way; a robot carries the part to a static dispensing gun, and fluid is placed on the surface or joints of the part. The latter method is limited to being used for small parts only, but it offers a role for the robot to serve as part-handling equipment simultaneously. In the first way of working, the weight of the dispensing tool must be considered when dimensioning the robot's carrying capacity. (Wilson, 2019, p. 81)

Applications such as spray painting, sealing, and glueing are often found in the automotive industry. However, they can also be found in the food and pharmaceutical industries, where applications with dispensed fluid materials are also prevalent. Due to the variation in requirements for different applications, dedicated robots and equipment have been developed. In spray painting applications, a dedicated spray painting robot with seven axes and an infinitely rotating wrist is used so that the spray gun does not have to be returned to the initial position. For sealing and glueing, generic robot models can be used; however, the control of the sealing equipment and tooling is integrated with the ability to absorb the glue slightly to avoid leaving a tail. For the food and pharmaceutical industries, special requirements are placed on hygiene factors. (Blomsjö, 2023, p. 118; see also Latokartano et al., 2023, p. 63)

Dispensing and especially painting applications are ideal tasks for utilising robotics due to unpleasant and monotonous working conditions and exposure to dangerous chemicals. From a quality perspective, it is worth investing in nozzle selection to avoid spray variation in painting or bubble formation during glueing. The solutions in the painting are special arrangements designed to prevent blockages, specifically in connection with cleaning the spray head. The traces of glueing must be detected with separate equipment. Both in painting and glueing, with the help of the robot application, it is likely to be possible to save material due to the standardised trajectories. (Latokartano et al., 2023, pp. 62-63)

3D printing is a quite new field where robots are used, and which resembles dispensing applications. 3D printing is a technology used to manufacture physical objects from digital models. A part is manufactured by adding material to it layer by layer. Robots have been used in track driving processes, such as welding, cutting, and dispensing, which makes them ideal for 3D-printing applications as well. The limiting factor is the size of the working memory used to control the robot. Since 3D printing occurs in layers, the working memory limit of standard robot control is quickly reached. The solution to this is, for example, additional software developed by robot manufacturers for 3D printing, which enables the program to be loaded into the user's memory in small portions without affecting the quality of the robot's movements. (Latokartano et al., 2023, pp. 64-65)

4.5.2 Welding

Welding is one of the most important areas of robot applications. Development work in welding applications has continued for several years, resulting in a standard offering of fully integrated and reliable solutions. For users of the solutions, this has meant the opportunity to choose a suitable standardized entity from many robot suppliers and integrators. (Wilson, 2019, p. 76)

There are various welding types, including arc welding, spot welding, laser welding, and other welding processes, such as friction stir welding, as well as soldering, which are closely related to welding. Each welding process includes process-specific variants and equipment with special requirements, which affect the selection of the robot and robot cell. The only common factor is the use of thermal energy to join materials. (Blomsjö, 2023, pp. 116-117)

Spot welding is one of the most robotised welding applications, mainly due to the automotive industry, where spot welding is used in body shops. Another primarily used application area is in the manufacture of various large-shell home appliance housings, such as refrigerators or washing machines. In Finland, there is limited manufacturing of household appliances, and Valmet Automotive primarily represents the automotive industry. (Latokartano et al., 2023, p. 36)

In spot welding applications, a robot is required to handle and orient larger weld guns than operators can, allowing for a wide range of motion. Even though the robot is not moving the parts, carrying welding guns requires hundreds of kilos of payload. Robot applications may offer the possibility of achieving welds that could not be made by humans, allowing for greater flexibility in part design. The application can be built without full automation since a fully automatic solution would be unnecessarily expensive compared to the benefits. The loading of the cell can be done manually, and during the unloading, the operator can make a quality check for the welded part. From the accuracy point of view, the robot's path repeatability is insignificant, and a positioning accuracy of about ±1 mm is usually sufficient. However, the accuracy of used fixtures can be set with quite strict requirements regarding size and shape. The piece to be welded takes its final shape only when all welding points have been welded. Additionally, separate sensors may be used to assist with quality control and locate the correct welding point. (Latokartano et al., 2023, pp. 36-37; see also Blomsjö, 2023, p. 117)

The most essential issue is likely the so-called dress package, which provides a cover for the robot. It is necessary to be reliable, not impede the robot's motion, and have access to the parts to be welded. The dress package is most exposed to wear and tear caused by the twisting during the operational cycle. The complete dress package consists of several different elements that are integrated within the whole robot arm. This solution enables the quick removal and replacement of a damaged element in the dress pack without the need to remove the entire package. In an automotive body shop, there will be several different sets of these dress packages, based on the varying application requirements across the facility. In case of event failure or application setup change, the replacement element can be changed quickly without the need for reprogramming. This fastens the setup times and ensures a quick continuum of production. It is worth noting that the cost of the dress package can account for a significant portion of the total robot costs. (Wilson, 2019, p. 79)

Arc welding applications can be found quite largely in the Finnish machine and metal industry. In arc welding, moving pieces can be done either manually or automatically. In the manual version, the parts to be welded are attached to separate fastening tools, i.e. jigs, where they remain in place during welding. In the jig-free implementation, a separate internal part-handling robot is utilised, eliminating manual work steps. This is especially suitable for flexible small-series production because separate product-specific fasteners do not need to be manufactured or replaced. (Latokartano et al., 2023, pp. 38-39) In both automated and manual cell applications, separate sensors are often used to measure positioning accuracy and to search and follow the welding groove (Blomsjö, 2023, p. 117).

Wilson (2019) provides concrete examples and points that can and should be considered when planning an arc welding application. Firstly, an arc welding cell can consist of two workstations, which enables a higher robot utilisation rate and throughput than in a single workstation model. The two-workstation model can be conducted using a turntable or two separate workstations. Either way, the idea is that while the robot is welding at one station, the human operator can unload and reload the other station. Secondly, it is equally important to pay attention to the unloading and reloading operations as much as the actual arc welding process. To minimise errors and increase output, fixtures should only allow parts to be placed in the correct location and orientation. Additionally, the unloading and reloading of fixtures must be quick if the cell is intended to produce a variety of products and multiple fixtures are required due to product variation. This allows quick changeovers and ensures that the robot is not waiting for the operator. This comes as a downside for the application, as the need for more sophisticated fixtures will increase both the complexity and the price of the robot cell. (pp. 76-77)

Robotised laser welding application provides a more flexible and ingenious solution compared to other forms of automation. The downside for these applications is the cost due to the equipment required to perform the task. The gaps between parts to be welded need to be kept minimal, which sets high requirements for the presentation of the parts or the fit-up. The laser must be fed to the robot's wrist in a way that does not reduce the robot's performance but still guarantees reliability. An expensive option is the use of a robot, where the laser feed is integrated within the robot arm. The alternative solution is the use of dedicated laser packages, which are designed to suit the selected robot arm. From a safety perspective, laser welding must be operated in an enclosed space, eliminating any risk of personnel being affected by the beam. This increases the guarding costs as well as affects the way how parts can be fed into and out of the cell. (Wilson, 2019, pp. 80-81)

In general, for all welding applications, it is possible to achieve better working conditions for human operators by automating tasks that require heavy tools in non-ergonomic working positions. This can be accomplished with the help of a robot. At the same time, a higher production rate can be achieved with robotic welding. In spot welding applications, collaborative robots are not suitable due to the need for a high production rate and a higher payload, as well as the tooling and sparks caused by the welding process. (Latokartano et al, 2023, p. 36) Thus, as Blomsjö (2023) notes, for arc welding applications, collaborative robots are suitable due to the required payload of around 10 kg. (p. 117)

In arc welding, Latokartano et al. (2023) claim that productivity can be increased up to 3-4 times compared to manual arc welding, which usually means payback time to be around 2 years. (p. 38) Wilson (2019) says that typically, a robot system operates at an 85% utilisation rate or even higher, while a manual welder achieves a typical utilisation rate of 35%. Manual welding is subject to variation because human operators cannot maintain the same level consistently throughout a shift, whereas robots can. At the same time, quality may be improved, as well as the optimum use of energy and consumables. (p. 78) All in all, for many welding processes, such as laser welding or friction stir welding, manually operated welding is not possible. By robotising the welding process, significant improvements to the human working environment can be achieved. (Blomsjö, 2023, p. 118)

Ultimately, it is crucial to strike a balance in the system's design. There are numerous standardised welding solutions available, and it is essential to select the most suitable one for the intended purpose. The most appropriate option is usually the simplest, which achieves the desired welding quality level and throughput. (Wilson, 2019, p. 77)

4.5.3 Material processing

Like in welding, there are several possibilities and applications for material removal processing. The removal of material can be adjusted from refining the surface to actual material removal, which can be achieved, for example, through grinding, deburring, polishing, or cutting. Besides the requirements related to the task to be performed, the material removal process, as well as the type of workpieces and material, affect the robot cell´s design and configuration. (Blomsjö, 2023, p. 119) Latokartano et al. (2023) specify that basic robots are not suitable for traditional machining work, i.e., material processing work that causes the material to chip. In these cases, materials tend to be strong, which makes basic robots unsuitable due to their structure and accuracy. (p. 46)

Material removal applications can be categorised into two primary solution models: part-to-tool and tool-to-part approaches. In the part-to-tool approach, the robot handles the workpiece and moves it to the necessary process equipment for processing. This method is typically used for smaller materials or when the tools are too heavy or large for the robot to carry. It is also preferable when the required quantity of processing tools is moderate. The selection of the robot and its tooling must ensure that the robot can navigate specific paths and positions without interference from the end-arm tooling during material removal. However, from a productivity and usability perspective, this approach may pose challenges in automating the change of tool accessories. Conversely, the tool-to-part approach involves equipping the robot with suitable processing tools while the part to be processed remains fixed and presented to the robot. Unlike the part-to-tool method, this application is not limited by the size of the part being processed, offering a longer lifespan for the overall process. It also provides greater flexibility in utilising various processing tools within the entire cell. Both the parts being processed and the tools employed can be varied significantly without compromising the cell's layout. (Latokartano, 2023, p. 47)

In mechanical cutting operations, the process may contain sprue removal or trimming of plastic or aluminium die-cast parts. In some applications, there may be added machine-tending or part orientation operations before placing the processed part on an output station. By incorporating the material cutting operation into the die-cast machine cycle, the utilisation of the robot can be easily increased with minimal additional cost. The removal process of overblown material is done by trimming around the workpiece. This operation requires accurate positioning from the application to ensure the trimming is done under tolerances. The trimming process can consist of both internal and external trimming or material cutting. External trimming is done for the outside surfaces, while internal trimming is done inside the part. The most important criteria for choosing a robot are reach and load capacity due to the tool being transported. Additional focus may be necessary to account for the forces exerted on the robot during the process, which could result in the need for a larger robot. (Wilson, 2019, p. 85)

Cutting processes can be performed using plasma, laser, or water, depending on the application.

- Plasma cutting is ideal for electrically conductive materials. Robotic plasma cutting excels when shape bevels are needed during the cutting process, particularly for pre-bent plates. This challenging task is characteristic of robots with six degrees of freedom.
- Water jet cutting involves high-pressure water directed through a nozzle as a fine jet to provide cutting force. It has been highly effective for trimming plastic mouldings. By mixing abrasive material with water, this method is also capable of cutting hard materials, such as Kevlar. Water jet cutting can be implemented in two ways:

    - Using a fixed water jet head, where the robot holds and orients the part being processed near the nozzle.
    - The reverse process occurs when the workpiece is clamped, and the robot directs and carries the nozzle. The first method requires a robust gripper to securely hold the workpiece, exposing both the robot and the gripper to the process. The second method often involves creating a spiral water pipeline around the robot's arm to enable water flow to the nozzle, alleviating the need for a strong gripping force
- Laser cutting is an efficient process that can be applied to robots, particularly for parts requiring 3D shapes. While the process is extremely precise, the robot's path performance should be carefully assessed when processing small holes.

(Wilson, 2019, pp. 86-87; Latokartano et al., 2023, p. 43)

Collaborative robots can be used for plasma-cutting processes. Using robots for water or laser cutting may not be a desirable solution from a productivity perspective, as using dedicated tools and manual processes often offers better productivity than the robotised solution. The attraction towards robotised solutions is based on the total cost of the solution, which is typically lower. The robotised solution also offers other possibilities to process the cutting of pressed and assembled plates that may otherwise not be cut. (Blomsjö, 2023, p. 119; see also Latokartano et al., 2023, p. 43) Different protection needs to be taken into consideration, like in welding, and especially for water jet cutting, the robot is required to achieve IP67-rated protection due to water mist (Wilson, 2019, p. 86).

Material removal processes can be categorised into three levels: deburring, grinding, and polishing.

- Deburring is the most straightforward process, primarily focused on cleaning sharp edges of the processed part to protect personnel. The goal is not to achieve specific dimensions but to ensure safety. Deburring typically requires a light touch around a secured and constant workpiece. In these applications, the robot does not require the same level of rigidity as in grinding processes.
- Grinding involves achieving precise dimensions, making it a more demanding process. The challenge lies in variations in the amount of material to be removed. Unlike deburring, grinding often requires considerable material removal, necessitating robust robots and holding devices to manage the processed part against the applied

forces securely. The part-holding devices, whether robotic or fixture-based, must ensure stability during processing.

- Polishing is the most complex process, requiring specific surface finishes that are often better achieved by experienced operators relying on visual feedback. Robotic systems face challenges in replicating this precision. Polishing may involve multiple work heads, as different grits are used for grinding and finishing. Force control devices can be employed to regulate pressure and speed, maximizing the robot's efficiency and enabling the use of more miniature robots. However, force control devices add to the cost and complexity of the solution. For polishing applications, force control is justified to ensure the desired surface finish.

(Wilson, 2019, pp. 87-90)

Not all robots are robust enough to perform material processing tasks. Limits are set either by the weight capacity of the handled material or the tools used, or by the contact forces involved in the specific process. The direction of the force relative to the tool flange and the distance of the payload must be known in advance because the contact force is applied to the sixth joint of the robot. Other requirements include the required protection class and the necessary equipment for absolute calibration. Manufacturers offer models with different IP ratings, or the robot can be equipped with hoods to improve protection. The possibility of absolute calibration should be investigated, especially in surface finishing applications, as they require high path accuracy. (Latokartano et al., 2023, pp. 47-48)

Overall, material removal applications are suitable for 24/7 operations. All material removal processes offer possibilities for long, uncrewed work cycles. The key is to ensure the availability of materials to be processed and, in terms of tools, both their availability and the automated change of machining heads. (Latokartano et al., 2023, p. 48) Reasons for automating material removal operations can be found in stringent health and safety standards that target minimising risks for "white finger" and repetitive strain injuries. (Wilson, 2019, pp. 87, 89)

4.5.4 Quality control

Robots can be widely utilised for different quality control tasks, directly implemented as a continuation of the production line. Robots can be equipped with measurement devices to be moved around the workpiece for inspection. This measurement method is non-destructive and does not alter the measured cell. Additionally, this type of solution can be integrated directly into the production line, eliminating the need for a separate inspection cell. Depending on the solution and part to be quality controlled, manual measurement may require special skills and can be ergonomically challenging. (Latokartano et al., 2023, p. 51)

A mechanical inspection process has also been applied to replace the bespoke systems. The benefit is achieved from the reduction in the cost of the overall system, even though the devices to be used are equal in both scenarios. Robots are better at offering motion compared to the built-in bespoke system. (Wilson, 2019, p. 97)

In general, the robot can be used to automate the changing of the measuring device, and thanks to the flexibility of movement, very different pieces can be measured with one device (Latokartano et al., 2023, p. 52)

4.5.5 Machine tool and press tending

Usually, machine tools are already automated. The only work cycle that remains manual with machine tools is unloading the completed part and loading the new part to be processed. The automation of this process is called machine tool tending. By this, the utilisation rate of the machine tool can be increased. (Wilson, 2019, p. 94) Asfahl (1992) points out that another approach, in addition to directly increasing productivity, is to indirectly increase productivity through safety. Over the past few decades, especially in punch press operations, this has been one of the most historically dangerous factory jobs. This is mainly due to the risk of amputation when the press is fed. With the increased implementation of robotics, it has also been possible to transfer the handling of heavy loads away from humans. (p. 265) Press tending and stamping operations may add specific requirements to the complete robot cell. This is mainly because the materials usually handled are large and thin, and the production environment can be harsh. Otherwise, the requirements set for the robot and tooling vary with the designed process. (Blomsjö, 2023, p. 116) At a general level, machine tending requires repetitive motion and high-level consistency for hours. With automated options, human operators can be assigned more valuable tasks with reduced ergonomic and general safety hazards. (Tarantino, 2022, p. 326)

The utilisation rate can be increased by ensuring that after the piece is completed, the machine tool is emptied and loaded again. In a manual process, the operator is not necessarily present after the machine's work phase has ended. By adding automatic setting switching between different sets, the utilisation rate can be further increased. By buffering the components, the robot can work either the entire shift or at least some of the hours outside of regular factory hours. (Latokartano et al, 2023, p. 55) This can lead to both a reduction in the number of required machines and a reduction in the area of work needed. Alternatively, and depending on the machine cycle, the robot can work with multiple machines, which increases both the utilisation of the machines and the robot as well as the effectiveness of the automation. Another option is to perform secondary operations with the robot, such as deburring, automatic tool changing within the machine tool, or cleaning of the machining swarf. The investment payback does not result in all labour savings, as the possibility of reduced investments in additional machines exists, as well as increased productivity from the actions of additional processes. (Wilson, 2019, p. 95)

Alternative tasks can be integrated into machine tools, thereby enhancing productivity. Part orientation can be implemented between operations to ensure correct positioning, while part inspection and palletising tasks can be added at the end of the work cycle. Depending on the machine tool and its process requirements, a separate palette can be utilised. The optimal workflow for the robot involves loading the palette during the machine tool operation. During this process, the robot loads and unloads palettes from the machine tool. While the machine tool is active, the robot can unload individual parts from the palette and load new parts onto the palette for processing. When handling single parts for the machine tool, the robot can be equipped with a double gripper: one for holding the processed part and another for the part to be processed. It is essential to consider the robot's carrying capacity, as it will handle two parts during the cycle. (Latokartano et al., 2023, pp. 55-56; Wilson, 2019, p. 97)

The suitable robot is selected mainly based on the combination of reach, carrying capacity and gripper. Reach is determined by access to the machine and other elements related to the system around the robot. The robot's reach, access to objects, and the possibility of serving multiple objects can be improved with the help of the robot's mounting solution. Typically, a floor-mounted solution is the preferred option; however, overhead-mounted solutions and track-mounted solutions can also be used. Furthermore, tracks can be mounted on gantries, which provides the benefit of maintaining clear areas with easy access to the machines for tooling changeovers and maintenance. The selection of a gripper is highly dependent on the tasks to be performed. The gripper, as well as the parts to be handled, are needed to count the weight and the orientation of the wrist. These factors influence the required carrying capacity of the robot. (Wilson, 2019, p. 96)

4.5.6 Pick & place (/present) and palletising

Like tending applications, other material handling processes, such as palletising and pick-and-place, follow the same basic principles of handling materials. It is all about handling materials with a gripper and performing motions in the robot's workspace. (Blomsjö, 2023, p. 115) Tarantino (2022) highlights the ease of implementation and the 3PL perspective on the redeployment of pick-and-place type applications. Firstly, these tasks can be easily implemented with plug-and-produce collaborative grippers. After the initial implementation, replication of the installed system can be performed for similar tasks. Plug-and-produce collaborative EOAT is a versatile solution which enables easy redeployment in case of product or contract changes, especially for 3PL providers. Moreover, since collaborative robots offer the possibility for quick relocation without the requirement of guarding, a single robot can be utilised for multiple processes. By using dual grippers, the application can simultaneously handle different shapes and sizes of boxes. Vacuum grippers do not necessarily need an external air supply if new electric vacuum grippers are used. (p. 326)

The palletising tasks can usually be seen at the end of the production line, where the robot lifts the products from the conveyor to the pallet. The robot must be able to provide information on when a product or product group can be picked up. After this, the robot grabs it with a gripper and takes it to the stage. The dimensions of the finished products are usually very standard, and the pallet on which they are lifted usually remains standard. In palletising applications, payloads can range from small payloads to as high as 1000kg. By increasing the degree of automation for handling full pallets, there is no need for human operation at all. The solution is semi-automatic, with the operator taking a full pallet and bringing in an empty pallet. In a semi-automatic solution, the application's user interface can also be implemented without a programmed solution, where buttons or their controller facilitate the robot's control. In a fully automated solution, the introduction of empty pallets and the removal of full ones are automated, for example, with AMR robots. (Latokartano et al., 2023, p. 57; see also Blomsjö, 2023, p. 116)

The general principle of lifting products also applies in picking and packing applications. Suction cup or suction plate grippers are usually used as grippers. Depending on the shape of the piece, it can also be handled with a squeezing gripper, assisted by a suction cup or a base plate that supports the piece. The difference is related to the need for a vision system to identify the location of the products to be picked. As a secondary solution, the vision system can provide an additional step in quality control. For many packing applications, the gripping technique becomes a challenge. The gripper may weigh more than the products to be handled. The shape of the products being processed also affects the gripper selected. For the entire solution, the working environment, such as food factories, sets hygiene and washdown cleaning requirements for the robot, its tools, and accessories. Therefore, the choice of the robot cannot be determined until the grip and its operation technique are known. One considerable characteristic is reach, especially in palletising applications, while for pick-and-place applications, the robotised work is usually done closer to the robot. (Wilson, 2019, p. 99; see also Latokartano et al., 2023, p. 57)

Reasons for implementing pick-and-pack and palletising applications include labour savings and increased throughput, especially for multi-shift operations, as well as increased operational speed. Health and safety improvements are also gained by removing human operators' heavy lifts and/or repetitive lift tasks. When comparing dedicated palletising machines with robots, a robot provides more flexibility and palletising reliability, particularly for light packages. In comparison with more dedicated palletising machines, a robot offers increased flexibility and, in some cases, particularly for light packages, improved palletising reliability. Robots can be programmed to palletise different packages to different pallets without time lost for pallet changeovers, even if the packages arrive on the same production line. Teaching complex staging patterns is accomplished using either machine vision or artificial intelligence applications, while simpler staging patterns can be created directly from the robot's control console. (Wilson, 2019, pp. 98-99; see also Latokartano et al., 2023, p. 58)

The section of the robot depends on the required throughput in that specific case. Pick-and-place applications in the food industry require a much faster pace from the robot than in an industrial environment. In the food industry, the application may require a throughput of hundreds of products per minute, while in the industrial environment, the throughput rate can be hundreds of products per hour. Delta robots are commonly used in fast-paced food industries, while articulated arm robots are employed in industrial environments for pick-and-place and palletising applications. Vision can be added for recognising part orientation, quality control, or other inspection purposes. An example of this is an application where vision control is used to ensure that returned empty boxes are empty. If the box is not empty, the box is directed to the inspection line for manual control. (Latokartano et al, 2023, pp. 59-61)

4.5.7 Assembly

Assembly is one of the growing application areas. Major users of these applications are in the electronics industry, particularly in the production of consumer electronics products. Typically, SCARA robots have been used in these applications, but delta robots and six-axis articulated arm robots are also emerging in assembly applications. The main advantage of SCARA is its ability to operate in a high-volume environment, performing rapid repeats for picking and placing operations in very effective working areas. With delta robots, high speed is achievable, but delta robots require being mounted above the assembly area in which they operate. This limits the working envelope. The main benefit of using a six-axis robot is its flexibility and additional orientation capability, which reduces risk in the assembly system design. (Wilson, 2019, p. 101)

Several special characteristics distinguish assembly applications from other manufacturing processes. Assembly applications are more linked to the specific product to be assembled than to the similarities between other robot systems in the same application area. From a robotic automation perspective, processes may vary from the simplest, such as inserting a pin into a hole, to complex processes involving flexible materials and the need for sensors. Robotic assembly consists of multiple factors, including feeding devices, grippers, the number of components to be assembled, tolerances, and cycle time, all of which contribute to the different specifications of the robot system. The assembly task is typically at the end of the product manufacturing process, where several different components are attached to a single manufactured piece. The general trend towards high-mix, low-volume production, driven by customised products, sets higher requirements for the equipment used in robotic manufacturing. (Blomsjö, 2023, p. 120)

Regarding accuracy, positional repeatability is one of the most critical issues in assembly applications. When two parts are joined together using some mechanical procedure, the parts must be positioned within tolerances to allow mechanical fastening. This sets requirements for the components to be used so they are repeatable. For example, when inserting components into a printed circuit board, the legs of the components must be straight and undamaged. This problem can be solved by using a chamfer on the parts or vision technology to identify the parts and their location. (Wilson, 2019, p. 102)

For the majority of products, assembly costs account for a small portion of the total costs. The biggest impact on the benefits of assembly operations can be improved by considering the entire process from design to assembly. The standard DFM (Design for

Manufacturability) method is used for designing the product and its subsequent development. By using this technique, broader consequences beyond the assembly can be considered. Several types of information are used in the DFM process, including sketches, drawings, a detailed understanding of production and assembly processes, strategic choices regarding suppliers and their configurations, and estimates on manufacturing costs, production volumes, and ramp-up timing. It involves not just expertise from design and manufacturing engineers but also supply chain managers, cost accountants and production personnel. This method plays a significant role when allocating the logistics cost of the product. (Ulrich, Eppinger & Yang, 2020, pp. 262-263)

A subset of DFM is DFA (Design for Assembly), which helps to more precisely influence the product's installability through indirect benefits, such as overall parts count, manufacturing complexity, and support costs, as well as the direct work cost of assembly. Ideal characteristics are:

- *The part is inserted as a top-down movement.* The attribute of a part and assembly is called a Z-axis assembly. Using this method, the assembly never has to be reversed; gravity helps stabilisation the partial assembly, and the operator can see the location of the assembly.
- *The part is self-directed.* If the part requires fine positioning, the assembly operation will need fine motor control from the operator, which slows the process. The most common self-directed feature is chamfer.
- *The part does not need orientation.* Parts, such as spheres, do not require orientation compared to screws. Once again, assembly time increases as more orientation is required.
- *The part can be assembled with only one hand*. This describes the sizing of the part and the effort required to handle it. Some parts may require the use of a crane rather than one-handed handling.
- *The part requires no tools*. The use of tools generally increases the time required for assembly compared to situations where tools are not needed.
- *The part is assembled in a single, linear motion*. Screwing requires more time than pushing a pin. Commercially available solutions, where only a single, linear motion for insertion is required, occur quite widely.
- *The part is attached immediately after installation*. A subsequent securing, like tightening or the addition of another part, may be required. Fastening makes the assembly stable. Until then, extra care or fixtures must be used, which will slow down the assembly.

(Ulrich, Eppinger & Yang, 2020, pp. 277-278)

The reasoning behind the application can be found in the requirements of high-speed manufacturing, which involve repetitive tasks. The weight of lifted items is usually light and small, which makes them difficult for humans to handle. Secondly, the assembly task is ergonomically challenging and monotonous for human operators. Robots provide precision, speed, and consistency to an extent that is not achievable manually or with separate, purpose-designed assembly systems. It should avoid the most complex operations due to the greater risk posed and rising costs, which do not meet the financial targets. (Wilson, 2019, p. 100, 121; Latokartano et al, 2023, P. 53)

Latokartano et al. (2023) mention that the best-fitted assembly work for robots is a sub-assembly task that serves to reduce the throughput time in the final assembly. Robot assembly operations are ideally suited for a collaborative robot, as the assembly process often eliminates the need for human effort. Human labour can be shifted, depending on the case, to display materials or remove the finished piece. Another example of the collaborative robot's flexibility is the ability to place the robot on a movable transport platform, which enables the robot to be programmed to perform different tasks at various workstations by simply moving the platform. After identifying the workstation, which the operator can do through a touchpad, the robot can operate at each workstation according to a pre-programmed program. (p. 53) Depending on the case, the material displaying process can be automated with bowl feeders. In that case, the feeding mechanism must be reliable to secure the success of the application. (Wilson, 2019, p. 102)

4.6 Supporting equipment

Characteristics of the robot vary between each robot type and are one of the selection criteria to be considered. Still, the robot is just one part of a robot cell or an entire automation system. To perform the selected tasks, other automation devices and components must also be implemented. To achieve the desired operation with the required performance metrics, the selected components are required to match the chosen robot and vice versa. Therefore, it is essential to specify all related requirements to the intended operations of a robot and the robot system as a whole, robot cell or a complete automation system. (Blomsjö, 2023, pp. 97-98)

Most robotic systems are customised on a case-by-case basis, and the associated peripherals vary greatly. The selection of supporting equipment is based on the application and its environment viewed from the perspective of peripherals. Issues to be clarified include performance rate, connectivity to the robot controller, size and weight of the equipment, as well as a suitable power source for the equipment. Pneumatic devices are ideal for light and medium-duty work, offering benefits due to their relatively inexpensive and easy maintenance. Pneumatic devices can be replaced with servo-controlled electric devices. For heavy-duty work, hydraulic equipment is a suitable option. Connectivity involves the transmission of signals between the robot and the attachment. By using a digital network connection, diagnostics can be easily added to the communication, and a wider range of process data can be collected. In today's world, regardless of whether wired or wireless connections are used, cybersecurity is becoming an important issue. The review must be carried out to ensure both the operation during use and the availability of spare parts even years later. (Billing, 2023b, pp. 190-191)

Depending on the intended task and operations to be executed, an automation system incorporates several forms of supporting equipment, devices, and components. A robotic solution can be made with a minimum of an end effector and a safety-related system. Alternatively, even simpler, when using a collaborative robot, the safety feature is a built-in feature. At the other end is a system where machines and robots are integrated in accordance with the needs, resulting in a complex automation system. The determining factor is the required system performance. In complex systems, the balance of material flow between different robot stations must be in balance with the whole. To achieve this balance, the definition of a robot system is an iterative process. This means that different alternative ways to achieve a solution must be evaluated. (Blomsjö, 2023, p. 101; see also Latokartano, 2023, p. 112)

Wilson (2019) emphasises the importance of the material handling job. Regardless of whether it is done manually or automatically, either way, material handling steps in the process do not add value; they only add costs. Poorly designed material handling negatively affects the functionality and effectiveness of the automated process. The basic principle of material handling relies on delivering the right parts to the right place at the right time, in the right quantity and quality. To be able to follow the principle and to ensure the needed performance, both feedings of the components as well as the removal of finished products need to be considered. The consequences of a poor material handling process will be revealed in the amount of work in progress, idle time and inconsistent storage. (p. 41) Blömsjö (2023) adds that all activities related to moving materials also include different facilities and equipment. These are storage and retrieval systems, forklift trucks, AGV and other equipment such as conveyors. (p. 101)

Billing (2023b) highlights the importance of layout and maintainability. In layout design, it is essential to consider both the robot's accessibility and its reach. Accessibility ensures the success of maintenance and the robot's ability to cover the desired working area, as well as to minimise unnecessary movement paths. From a maintainability perspective, a typical industrial robot can last for a decade if properly maintained. It is reasonable to demand the same level of requirements from supporting equipments. (pp. 191-192)

4.6.1 Feeding devices

Asfahl (1993) highlights the difference between humans and robots in part feeding. While humans are very capable of picking a single component from a random pile in a random orientation, most robots need the same component precisely positioned. A machine vision-assisted solution, known as bin-picking, has been developed to address this problem. In assembly applications, feeding the component in the correct direction and the actual assembly usually go hand in hand, meaning that if one problem has been solved, the other problem is often very close to being solved. Therefore, parts feeding and assembly applications should be considered together as a single solution. (p. 55)

Westcott et al. (2024) sum up the selection of feeders. Regardless of the type of feeders chosen, they must be reliable. It should provide uninterrupted material flow from some upstream device, such as a bin or a hopper. There should be a possibility to control the feeding rate within the necessary range to adjust the device's usage. The connection between the upstream device and the actual feeder should be constructed in such a way that it does not affect the operation of the feeder or damage the components being handled. (pp. 374-375)

Equipment that supports material handling in robotic cells includes:

- AGV or AMR
- conveyors
- vibrator-based feeders
- tray or pallet
- stacked parts
- bin picking

(Blomsjö, 2023, p. 102)

AGV or AMR is comparatively slow compared to other part-feeding methods and requires a significant amount of capital at the start-up stage. On the other hand, they are highly flexible when it comes to routing and flow of parts. They can operate in a dark environment, meaning they do not require separate monitoring. It is best suited for an environment that can support not only the robot cell but the entire production. (Blomsjö, 2023, p. 101)

Conveyors come in various types, standard or customised, and are used for moving goods, intermediate storage, and delivery to production cells. Suppliers often provide 3D models to support virtual design and engineering. They are categorised by mechanism (e.g., belt, roller) and arrangement (e.g., floor, overhead). Conveyor motion can be continuous or indexed, making it suitable for high-volume transport with defined routes. Among the most common types:

- Belt conveyors: Powered by electric motors, made of rubber or plastic, and customised for flexibility and grip.
- Slat conveyors: Constructed with steel or plastic slats, ideal for steep curves and spirals.
- Chain conveyors: Use chains with attached protrusions for transport, including overhead applications like painting lines.
- Roller conveyors: Operate via gravity or mechanical power, moving goods on rollers or discs.

Combining different conveyor types enables efficient material flow in industrial settings.

(Billing, 2023b, p. 192-194)

There are different ways, such as magazine, bandolier and vibrator-based feeders, to deliver components to specific positions for subsequent operations. Magazine- and bandolier-based feeders require the component supplier to pre-pack components in a manner suitable for such feeders. For magazine feeders, components are pre-packed either into trays or dispensers. Trays themselves can be moulded, which makes them a low-cost solution. It is often possible to use trays to provide transport between manufacturing operations. Dispensers are often used in packing systems that hold a stack, and items are removed with a single-arm robot using a vacuum gripper. (Wilson, 2019, pp. 43, 46)

Many components are shipped loosely in boxes due to the cost of repackaging; therefore, the automation system requires a mechanism to accommodate randomly presented components. Vibratory-based feeders are used to sort and deliver the components to the required position with the required orientation. Vibratory-based feeders can be bowl or linear-type feeders. Bowl feeders are very simple and highly reliable, which is why they are used in approximately 80% of cases. Components can be poured on the belt (linear feeder) or on the bowl (bowl feeder), where the vibration causes the components to be moved forward in a certain way along a track to reach a defined pick position. The track is designed to allow a single component to pass with the proper orientation to the pick position. The bowls themselves are replenished either manually or by an external elevator, which takes components from the bulk hopper. The elevator is indexed to control the quantity of components in a bowl. Linear feeders work equally as bowl feeders, but the motion is in a straight line rather than a spiral. Linear feeders can be used for feeding larger and more delicate components than bowl feeders. However, the linear feeder does not provide any orientation, which must be done by another device commonly before the linear feeder. (Wilson, 2019, pp. 43-45; see also Blomsjö, 2023, pp. 102-103)

One type of feeder is a blowing feeder, where the component is blown into a tube, which then travels to a device at the other end, typically a robot. This technique offers the possibility for complex or variable paths. Blow feeders are typically used to feed screws and rivets to a robot, which secures the components of the assembled product. (Wilson, 2019, p. 45)

If a component is fragile, sensitive, or unsuitable for the previously mentioned feeders, a tray or pallet can be used as an alternative feeding mechanism. This approach may be appropriate when the tact time or cycle time is low enough to accommodate slower feeding methods. For larger parts and longer rotations, components can be retrieved from a EUR pallet using a robot, which must be equipped with sensors to identify the correct pickup location accurately. If components are stacked on top of each other, safe unloading becomes crucial, as parts may stick together. Separation processes should be tested under actual conditions for both heavy and light materials. Solutions for separating components include sliding movements or magnetic devices. (Blomsjö, 2023, pp. 103-104) When trays are utilised, components can be positioned using their external features, eliminating the need for machine vision or other assistive systems for the robot to pick up the parts. However, this approach requires components to be stacked on the tray, which can be done manually by an operator or automated, particularly if the placement from the previous step is already known. (Billing, 2023b, p. 197)

The combination of vibrating conveyors and machine vision picking is called a flexible feeder. The solution consists of two separate parts, both of which feature a vibrating conveyor. The parts are poured onto the first part, from where the vibrating conveyor transfers a controlled amount to the second part. The vibrating feature of the second part is intended to position the components in the desired location, from which they can be identified using machine vision and picked up with robot assistance. These have been implemented in various combinations, with a common feature being the positioning of the part to the desired location and machine vision picking. The advantage of the solution described above is the ease of product change and the possibility of automating the change, as well as the simultaneous processing of diverse and different parts. (Billing, 2023b, pp. 196-197)

4.6.2 Bin picking

Bin-picking is an option when the available feeding system is unable to feed complex-shaped components. Bin picking is a vision-guided solution which is used to localise components within a random stack and to pick components from that stack. After localisation, the application calculates the robot's trajectory, enabling it to pick up and move the desired component to the specified location while avoiding collisions with the environment, other objects, and the robot itself. Typically, picking is performed from a tray or pallet and is used in processes that require high repeatability or accuracy. Bin-picking applications are commonly found in machine tending and various sorting processes. In machine tending applications, metal blanks can be picked from a pallet to a machine tool. Sorting can be used to arrange bulk material coming on a pallet onto a tray or for puttying for assembly. (Latokartano et al., 2023, pp. 66-67)

Before implementing the bin-picking application, tests should be run in the planned location to ensure the quality of accepted picks, the time to pick, and other environmental conditions, such as lighting and shadows. Additionally, the selection of the gripper and its principle should be based on the considered components and their geometrical features and surfaces. (Blomsjö, 2023, p. 104)

Bin picking, as well as AI-based machine vision, has been studied for decades; however, it is only now that bin picking can be applied using various methods. Identification of the component can either be based on model-based recognition, where 3D models of the components to be identified are entered into the system, or on AI, where the system learns to recognise the components on its own. Currently, AI-based applications are aiming at reducing the time for teaching rather than increasing the application's operational performance. Bin picking can be implemented with two-dimensional cameras, but the lack of depth information limits the application's performance. The challenge in determining the position of components is that selecting one component can alter the position of other components; others may partially obscure them, or their surfaces may reflect light into the camera lens. If components are supposed to be picked from a box with sides, the location of components near the sides can also be a problem. (Latokartano et al, 2023, pp. 67-68)

4.6.3 End of arm tooling

In robotics, a device or a tool connected to the end of the robot arm is called an end effector. In the earlier days of robotics, industrial robots were used as stand-alone devices. Today, robots are utilised in increasingly complex applications, such as assembling components or attaching them to clamps and fixtures. Increasingly, the tasks performed by robots require the accuracy of both the robot arm and the end effector. It is also worth noting that most production problems are caused by poorly designed tooling rather than the robot's faults. (Westcott et al., 2024, pp. 455-456)

A robot needs a tool to be useful. Without a tool, the robot is useless. Robot creates movement, and the movement becomes useful only when it can be utilised. Utilisation occurs with the help of a tool, which means that the actual work for which the robot system is designed is done with the help of the tool. Tooling, in general, consists of all the devices, tools, equipment, grippers and other tooling which are attached to the end of a manipulator and used to interact with and influence its environment. This tooling principle is also called EOAT. With the EOAT dissociated, the tool is attached to the end flange, which is separate from the other part of the robot's workspace. (Dinwiddie, 2019, 79; Liuha et al., 2023, pp. 201-202) Westcott et al. (2024) define EOAT as the subsystem of an industrial robot system which connects the mechanical part of the robot (mounting plate) to the workpiece in the form of a specialised device. The mounting plate is the interface between the end effector and the controller, and in this way, a robot becomes a production machine. (pp. 456-457)

As a general rule, tooling can be divided into two categories: those that handle parts and those that perform some work. The first mentioned group handle parts for assembly, machine tending or general material handling and movement. The second-mentioned group uses the tool to do and control the actual process work. (Wilson, 2019, p. 49) This means that when a welding gun is attached to the robot, the robot becomes a welder. With a paint dispenser, the robot becomes a painter. Some combinations also exist, like robots serving the plastic press. The gripper is equipped with a sprue-cutting device and a press-sliding injection nozzle. (Liuha et al., 2023, p. 202)

Programmability and versatility are hallmarks of the modern industrial robot, as manufactured by its manufacturers. However, from the robot manufacturers' perspective, the selection of the end-arm tooling is left to the user. (Asfahl, 1993, p. 151) There are some companies which produce both robots and tooling, but most of the companies are strategic partners. Robotic tooling is a booming field where these companies focus on creating tooling that works with most, if not all, of the robotic systems in the industry. New types and configurations of tooling are continually being developed to meet the evolving needs of the industry. The development of EOAT is driven by the end-user's desire and need, as new ways to utilise robots are discovered. It is worth noting that evolving the EOAT, the best-selected option today, can render it obsolete within three to six months. Therefore, it is essential to re-evaluate the tooling in use periodically. On the other hand, this may offer a solution if problems arise with the solution. (Dinwiddie, 2019, p. 79) Robots can be equipped with the same equipment as used in manual processes. The development of the process equipment has resulted in a system which is closely integrated with robots, both mechanically and within controls. This has led to more effective, robust and reliable solutions to offer more suitable solutions for each application. (Wilson, 2019, pp. 49-50)

Tarantino (2022) highlights the innovation around end-of-arm tooling related to collaborative robots. Some features related to collaborative robots are also applied to collaborative EOATs. This means that a collaborative robot itself does not make the application collaborative. These features will enable companies to exploit robotics in new ways. Used tooling must meet the ISO 10218 standard, which defines the safety standard for robots and robotic devices. EOAT designed according to this standard minimises the risk of injuries caused by the robot and its tooling. For example, it determines the force and pressure exerted by a tool on the human body, minimising injuries. Moreover, using plug-and-produce EOAT implementation reduces the cables needed to connect the tool to the upper control system. These tools also offer easy-to-use benefits, including programming and overall control via the robot's own teach pendant. Collaborative EOAT has become a critical element, especially in collaborative applications such as machine tending and packing. Future development in this field will ensure an increase in output, quality, and profitability. (pp. 324-326)

4.6.4 Grippers and their selection

Westcott et al. (2024) point out four categories where grippers are exploited. No gripping is required when the part being processed is held in a jig, and the robot performs the activity on it. These types of jobs include spot welding, flame cutting, and drilling. When the robot is used for holding the workpiece, but the gripping does not need to be precise, coarse gripping is used. Examples of job types are stacking boxes or sacks, unloading furnaces, and handling and dipping casting. Precise gripping is used when accurate positioning is required. These kinds of jobs are machine tool loading and unloading. For assembly, where the robot is programmed to assemble parts, precise positioning is required, along with some form of sensor feedback. This enables the robot to monitor and correct its position. (p. 459)

Several standard grippers are available for everyday work tasks, featuring various designs, operating principles, and sizes tailored to specific applications. The selection of the gripper for a particular application is based on the grasp and hold of a specific object within defined geometrical dimensions or other relevant constraints to the gripper. If a standard gripper is not suitable for the designed application, customised and tailored grippers can be created. (Blomsjö, 2023, pp. 105-106) General parameters that affect gripper selection, whether using a standard or tailored one, are listed in Table 4.

Table 4 - Parameters for gripper selection (Blomsjö, 2023, pp. 106-107; Liuha et al., 2023, pp. 202-204; Westcott et al., 2024, pp. 459-463; see also Dinwiddie, 2019, pp. 80, 85)

Parameter for the selection of the gripper	**Factors influencing the choice**
Weight	The weight of the gripper is deducted from the robot's payload capacity. The robot's technical sheet payload is for empty robot mechanics. Everything attached to the robot reduces the payload. The larger the load on the robot's gripper, the slower its movement is usually programmed. This prevents the load from accidentally coming loose. At best, the system can issue a warning of overload. The more the robot must work at the limits of its payload, the faster it will wear out. A good rule of thumb is to keep the payload as low as possible, below 75% of the maximum.
Geometrical size and design	The geometrical size and design of the robot affect its workspace for different orientations and the risks of collisions with other devices and equipment. Secondly, it is important to consider the tool's centre of gravity. Too much distance puts strain on the robot's wrist joints and may significantly limit the payload.
Contact force and its surface	For determining the required gripping force, the weight, shape, and friction of the object being handled are important parameters. Objects may have limitations in terms of contact forces or surface

	sensitivity, which can affect their ability to avoid scratches. The gripper can be equipped with spring-loaded overload protection, which gives a signal to the robot to stop work if the workpiece is too heavy. If easily breakable parts are identified, these can be considered in the gripper design and made easily replaceable.
Mechanism of action	Gripping action is external or internal. External gripping is used to capture the component from its exterior surface with closed fingers. Internal gripping captures components from its internal surface by opening the gripper's jaws.
Gripping style	Gripping styles can be either parallel or angular, with two or three jaws, and the selection of a gripping style is based on the application's needs. Parallel jaws move parallel to the gripper body. Angular jaws open and close around the central point of the gripper. Angular grippers are usually the most economical choice and are used when the tool needs to be moved out of the way. Due to sweeping action, an angular gripper is not always a practical option. Parallel grippers are used to pull components inside a machine because the gripper fingers fit better in smaller spaces. The most popular type is a two-jaw parallel gripper because it is easy to design and program.
Accuracy and repeatability	The required accuracy and repeatability depend on the application to be implemented. Especially in assembly tasks, the combined effect of process tolerances and robot and gripper inaccuracies must be analysed. If necessary, a specific gripping procedure can be applied to ensure a higher level of accuracy and repeatability.
Environment and robustness	If the robot is equipped with external sensors or other devices, it is often necessary to transmit data and signals. The most common method is wired, which causes the need to protect the wiring. Depending on the application environment, conditions such as temperature, humidity, and chemical substances can increase the demand for gripper selection or external protection.
Safety	Ideally, the gripper must hold its load even if the power is lost. The exact requirement also applies in an emergency stop situation or when the control signal is interrupted.
Sensing	An intelligent gripper can adapt to changes in its environment and to its knowledge of its state. The

	minimum requirement is to communicate the failure of the task to a higher control level.
Source of power	Pneumatic grippers do not have motors and gears, which makes them simple operating devices. Additionally, in manufacturing facilities, compressed air is typically available for use. Hydraulic grippers are a worthwhile alternative for pneumatic grippers from a cost perspective, as well as when extra gripping force is required. Power output is based on the properties of the hydraulic fluid compared to pneumatic air: it does not compress. Hydraulic grippers are not as accurate as pneumatic or electric grippers, and they are not suitable for cleanroom applications. Additionally, untidiness and high maintenance costs often lead to the preference for other options. Electric power is the primary option for power sources for grippers. Electric-powered grippers are relatively new technology compared to hydraulic and pneumatic-powered grippers, which is why electric grippers have become cost-effective only recently. Electric grippers are suitable for applications that require high speed and for those that require light or medium gripping forces. The advantage of electric-powered grippers is their control possibilities and tidiness. An additional motor can be easily added to control opening and closing, as well as for versatile control of gripping force. Electric grippers are the cleanest of all three options because it does not leak or leave any dirt behind. Downsides are the gripper's dimensions due to the motors inside the gripper and the low gripping force compared to pneumatics.

Mechanical grippers consist of two or more fingers powered by pneumatic, electrical, or hydraulic systems. The fingers can be either stiff or soft and may include joints that enable them to wrap around the workpiece. The gripping mechanism operates either through compression, where the object is grasped by squeezing the fingers together, or spreading, where the gripper's fingers move outwards. The gripper's attachment can be centring, allowing for the correction of minor positioning errors, or non-centring, where the gripper secures the part precisely as positioned. The gripping force is adjustable via pneumatic or hydraulic systems. Electrically powered grippers offer precise control of both power and accuracy, especially when equipped with servo systems. (Liuha et al., 2023, pp. 204-205)

The number of fingers plays a critical role, depending on how the robot grips the part. Two-finger grippers provide side-to-side centring, while three- or four-finger grippers are ideal for circular or standard geometric parts, ensuring consistent centring in two directions. For irregularly shaped parts, five or more fingers may be required, though these designs are highly specialised and more expensive compared to common three- or four-finger variations. To determine the gripping force, several factors must be taken into consideration. The centre of gravity of the part indicates the point where its total weight is concentrated. By supporting the workpiece at this point, forces remain balanced. Challenges may arise if the centre of gravity is located outside the gripper line, potentially causing excessive force issues. This can be mitigated by introducing friction to reduce slippage between the two materials. Friction enhances resistance, ensuring the part is securely held by the gripper's fingers. (Dinwiddie, 2019, pp. 81-83)

Another popular gripper type is the vacuum gripper, which is mainly used to grasp objects that are difficult for mechanical grippers. This may be due to the sensitive surface, the required gripping force, or the object's shape, which makes it difficult for a mechanical gripper to grasp. It is worth noting that the term vacuum is not an absolute vacuum but rather a vacuum level of 30-50% of sea level air pressure. (Blomsjö, 2023, p. 108) Another type of vacuum gripper is a device with a flexible suction cup. The cup is pressed against the workpiece, and it is released by blowing compressed air into the suction cup. It will still function, and the workpiece will not fall, providing a clear advantage in power failure situations. (Westcott et al., 2024, p. 472)

Most commonly, flat objects are grasped with vacuum grippers, but vacuum grippers are also suitable for small boxes and similar objects. Generally, vacuum grippers are very effective, quick to operate, and usually do not damage the surface of the part being handled. Vacuum grippers also have some limitations or points to pay attention to. When operational conditions, such as temperature changes, are present, the material used in cups may behave differently. Rubber that works well at 20°C may not be suitable for use at temperatures below 4°C, as it becomes hard and loses its suction power. A factor affecting process efficiency is the size of the suction cup, which should be kept as small as possible, as the suction time of a larger suction cup is longer than that of a smaller one. Flexibility is provided by the ability to rearrange the array of vacuum cups on the gripper to suit better the parts being handled. (Wilson, 2019, p. 60)

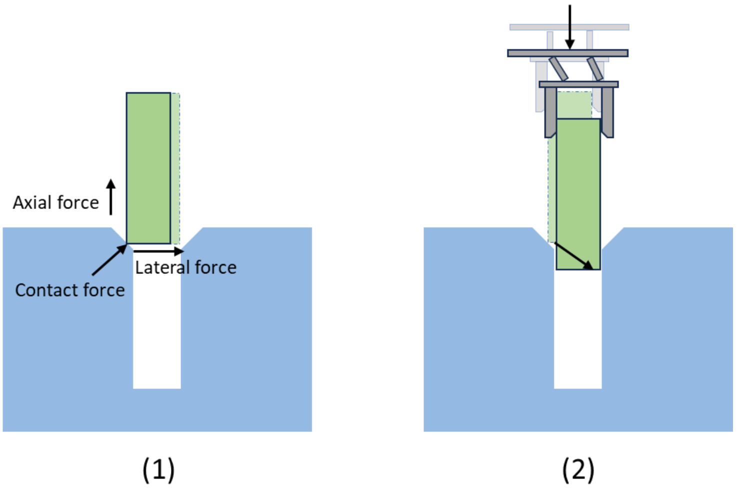
When components to be handled contain ferrous content, a magnetic gripper can be considered. The principle of the magnetic grippers is the same as that of vacuum grippers, without the suction cup. With a magnetic gripper, metal components are handled quickly, even irregular objects. Any air gaps will reduce the power of the magnetic force, making flat sheets of metal the best suited for this gripper type. The downside is temperature, which causes permanent magnets to become demagnetised when the temperature rises high enough. The heat can even occur via prolonged contact. Compared to other gripper types, the magnetic charge will turn off instantly, causing the component being lifted to be released immediately. This has two effects: it speeds up the removal of the component but exposes it to danger if it fails. Also, the force of the magnet can cause more than one metal plate to stick together in a lifting joint. (Westcott et al., 2024, pp. 473-474). Magnets consume energy only during the magnetisation and demagnetisation phases, or hold and release phases. (Blomsjö, 2023, p. 109)

When there is a need to use multiple tools within an application, several options are available, ranging from switching to a new tool as needed to using multiple tools simultaneously. However, at first, it is still necessary to determine what tools are needed and how often the change will occur. (Dinwiddie, 2019, p. 93) A low-cost and low-tech preferred solution is a tool change performed by the operator when necessary. The robot is programmed to move to a specific position and wait until the human operator has changed the tool and resumed the program. This can be a laborious and slow manner, but it is easy and affordable to implement. The second simplest option is to attach multiple tools to the robot simultaneously. A splitter is installed on the end effector, thus duplicating the end effector as it were. The position of the end effector is changed by rotating it using the turret gripper, whereby the desired tool becomes available. Since more tools are always attached to the robot, this causes the load carried by the robot to increase, which in turn may lead to the need to purchase a robot with a larger payload. Extra tools during the processing also increase the risk of collision. (Liuha et al, 2023, p. 225)

Tools can be changed by the robot either one by one or with automatic systems. To enable change, a quick-change adaptor will be installed between the robot's end flange and a tool, acting as an enabler for the automatic change process. The adaptor is equipped with pins that provide a consistent placement and a locking/detaching system to swap the tools when needed. For both the robot's end effector and the used tool, mount a similar adapter plate to allow the pins to attach. The power used for the locking and detaching process can be either pneumatic or electric. The location of the tool rack for the swap operation is known to the robot. Initially, the robot detaches the used tool from its designated location, moves to the new tool to be used, and locks it for use. The quick-change process is potentially useful in cases where frequent changes are required on a daily or even hourly basis. The system can operate for as long as needed and with as many different tools as necessary if the appropriate adapter plate is available. This may increase the setup cost since the adaptor and its plate become a crucial part of the setup. (Dinwiddie, 2019, p. 93)

Whatever tool and gripping solution are used, tool positioning can also become a bottleneck if the tolerances are too tight. The problem can be attributed to either the components used, the process, or the tools used in the application. The solution to correct tolerances is called remote centre compliance (RCC). (Dinwiddie, 2019, p. 95) Asfahl (1995) describes this as functionality where the robotic tool "gives a little". This refers to the feature of the tool, which is illustrated in Figure 35. In Figure 35_1, the robot is attempting to insert the pin in a hole. Due to the tolerances in the process, there is a lateral alignment error. Despite the bevel in the piece, too rigid tooling does not allow the pin to be placed in the hole. If the tooling is less rigid, there still might be a failure in the process due to lateral force caused by the component, which tends to rotate the pin. By enabling the RCC (Figure 35_2), the tool flexes a bit ("gives a little"), and the pin relocates laterally to the hole instead of rotating its top end. (p. 154)

Figure 35 - Remote centre compliance tooling (Adapted from Asfahl, 1995, p. 155)



4.6.5 Vision system

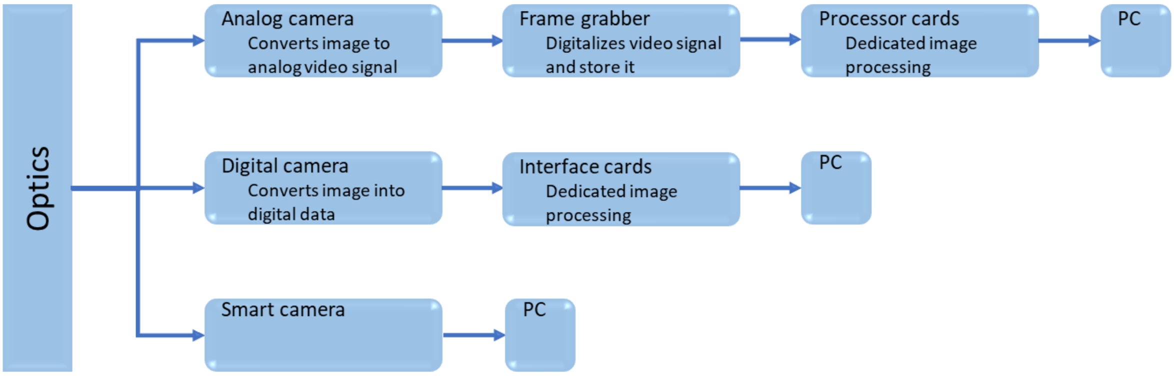
Increasingly, manufacturers are utilising machine vision technology to enhance productivity and lower costs. The need for these solutions has arisen from the growing demand for better control and higher quality. Machine vision utilises optical components with a computer-controlled system that is further integrated into the manufacturing process. The continuous, simultaneous reduction in hardware costs and the increase in computer processing power also enable the implementation of machine vision applications to become increasingly widespread. (Karabegović & Banjanović-Mehmedović, 2020, p. 72)

The roots of artificial vision applications stem from the need for object recognition for military purposes. Machine vision is the application of computer vision provided to industry and manufacturing. Computer vision is mainly focused on machine-based image processing, whereas machine vision requires digital input/output devices and networks to control other equipment, such as robotic arms. Machine vision technology combines an imaging system and a computer to analyse an image, and based on this analysis, the system can make decisions. (Westcott et al, 2024, p. 429; see also Karabegović & Banjanović-Mehmedović, 2020, p. 64)

One milestone for the broader use of machine vision is considered to have begun in 2006 when Nintendo introduced the Wii video game console. At the time, the wireless controllers that came with the Wii console included a new feature for their reasonable price: an accelerometer. The accelerometer made it possible to detect movement in three dimensions and output the resulting data stream as a view visualised by the game console. Sony Corporation replied with their game console, PlayStation, and replicated Nintendo's motion-detecting wand. However, Microsoft responded with something totally new. With the help of the company PrimeSense, they introduced a webcam-like device called Kinetic, which had 3D machine vision capability and associated software. This device could sense the distance of an object (a person) from the camera and produce an interactive image on the TV screen. What was amazing was not the technology used but its price. It was a lightweight device costing $150 instead of a device costing tens of thousands. Within weeks of Microsoft's release, DIY inventors and university engineers had hacked Kinetic and uploaded videos to YouTube of robots that utilised 3D vision using Kinetic. (Ford, 2013, pp. 3-4)

Elements of the machine vision system can be seen in Figure 36. Three different camera technologies are available. Some systems use analogue cameras, whereas an increasing number of systems are using digital cameras. Other peripheral steps are required to send data to the PC for these two. Smart cameras instead provide a complete vision system in one package. Despite the differences between these three options, all of them can provide high image quality. The system produces an analysis based on the information it receives, which is the image obtained. The quality of the analysis depends on the quality of the image produced, which can be best influenced by the lighting and optics used. Nonetheless, optics is the most unattended part of the machine vision solution. The image cannot be improved with the help of the software. (Karabegović & Banjanović-Mehmedović, 2020, p. 73) Most machine vision systems still use black-and-white cameras, but colour cameras are becoming more common. Additionally, the trend in machine vision systems is shifting towards digital camera equipment for direct connection, rather than using separate devices. (Westcott et al., 2024, p. 431)

Figure 36 - Elements of machine vision system



The advantages of machine vision come in terms of precision, consistency, cost-effectiveness and flexibility. Well-designed vision systems are capable of measuring dimensions with an accuracy of one thousand or better. By comparing consistency between machine vision applications and humans, the machine vision system is not subject to fatigue and is configured to produce identical results. Human operators tend to lose focus on repetitive tasks, and the number of errors increases, particularly when the level of performance is required to be faster or more accurate. This is one of the primary reasons why machine vision systems are in high demand. Machine vision systems are nowadays also cheaper and more flexible due to the price drop of computer processing. One vision system can make measurements over a wide range, and adding new measurements or making changes to the current system is achieved through software updates. The investment cost of a machine vision system can be half of a human operator's yearly salary. As a bonus, the operating and maintenance costs of the vision system are low. (Westcott et al., 2024, p. 431; see also Asfahl, 1995, p. 229)

Ford (2015) underscores the evolution of camera technology by comparing its function to the human eye and brain in perceiving complex environments. He uses the example of single-coloured cardboard boxes stacked together for disassembly. In such a scenario, boxes may be slanted or partially overlapping. The human brain instantly processes this information, determining the dimensions and locations of the boxes and identifying which should be moved first to maintain the stack's stability. This presents a unique challenge for robots, as they lack spatial awareness. This limitation has been described as the "final frontier" of machine automation. In this area, robots must strive to achieve human dexterity in order to take over the routine physical tasks still performed by humans. (pp. 1-2)

4.6.6 Screwdriving

One assembly task suitable for robots is attaching components to each other using screws. In a robotic screw-driving cell, a screwdriver is attached to the robot, which must be highly automated. The screwdriver must either be able to pick up the screw or have it transported to the screwdriver in some other way, be able to hold the screw at the tip during the transfer movements and have a torque limiter so that the screwdriver can stop rotating when the screw has been screwed all the way in. Depending on the process and its quality requirements, the torque must be set to a predetermined value, and the achieved torque may also need to be documented. For this requirement, the unit must be equipped with accurate torque measurement and data storage capabilities, enabling the accurate identification of product data from the assembly. (Liuha et al, 2023, pp. 221-222)

Asfahl (1993) points out that although assembly machines are tailored to the individual configuration, the driving of screws is familiar enough in most assembly cases. Not only can the tightening of screws be automated, the entire process, from feeding the screw to applying the required torque to tighten it, can be automated. The first part is to orient the screw into the correct position to start the screwing. Tightening of the screw can be done either with electrically or pneumatically powered tooling. Pneumatic-powered tools can be noisy and less powerful than electric-powered tools. The advantage of an electric-powered tool, primarily if it uses a DC servo motor, is that the tool can hold its torque when it comes to rest under power. For high-torque requirements, hydraulic-powered solutions are also available; however, they are not as practical as pneumatic or electrically powered tools. (p. 47, p. 83)

Nut and bolt assembly is similar to screwdriving applications. Bolts are positioned with robots or linear actuators. Nuts are attached using the same kind of mechanism as in automatic screwdrivers. An alternative option is to use special grippers when the nut sizing is appropriate for the gripper. (Asfahl, 1993, p. 84)

4.6.7 Sensing and communication, fixturing and other accessories

An individual robot is lost on its own. It can recognise its position and locate itself with a tool to the required position with the required angle. From this point on, the robot does not know anything about its surroundings. Various sensory and communication systems are employed to address this, as the robot requires the ability to provide information about its surroundings. At its simplest, the information produced by a sensory system is on/off type information, whereas machine vision represents a more demanding information production system. (Liuha & Aro, 2023, p. 147) Networking has become a crucial element of modern manufacturing. The evolution of the field creates new options and device functionalities for sharing data through devices, as well as new functionality options. It is almost guaranteed that at some point in the automation, interaction between various networks occurs, which affects the application. (Dinwiddie, 2019, p. 187)

In practice, a robot's communication interfaces are typically a combination of three distinct levels of communication methods. The simplest messages are transferred using the I/O (Input/Output) method, where Input refers to a signal towards the robot, and output refers to a signal outward from the robot. The signal itself is digital, and the content of the information is one bit, either one or zero, expressed in mathematical logic, true or false. The wire carries voltage, which is either powered or not. Depending on the operating logic, an energised wire does not always necessarily mean that the device is activated. Most typically, it is signalled that the item has arrived at the pick-up point, in which case the value produced by the signal is true, meaning that there is voltage in the wire. However, this cannot be the case in safety device connections. In these, the logic is reversed, meaning that, for example, if the emergency stop button is pressed all the way down, the wire becomes de-energised, activating the circuit, and the safety function is activated. This ensures that the safety function is activated even in the event of a power outage. (Liuha & Aro, 2023, pp. 148-149)

Fixturing is used to hold parts in place, ensuring the correct placement of components in repetitive work, and then allows the robot to perform the required operation. Another function of fixtures is to provide control of the dimensions. In addition to holding, the fixtures must also provide easy loading and unloading. This must be done with both individual components and assembled parts. In the case of a welding process, it must be possible to remove the products even when they are still hot. The fixture must be suitable for use with various tooling, ensuring that the tool and fixture clamps do not collide. (Wilson, 2019, p. 62)

The fastening mechanism in fixtures can be manual or automated. The manual is a low-cost option requiring the operator to close all clamps correctly. A semi-automatic option where the attachment is manual and detachment is automated. This allows the operation to ensure attachment and faster detachment of parts. Auto-on and auto-off operational clamps are the most expensive. The components are loaded into the tooling, and the clamps will close automatically in response to the agreed-upon signal and open automatically when the work cycle is complete. This method saves time for both loading and unloading, reducing the operator's workload. It also enhances process reliability, as the tooling must meet a high-quality standard to ensure operational success for the fixtures. Using separate plates or structures allows for the same fixture to be used for different setups. Simply, a change to the tooling plate allows the robot to switch to perform another pre-programmed task. (Wilson, 2019, p. 63)

Reliability is the most critical element of fixtures or tooling. A simple solution is usually the most reliable one; with sensors, operational mistakes can be reduced even further. The cost of fixturing and tooling can often be a significant proportion of the price of a robot cell, as these are typically the most bespoke elements of the system. The fact is that a robot cell is only as good as the presentation of its components. (Wilson, 2019, p. 64)

Most robot applications require monitoring and control. These are achieved through the robot's sensors as well as additional sensors connected to the process. The primary goal is to observe the system's operational state, including the position of components and the functioning of tools. Error recovery logic can be integrated into the application. If a sensor detects an error, the robot can be programmed to recover using a predefined routine. Sensors may guide the robot in performing specific motions, adjusting process parameters, or initiating recovery actions. (Blomsjö, 2023, p. 111) This process is referred to as "repairing the robot's track." The robot program must adapt to new conditions, whether during commissioning or after a change in workpiece. This need arises because of discrepancies between the digital world, which is precise and constant, and the real world, where variations exist even among pieces produced by the same machine. In the digital realm, the environment is always predictable. However, in the real world, sensory systems are crucial for determining the robot's position or the location of an object. For instance, an optical sensory system may be employed to take measurements, enabling the robot to execute a programmatic correction movement based on the data. (Liuha & Aro, 2023, p. 167)

There are several different types of sensors available, and they are divided into groups based on the complexity of the information they provide. Sensor groups are proximity sensors, measuring sensors and image sensors. (Karabegović & Banjanović-Mehmedović, 2020, p. 51) Additionally, Westcott et al. (2024) categorise sensors based on whether they measure the robot's external environment or internal parameters. Sensors for measuring the external environment can also be categorised based on whether contact is required for perception. (pp. 442-443)

Contact sensors can be found in any manipulator interacting physically with the environment in a non-structured manner. It is the robot's talent to assess the shape, size, and weight of the workpiece - even the surface structure of the workpiece can be detected. The contact sensors are located on the gripper, where the information is transmitted to the wrist or joint of the robot. This feature is crucial in grinding and assembly operations, enabling functionalities such as searching, recognition, grasping, and movement. The most important types of contact sensors are tactile and force sensors. (Westcott et al., 2024, p. 443)

4.6.8 Robot programming, simulation and modelling

One main difference between robots and special machines dedicated to specific applications is the essential feature of robots. This feature is their programmability. In the early days of robot programming development, robot programming primarily focused on describing a series of robot movements. A significant step forward in programming development was taken in the 1980s when programming robots using hand controls became more common. General technological and electronic developments have increased the computing power of hand controls, allowing for the increasingly complex and simultaneous programming of multiple robots using a single hand control. Additionally, programming various additional components and devices, such as tools, sensors, and simulation and maintenance-related support functions, is possible using a handheld terminal. Hand control devices are transformed into teach pendants for programming, offering graphical simulation tools and other optimisation tools such as VR/AR (Virtual Reality / Augmented Reality) technology. (Blomsjö, 2023, pp. 127-129)

Dinwiddie (2019) defines a robot program as a user-defined set of instructions for controlling the robot's actions, answering questions about what, when, and how the desired action is conducted. The program defines much of the robot's performance, and since the program is user-defined, the robot's performance relies heavily on the programming skills of the person who programmed it. Even the programming of the robots is an evolving field; each robot manufacturer uses slightly different programming languages and controllers to program the robots. This can become a challenge if multiple robot types and manufacturers are used. In general, there are similarities between robot types and programming languages; once the basics of programming and applications are learned with one, it is easier to learn with another. (p. 100)

Westcott et al. (2024) define a robot program as a path that is followed by the manipulator, combined with the actions of peripheral devices. These actions support the work cycle. (p.

478) Kolehmainen (2023) defines the task of programming to deliver the robot to the predefined location at the right time and with the correct type of movement. (p. 230) However, although each robot manufacturer has its programming language, they are based on traditional programming languages such as BASIC, Pascal or C. With the increase in peripherals, the use of more general programming languages , such as Python or C++, has also increased. Although robot programming languages are based on general programming languages, programming robots is different from writing computer programs. The process of robot programming consists of teaching the task to be performed, storing and executing the program and debugging it. There must be a sequence and logic for the movements of both the robot and its accessories, synchronising the robot's movements with environmental signals and defining the robot's behaviour in error situations. Depending on the robot manufacturer, there can be over 150 different standard commands, such as movements, data storage, conditional, repetition, and looping structures, as well as ready-made, pre-programmed palletising and de-palletising applications, available for the robot. Additionally, it is possible to have application-specific special commands, such as those for welding or paint dispensing. (Westcott et al., 2024, p. 478; Kolehmainen, 2023, p. 230)

Safety aspects must be considered during the robot programming phase. Protective equipment is primarily determined in machine safety, whereas safety-related matters, which are programmed, are more closely related to the robot and its peripheral devices. This can be, for example, defined protection zones, which are the areas where robots are allowed to move or are prohibited from moving. Also, axis-based positions can be defined to ensure that part of the robot or its tool is not inside the machine when it starts. (Kolehmainen, 2023, pp. 247-248)

There are several different techniques to teach the robot. Online and offline programming do not reveal any details about the language used or its features. It expresses whether the physical robot system is used for programming. Online programming has been a dominant method, offering some advantages. It is intuitive and direct, as the programmer uses the teach pendant to walk through instructions and sequences, much like manual operations. The programming is done in a real operating environment corresponding to the application to be implemented, regarding the parts to be processed and their accessories. Function checks and adjustments of the program are verified and changed as needed. The feedback is visual as the program is running. The online programming method is challenging for programs with complex structures, and it occupies the robot for the duration of programming, diverting it from production work. (Blomsjö, 2023, pp. 133-135)

Offline programming is a cost-effective method because it is performed during the robot's normal operating cycle, without the need to interrupt production. Verification is performed through simulations and visualisations, creating program documentation simultaneously. For smaller robotic operations, offline programming can be challenging due to the need for investment in offline programming systems and comprehensive user training. (Westcott et al., 2024, pp. 485-486) Depending on the robot, it may be possible to write the code using a text editor, such as Word, and then use a separate editor to translate the written code into the form required by the robot. The actual testing and debugging must be done by the robot anyway. (Kolehmainen, 2023, p.232)

A significant portion of currently used robot applications is programmed using the walk-through programming method. This is a method where the robot arm is moved to the desired positions, and coordinate values are stored via a teach pendant. Other programming instructions, as well as the logic of the operation and options for different motion paths, are processed by a computer, either using the robot's own software or universal virtual software. Lead-through programming was once a popular method, but the development of teach pendants and computer-based remote programming has largely displaced its use. In this method, the programmer was instructed to move the robot according to the desired trajectory, and this information was stored on the robot. The movement of the robot's actuators was possible by releasing them during the movement definition phase. This method has gained popularity due to the increased market share of collaborative robots. When ready-made program sets have been brought to the teach pendant as graphical interfaces, this programming method has become the most advanced, fastest and easiest way to program robots to perform simple processes. With both methods, the downsides include interrupted production during programming and possible limitations regarding the teach pendant and its capabilities for other decision-making logics and computer subsystems in the factory. The main advantage, at least as it relates to the lead-through method, is its ease of programmability: no engineers or advanced programming experience are required to program the robot. (Kolehmainen, 2023, p. 231; Westcott, 2024 et al., pp. 482-484)

Simulation is a digital tool used to design, configure, and test robot systems. In general, simulation is not a design method but a tool intended to support programming. Simulation and digital models offer possibilities to support robot system design and the configuration phase based on what-if questions, which are analysed based on the data and results produced by the simulation model. It is possible to conduct early tests and digital verification of concepts before taking them into real life. (Blomsjö, 2023, pp. 149-150) The simulated environment is digital and artificial. The necessary equipment is introduced into the environment as three-dimensional digital simulation models (components) and virtual controllers. All required digital components in the model must be included in some way. This could be done by using simulation software, third-party ready-made component libraries, or by designing yourself, for example, using CAD software. At best, the functionality of the cell can be verified using the tools already employed in the product design phase, but at least during the design phase of the robotic cell. (Pöysäri & Kytöharju, 2023, p. 252)

The digital model needs to be built on the designed physical cell. If the simulation is done for an existing cell, the same is done for that. If the digital model is used or is going to be used, it needs to be updated whenever there are changes regarding the layout or other equipment, such as tools, feeders, and conveyors, used. The same applies when the product model is changed, since it might affect the tooling and fixturing. Before commissioning, the system must be simulated and calibrated. The simulation is performed on a virtual model, and its purpose is to verify the operational capability of the robot program, including trajectories, workflow, communication between the operator and other devices, as well as checks for collision and other error situations. The purpose of calibration is to ensure that the simulated digital model corresponds to the physical robot cell. In practice, the observation and correction of possible differences are verified from the physical world, which is transferred to the virtual world. If the robot is programmed for remote programming, calibration is a mandatory procedure. During online programming, calibration takes place during the programming process. Generally, calibration is a one-time procedure; however, it must be performed separately for each product manufactured. Calibration of a robot cell under design is only performed after programming and completion of the robot cell. In contrast, calibration of an existing robot cell can be performed before programming, allowing the robot program to be completed in one step. (Pöysäri & Kytöharju, 2023, pp. 253-261)

There is a need to balance the amount of data represented by the physical object. It is essential to distinguish between those parts and components that are crucial and those that have only a minor impact, if any. Positioning accuracy of robots and other controlled devices related to workpieces is also vital. This will determine whether and how a simulation can be used as intended. (Blomsjö, 2023, p. 151)

General advantages of simulation are gained through supporting the design optimisation and early tests to justify the business case. The benefits of the planning and implementation phase are achievable through design, programming, testing, verification, and optimisation processes, resulting in an overall shorter implementation time. With simulation, it is possible to carry out various studies of different scenarios if the number of parameters is at a reasonable level. For the desired robot application, many requirements are set, and some of them may conflict with each other. Modelling and simulation of the application highlight the importance of adjusting the parameters and the impact of optimisation. (Blomsjö, 2023, pp. 149-150)

The selection of the simulation tool and other complex software should be defined at the same appropriate level as the investment in the robot cell. There are general simulation tools available on the market, as well as simulation tools offered by robot manufacturers. The tool provided by the manufacturer supports the selected robots from the same manufacturer. In contrast, the general simulation tool may suffer from compatibility issues due to different robot manufacturers using various programming languages and controllers. As an advantage, a general simulation tool may offer the possibility to use the software for all types of robots. During the selection process, it should be ensured that the selected program supports interfaces to other systems, allowing the simulation to achieve the benefits of simulating the entire system. (Blomsjö, 2023, pp. 152-153)

4.7 Robotisation as a project and life cycle

There is always a duel between fixed and flexible automation. Robots present flexible automation with their general-purpose design and re-programmability; thus, they are a more expensive choice. The shorter the batch size is, the more expensive the fixed automation solution becomes. Robots can be utilised for other tasks, for example, in the production of end-of-life products and the production of new products. With a fixed automation solution, it may be necessary to design and build an entirely new fixed machine. Speed is another criterion to be evaluated. With high-speed requirements, usually fixed automation solutions are faster. Robots themselves are generally single-function devices, although they can be equipped with dual-tooling functionality, and controllers can signal multiple functions to be performed by other machines. (Asfahl, 1992, p. 243)

Colestock (2004) states that the novelty of the industrial robot should not hypnotise one, nor should one forget the even greater savings that can be achieved with fixed automation. Based on the argument, a key critical factor is the manual operator, the industrial robot, and the fixed automation, which presents some of the most dominant guidelines for the successful use of industrial robots. (p. 193) The critical factors are shown in Table 5.

Traditionally, robots are investments that are directed at a company's assets. The expeditious growth of RaaS (robots-as-a-service) lowers the threshold for robotics applications and enables them to be acquired by small- and medium-sized companies as well. RaaS enables companies to lease robotic applications as a subscription service, thereby alleviating the burden on their balance sheet and maintenance concerns. It is also the question of scaling up and down easily, which helps diverse industries such as warehousing, healthcare and security. (Marr, 2020, p. 147)

Table 5 - Deciding factors for manual operation, industrial robot and fixed automation (Adapted from Colestock, 2004, p. 193)

	Manual operator	**Industrial robot**	**Fixed automation**
Capital expenditure	Lowest	Medium for low-volume runs	Highest for low volume runs
Flexibility	Highest	Medium to high	Lowest
Speed	Lowest	Low to medium	Highest
Tolerance to adverse environments	Low	High	High
Space requirements	Low	Medium	High
Mobility	High	Medium	Low
Tolerance to repetitive tasks	Low	High	High
Quality of parts required	Lower	Higher	Higher
Quality of parts delivered	Lower	Higher	Higher
Maintenance costs	Lower	Higher	Higher
Lead time required	Low	Low	High

Armstrong & Shah (2023) accentuate the selection of KPIs to measure the success of automation. Initially, it must be acknowledged that there is no single correct metric to evaluate the success of automation. KPIs should be developed from multiple perspectives, not just productivity and human versus robot comparisons. Moreover, the KPIs should reflect the reasons behind the automation. Armstrong & Shah (2023) suggest developing a set of indicators to reflect developments at three levels: the machine, the system and the team. Flexibility can be measured at the machine level by comparing the time required for humans and automation systems to learn new tasks. At the system level, the ramp-up time of the new process with an automated system reflects the switching of costs. (p. 94)

Colestock (2004) challenges traditional economic productivity metrics and proposes new parameters for measurement. The standard definition of economic productivity is the ratio between the output of a good or service and the input of one or more of the factors producing it. Alternatively, it can express the ratio of a change in production to the associated change in input. Additionally, the ratio can be described as an average, representing the total production of a specific category of goods divided by the total input of the relevant factor or factors. The classic economic productivity KPI is output per person-hour or units produced per input. The problem behind this classic ratio is the lack of consideration for related factors that are directly related to the work. Factors such as increased efficiencies in management, marketing, distribution, and sales, as well as reductions in paperwork and trivial tasks through computerisation, are often overlooked. (p. 5)

Regardless of whether robots pose a threat to humanity or offer an opportunity to improve production and working conditions, change is coming to the workplace. Those who will benefit most from this change will be those who seek opportunities for robot-human collaboration. (Marr, 2020, p. 148)

4.7.1 Why use robots?

Based on Harvard's research studies (Armstrong & Shah, 2023), the primary reason for automation is increased productivity. Behind that, the reasons vary from building a solution to handle dangerous tasks to tasks that workers would rather not do. Others are focusing on reducing waste and improving process flexibility. Some companies invested in automation due to curiosity and because their competitors were doing so. (p. 94) Karabegović (2020) suggests that the ideal application of industrial robots is in jobs that are difficult and unsuitable for humans to perform. Other motivators include productivity increases or cost reductions, balancing human labour skill differences, offering more flexibility in certain areas of production, and improving quality. (p. 3) Westcott et al.'s (2024) list of benefits is more inhumane than others. He approaches the issue with a labour shortage or high cost of labour, the need for medical insurance, vacation or humans suffering from a hangover. He continues the list of benefits of eliminating work environment requirements, such as lighting, air conditioning, ventilation, and noise control, when using robotic solutions. Among the benefits listed above, he also mentions more humane aspects, such as a better corporate image, improved product quality, and shorter lead times. (pp. 10, 402-403)

Dinwiddie (2019) lists job types into four-letter categories in an easily approachable manner. The categories of the four Ds are dull, dirty, difficult or dangerous, and the four Hs represent work types such as hot, heavy, hazardous and humble. These four-plus-four factors drive both management and workers' acceptance of the use of robotics. Behind these categories, precision, performance, and cost play a vital role in answering the question, "Why use robots?" (p. 35)

Dull is like humble. As it can be deduced from the name of the category, these types of tasks are repetitive and offer little or no intellectual challenge to the person. During this type of work, a person is not necessarily directly exposed to danger, but rather through the ability to concentrate. In long-term, repetitive work, a person can lose their attention, which may lead to accidents. Direct exposure occurs if a person must repeat the same movement for several months or even years. These injuries are most typical of the musculoskeletal system. A robot can perform thousands of repetitive actions with only minimal maintenance. At the same time, the human operator can be assessed for better-suited jobs, such as machine adjustment or quality control.

Dirty work may also involve working in hot and hazardous conditions. By performing the process of dirty work, various harmful factors, like dust, grease, slime or sludge, arise from the work. These factors can cause everything from dissatisfaction and messes to health risks, including allergic reactions or skin irritation, as well as slips or trips. As human operators need to be equipped with proper protective equipment, the same applies to the robots as well. Other factors are beneficial for robots, as they do not care about working conditions in general or the possible discomfort caused by the protective outfit.

Difficult tasks are often also heavy. When work requires bending or twisting, robots become a more attractive solution. Usually, this is combined with weight, where a person might be able to move in a specific position, but the added weight of the process part adds strain on joints and muscles for humans. The robot is also remarkable in terms of joint movements. Where the human elbow is limited to approximately 90°, the rotational joint movement of the robot can be 270°, not to mention the 360° wrist rotation by the robot.

Dangerous tasks and hazardous tasks go hand in hand. This kind of working conditions includes a high risk of injury or illness for humans. It is possible that a robot may also be damaged in such environments, but damage to a robot is much easier to repair compared to damage to a person. Examples of these environments include excessively hot conditions, toxic fumes, or radiation. In case a robot is exposed to radioactivity, the robot will be disposed of in the same place as the other radioactive waste.

Precision achieved with robotics is based on the robot's ability to perform accurately, surpassing that of humans. While robots also come with tolerances ranging from 0,35mm to 0,06mm, the range is still at a level that is difficult, if not impossible, to achieve by humans. The variance in human body construction, vision, and experience is too great, which has led to the use of robots in the production of electronics, aerospace components, and other precisely manufactured parts.

Consistency is the ability to produce the same results every time. Repeatability refers to the ability to perform the same movements within a specified tolerance. The fact that humans are an organic system with emotions, and robots consist of mechanical and electronic parts controlled by a program. Robots are not affected by performance fluctuation caused by illness, injury, fatigue, emotions, job satisfaction, temperature or other distractions. As long as the robot's mechanical and electrical parts, as well as the program, run as planned, the robot is able to perform in the same way from Monday morning to Friday evening or even the weekends at the same rate.

(Dinwiddie, 2019, pp. 35-37)

Unimate was used for a production line to manufacture car parts. It was programmed to transfer hot car parts to the coolant and eventually lift car parts onto the conveyor. For workers, the task was dirty, dull and dangerous. This is believed to have been the reason why factory workers did not object to the robot's arrival on the production line at that time. (Hänninen, 2022, pp. 59-61)

According to Westcott et al. (2024), the current emphasis on automation has shifted from merely increasing productivity and reducing costs to enhancing quality and flexibility in the manufacturing process. Increasing productivity and reducing costs were seen as short-sighted reasons for automation, as automation created a new problem due to the lack of qualified workers to manage and maintain it. Additionally, the cost of automation investment was often too high to cover the desired benefits until the new process had replaced the existing manufacturing process. This has led to an increased emphasis on interchangeability. Manufacturers are demanding flexibility and the ability to switch from one product to another without needing to rebuild production lines. (p. 9)

Kauhanen (2016) reveals the perspective of robotisation's possibilities from the perspective of routine. In his opinion, the more routine a task is, the easier it is to be replaced by a robot, and the more likely a robot will also replace the task in question. Routines are based on rules that can be divided into a set of rules. If the set of rules can be described, the task can then be assigned to a robot. In other words, the easier a task can be divided into routines, the easier the task is to replace with a robot, either entirely or at least partially. A robot is likely to perform routine tasks faster, more reliably, more accurately, and cheaper than a human. (pp. 14-15)

When comparing fixed-guarded robot cells with cage-free robot operations, the latter offers significant advantages in supporting human operators without requiring major changes to work systems and layouts. While cage-free applications can be achieved using traditional industrial robots, collaborative robot solutions provide even greater benefits. These benefits include ease of programming and enhanced flexibility for redeployment, allowing the robots to switch between tasks or locations seamlessly. Collaborative robots also enable multiple programs to be saved on the robot's teach pendant. With collaborative end-of-arm tooling (EOAT), tool changes can be performed in minutes by simply plugging in the new tool and selecting the appropriate program. When multiple robots are utilised, the same tool can be interchanged among them as needed. The goal of implementing and adapting collaborative robots is to create a system where programming or modifying robot tasks does not require specialised robotics expertise. As organisations increasingly adopt robots, their internal knowledge, ideas, and potential applications also grow, leading to a rapid return on investment for both individual program adjustments and the deployment of new applications. Considering the low implementation time, affordable robot costs (starting at 15000€), and the absence of substantial investments in material handling or additional safety systems, simple applications are not only feasible but also highly attractive. (Tarantino, 2022, pp. 324–325; see also Braun et al., 2016, p. 13)

Asfahl (1993) points out that the speed of a human and a robot in performing a task should not be directly compared. In many applications, robots can be slower than humans; however, their use can still be justified by their higher productivity. This is picturised as a case of hare and tortoise where the human is the faster hare, but the robot keeps working through breaks, lunch hours and even the night like a slow tortoise. (p. 166) Armstrong & Shah (2023) continue to question the direct comparison between humans and robots. Whether investing in any automation, a lights-out dream or approach should be avoided. This approach seeks to compare the results of a robotics project by comparing the production costs of automated and human workers. By this comparison, the process improvements across multiple dimensions are ignored. The most important success factor is the success of human teams. The focus should be on questioning: Will the team be more productive by doing something new, and will the used automation technology generate more innovative ideas than it would without it? Does automation make the team better and enable the team to perform at a higher level than before? Can a human team apply their skills more creatively to be able to do things that could not have been done otherwise due to automation? (pp. 88-89, 95)

4.7.2 Why not use robots?

The possibilities of automation and robotics are practically limitless. However, the real-world problem is based on cost-effectiveness. There may not be opportunities to utilise fast, high-volume, high-power robots. That is why many robotic applications are designed to solve specific types of work. (Karabegović, 2020, p. 2)

The lights-out dream is also the reason why no investments are made in any automation. Based on research by Armstrong & Shah (2023), what companies gain in terms of productivity tends to be at the expense of process flexibility. Depending on the implementation method, even routine maintenance tasks, such as sensor calibrations, may have been outsourced to a third-party supplier. The same applies to the programming of the robots, which is practically locked and does not offer the opportunity to utilise the innovative capabilities of the company's operational personnel. (p. 88) Asfahl (1993) also points out the importance of an honest look at production schedules regarding the time needed for setup and testing when process or product changes occur. Additionally, the timing of regular maintenance needs to be considered. Although robots are not said to suffer from sick leave like humans, neglected maintenance exposes robots to downtime, just like humans. Another review is needed from a quality standpoint and regarding the alleged consistency. Will the result be more consistently worse or better? (pp. 239-240)

Westcott et al.'s (2024) list of disadvantages towards robotics is more human, containing more confrontation with sustainable development than the list of advantages. Robots replace human workers, creating both social and economic problems. Salaries may be lost, and disfavour may arise between workers. Human operators are more capable of responding to emergencies which are not predicted. Non-predicted emergencies often pose safety risks to operators working with machines. If known, possible emergencies that occur can be included in the system from the beginning. The disadvantage can also be the initial cost of the application and the needed training and programming. (p. 402)

Before robotic solutions can be utilised, the dimensions of the objects to be lifted and handled, including their weight, are crucial. The lack of reliable data, so-called master data, creates barriers or slows down the adoption of robotics. As McKinsley (2024) states, it is challenging to demonstrate potential savings and immediate benefits through clear master data management, and therefore, the business case cannot be demonstrated or is prioritised below projects that deliver more visible benefits.

4.7.3 Human factors

The fact is that the installation of robotics will replace certain jobs. One of the most contentious debates, however, is whether the introduction of robots and automation will lead to widespread unemployment. If robotisation is carried out following the 4D and 4H principles, robots will replace humans in those tasks that are less suitable or unpleasant for humans. With the introduction of robots, there is a need for a new kind of expertise in robot programming and, in general, in the maintenance of the entire system. Since today's economy is global and affects all businesses, the importance of this awareness should be clear. The use of robotics, along with improved efficiency and flexibility, enhances a company's competitive position. Especially in higher-wage economies, all the skills and attributes of the workforce need to be utilised to perform added-value tasks. Not forgetting that health and safety requirements are demanding more attention and reduction actions towards dangerous and arduous jobs. (Wilson, 2019, pp. 17-18)

Apunen (2016) emphasises especially the role and possibilities of collaborative robots. These robots are designed to work in collaboration with humans, as their name suggests, by automating part of the work tasks in the process. Utilising a robot in operations is not an either-or question but a both-and approach. The task of a collaborative robot is, therefore, to support a human in the process, not to replace a human. At its best, a human + robot can produce more than a human or a robot alone. (p. 6)

Based on Harvard's learnings (Armstrong & Shah, 2023), if companies' ability to achieve the presented General Motors 'factory of future' in 1983, it would turn out for them not to invest in that. These companies have learned that people are essential for achieving productivity and flexibility in their production processes. The automation strategy should be based on enhancing human capabilities and value, rather than replacing humans with automation. It is a combination of the strengths of intelligent machines, managers, engineers and production line workers. The same result was also found later by Elon Musk when he tried to mass-produce Tesla's Model 3 in 2017. The robots were built to boost production, which led to difficulties for the company in hiring and training workers. This resulted in production delays and ultimately led to scaling down the level of automation and scaling up the number of skilled workforce. (pp. 90, 95)

Based on the research findings of Bauer et al. (2016), it is worthwhile to include staff in the design process in the early stages. The introduction and acceptance of new technology can be achieved only if operational participants are integrated into the planning process from the outset. New tasks related to robots open opportunities to upgrade new skills and work profiles in new ways of organising work, which is not currently used. This approach would be beneficial, for example, in training assembly workers to become proficient in programming robots. In these ways, operators and supervisors are always fully informed, adequately trained, and helped to accept that the change will be achieved. (Bauer et al, 2016, p. 10) Marr (2020) points out the importance of transparency with people about automation and its consequences. In the end, it will build trust and also help sell the benefits of robots in discharging dull and dangerous tasks, allowing people to focus on tasks that require more skill. When people are introduced to new technology that makes their tasks easier and safer, acceptance is more easily obtained. (pp. 146-147) Same findings are done by Armstrong & Shah (2023) in their studies. Engaging staff early on reduces the risk of failure and increases staff commitment. New low-code solutions empower operational staff to participate in programming, from minor tweaks to comprehensive workflow changes. This reduces the need for external consulting assistance, which can, in some cases, be significantly more valuable than implementing similar changes, such as re-hiring staff. (p. 92)

Armstrong & Shah (2023) continue to emphasise the role of our personnel, especially production personnel. Investing in training the company's staff is just as important as choosing the proper hardware and software. While the goal is to build line workers' autonomy in using technology and reconfiguring new applications, consideration should be given to training multiple employees across multiple roles to ensure that different perspectives, from design to measurement, are considered. In line with the training, the top-down approach towards automation is switched to a bottom-up approach. Line employees can offer the needed details for understanding the process, mostly on the needed flexibility required from the automation system and unplanned situations which occur in every process. Senior managers tend to analyse the processes only in targeting maximising productivity, which is the apparent downside of the top-down approach. An automation solution that lines employees directly enhances and accelerates the company's innovation capability. Plus, the bottom-up approach is the tool to win the workers' trust towards automation. (p. 92)

Wilson (2019) also drives the company's own personnel skill and expertise development to identify automation opportunities. As the drive to apply robots increases in the future, companies must offer opportunities for their personnel to develop these skills. Still, in the end, the successful implementation is based on lessons learnt from mistakes. (p. 18)

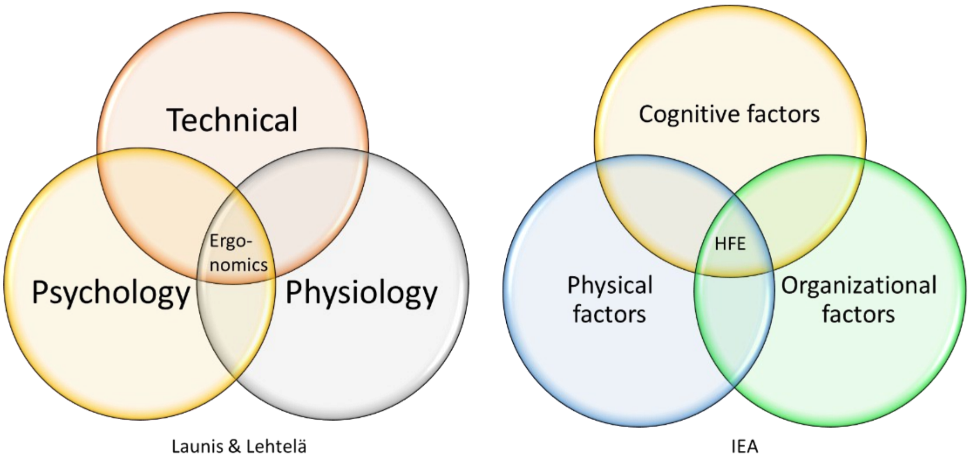
4.7.4 Ergonomics

According to the International Ergonomics Association (IEA), the term "ergonomics" originates from the Greek words ergo (work) and nomos (laws). In 2000, the IEA defined ergonomics as both a discipline that studies the interaction between humans and other elements of a system and a profession that applies theories, principles, data, and methods to design operational environments that prioritise human well-being while optimising overall system performance. Launis & Lehtelä (2011) emphasise that operational environments should be adapted to suit humans rather than the other way around. They provide a more practical definition of ergonomics, highlighting that its scientific foundation lies in understanding the physical and psychological activities of individuals interacting with technical solutions. By observing human activity, it is possible to identify deficiencies in both activities and working environments. The suitability of various solutions can be examined through modelling and testing. (pp. 19–20)

Karwowski (2007) categorises ergonomics into micro ergonomics and macro ergonomics. Micro ergonomics focuses on improving individual workstations or tasks, while macro ergonomics addresses entire production environments, encompassing organisational structures, policies, and processes. Reiman & Suokko (2020) highlight that Finnish ergonomics expertise primarily focuses on micro-ergonomic aspects, lacking the broader perspective necessary for managing entire production environments. They note that while occupational health, safety, and well-being have significantly improved over the long term, progress has stalled since the early 21st century. Despite evidence of substantial societal and workplace costs associated with these issues, the economic potential of mitigating them is often undervalued. Supporting this view, data from The Finnish Workers' Compensation Centre (Tapaturmavakuutuskeskus, 2025) reveal a 4% rise in workplace accidents. The top causes are slipping, staggering, or tripping (23%), injuries from sharp objects (16%), and sudden physical strain (12%).

Ergonomics has various definitions, as illustrated in Figure 37, with slight differences in emphasis. Launis & Lehtelä (2011) define ergonomics as a multidisciplinary field rooted in understanding human physical and mental functioning when interacting with technical solutions (p. 19). The International Ergonomics Association (IEA) offers a broader definition through Human Factors and Ergonomics (HFE), encompassing physical, cognitive, and organisational ergonomics. HFE considers factors such as socio-technical and environmental elements, as well as interactions between humans, their environment, tools, products, equipment, and technology. Key topics within HFE include working postures, repetitive movements, musculoskeletal disorders, mental workload, human-computer interaction, reliability, communication, resource management, cooperative work, and quality management.

Figure 37 – Venn diagram of ergonomics knowledge areas (Adapted from Launis & Lehtelä, 2011, p. 19 & IEA)



The principles of HFE are rooted in socio-technical values. This means that participatory design principles and methodologies apply across the design of a single task, as well as to working environments and industries. The core values of these principles are:

- Humans are seen as assets
- The purpose of technology is to be a tool to assist humans
- The target is the promotion of quality of life
- Individual differences are respected
- Responsibility to all stakeholders

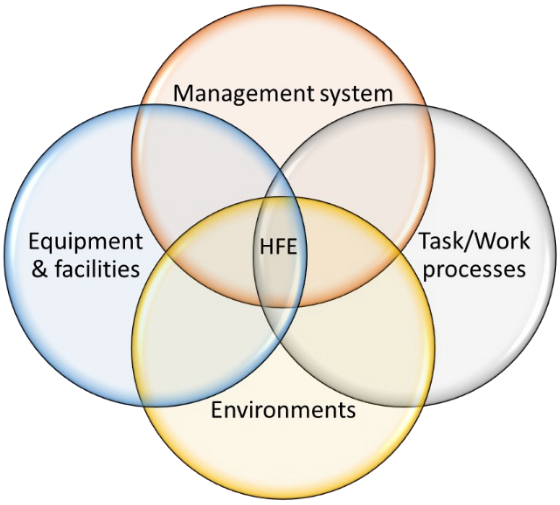
(International Ergonomics Association. (n.d.))

Macro ergonomics focuses on developing and applying human-organisational interface technology to improve organisational structures and processes. It adopts a systemic perspective, emphasising that individual system components cannot be viewed in isolation.

When designing work environments, the goal is to align all subsystems with the intended outcomes of the work unit or target group, contrasting with approaches that treat tasks or jobs as isolated elements. (Karwowski, 2007)

On the macro-ergonomical level, the International Ergonomics Association (IEA) highlights that Human Factors and Ergonomics (HFE) takes a holistic approach to system design, evaluating the interrelated effects of human, technical, and environmental components (Figure 38). HFE enhances organisational health by improving worker well-being, capability, and sustainability, while maximising performance and reducing costs associated with productivity losses, such as sick leave. Workplaces designed with HFE principles achieve better employee performance and business outcomes (International Ergonomics Association, n.d.)

Figure 38 - Venn diagram of HFE definition on macroergonomical level (Apapted from International Ergonomics Association. (n.d.))

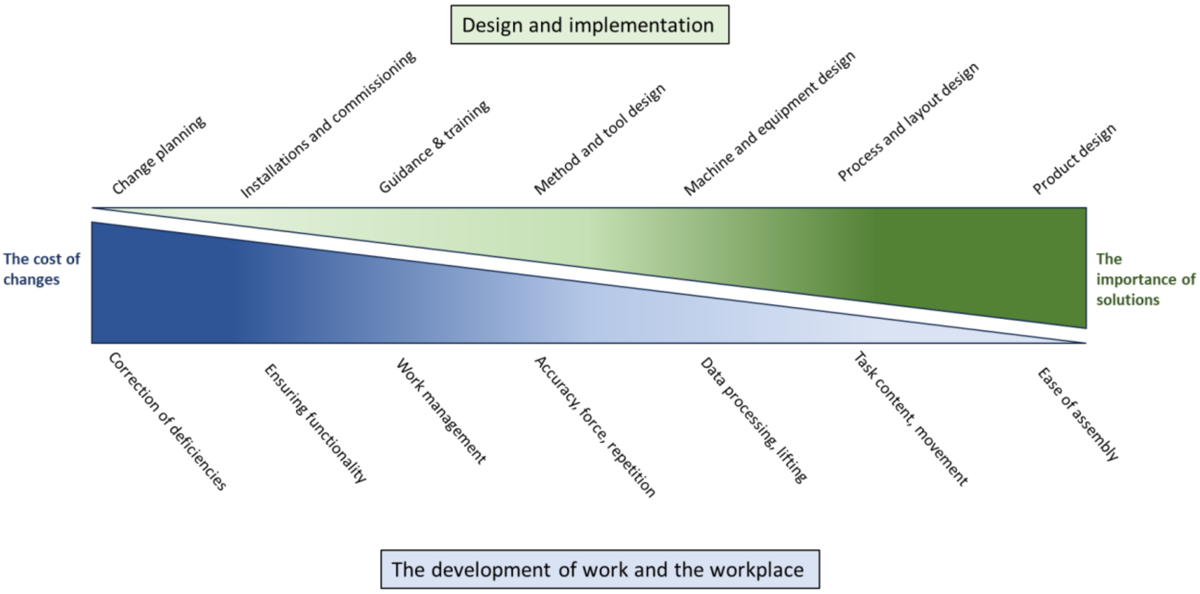


In designing technical systems, engineering professionals often prioritise the technical system itself, a trend reinforced by advancements in mechanisation and automation. This approach stems from viewing humans as both the weakest link and a costly factor. Consequently, humans are relegated to residual tasks rather than complete ones, as their necessity becomes apparent only during system planning. However, this contradicts the principle that humans should perform meaningful, complete tasks to fully utilise their abilities, with machines serving as efficient tools alongside them (Launis & Lehtelä, 2011, p. 292)

The ongoing development of production technologies and robotisation is unlikely to replace humans in production processes soon. Instead, humans will likely take on more operator-like roles, increasing both cognitive and physical load factors. This shift necessitates a deeper socio-technical understanding of organisational and personnel capabilities to utilise new technologies effectively. (Reiman & Suokko, 2020)

Launis & Lehtelä (2011) emphasise the significance of technical design phases and decision-making, which are directly correlated with change costs. As the design progresses, solutions build upon previous decisions, reducing the number of alternative options. Early-stage choices, often made by a few individuals with limited knowledge of the final usage context, are critical for human performance, such as manufacturing techniques and material handling methods. Corrective ergonomics, where deficiencies are addressed in nearly finished or deployed environments, often incurs high costs and implementation challenges. To mitigate this, ergonomics should be integrated into all design and development phases, as illustrated in Figure 39. This integration enables timely reactions and cost moderation. (pp. 293–294)

Figure 39 - The relationship between the importance of design solutions and the costs of changes (Adapted from Launis & Lehtelä, 2011, p. 293)



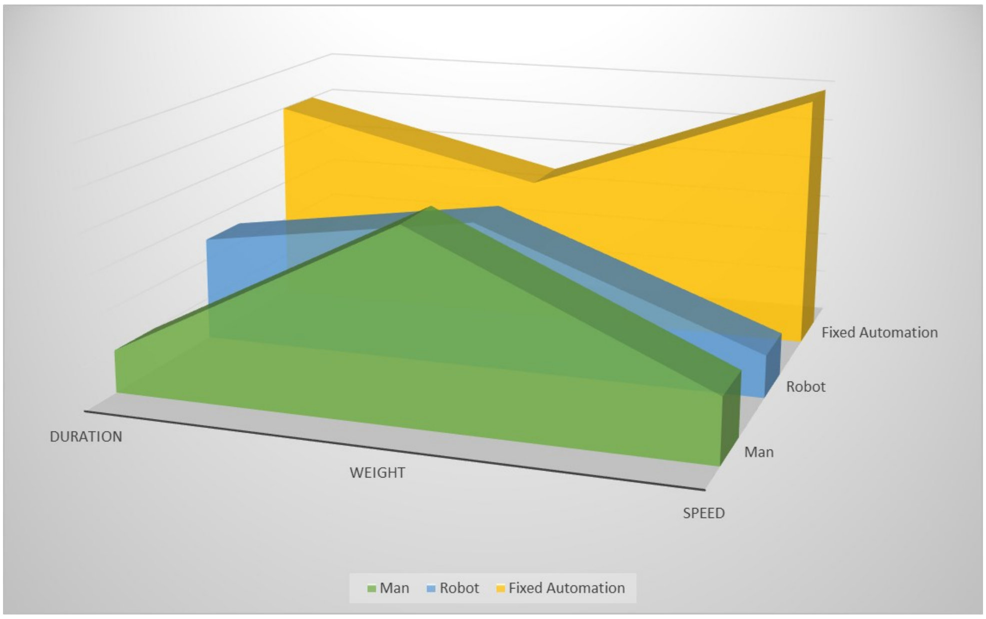
Reiman & Suokko (2020) analysed the impact of an ergonomics-based change project in a study published by The Finnish Association of Work Life Research (FAWORE). Their findings indicate that ergonomic process improvements enhance workplace well-being and productivity, with a short payback period due to reduced sick leave, fewer accidents, and associated cost savings. Increased production capacity further validates the project's success. The study highlights the effectiveness of a participatory approach, where employees actively contribute to shaping the changes. A designated ergonomic expert, authorised by management, played a key role in ensuring expertise was integrated throughout the process, enhancing both implementation and engagement. (pp. 184-186)

An unfavourable working environment can sometimes have a greater impact than economic factors, prompting the use of robots over manual labour. Humans, robots, and fixed automation each have their strengths depending on the weight of the workpiece and transfer distance. Figure 40 illustrates the capabilities of manpower-robotised and fixed automation solutions. While human operators may be faster, they lack durability. They can handle heavier loads with mechanical aids, but as weight increases, robotic and fixed automation solutions are more effective. Fixed automation excels in fast-paced operations due to its superior speed and durability. In analysing motion times for humans and robots with specific payloads in a semi-circular area from a human's shoulder, it can be concluded that:

- For carrying lightweight (under 1,13 kg) workpieces in a working area radius of 40 cm or less, humans are faster than robots.
- When the working exceeds 50cm, the difference is insignificant. With a greater radius than 70 cm, robots are faster than humans.
- The radius of the working area loses meaning when the weight of the workpiece is more than 10,5 kg. Beyond that, time increases in proportion to the increase in distance.
- The most favourable area for robot application is when a person's ideal working range is exceeded either by distance or weight.

(Colestock, 2004, pp. 23-25)

Figure 40 - Domains and capabilities of equipment (Adapted from Colestock, 2004, p. 24)



4.8 Initial process of developing a solution and successful implementation

Wilson (2019) states that the development process for robotic solutions is not a one-off research or ideation effort. The developed robot system uses several iterative steps to achieve the optimal outcome. The development and implementation of a robot system do not significantly differ from any major capital project. The main pitfalls to be avoided are related to a lack of understanding about the robot's capabilities, including what the robot can and cannot do, and how these limitations impact human workers. (pp. 103-104) Zamboni & Valente (2020) have listed the best features of humans and robots. They emphasise that a robot application should not imitate human skills. However, rather than that, the goal should be to identify key factors for the application and combine the best aspects of humans and robots within it. The list of best features of both is presented in Table 6. (p. 179)

Table 6 - Summary of advantages of human vs machine (Adapted from Zamboni & Valente, 2020, p. 179)

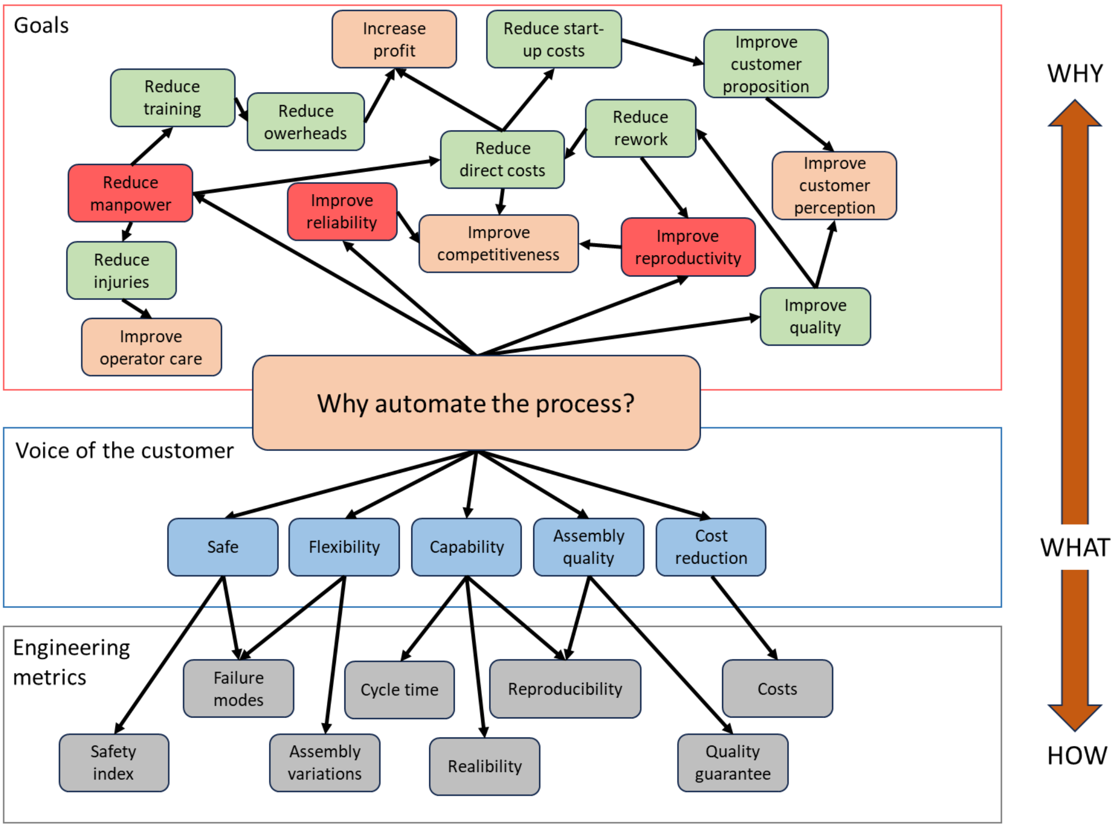
Human operator's advantages	**Artificial operator's advantages**
High dexterity, mobility & versatility, body strength/weight ratio, sensitivity for delicate tasks	High accuracy, speed and endurance, consistent production quality
Ability to learn rapidly, teach tasks, sense & apply tolerance compensation, and proactively make judgements	Ability to perform heavy and monotonous tasks

Problem-solving skills	Accurate sensing system
Naturally safe to work with	Immunity to diseases

In history, introducing robots into the process has been driven by the desire for a safer alternative to hazardous work for humans. The robot has, therefore, been implanted in a process similar to how humans do it. This approach is suitable for simple solutions. However, a better approach is to start planning the process from scratch, in which case introducing a robot into the process offers entirely new possibilities. (Bolmsjö, 2023, 8) Holamo et al. (2023) also state that the process by which the robot is being designed will change. The role of the human, as well as occupational safety, accuracy and repeatability in performing the task, will change. (p. 78)

A company investing in or researching robotics development possibilities needs to have a clear understanding of what is essential. A value graph, illustrated in Figure 41, can be used for this analysis phase, identifying factors by answering three primary questions: Why? What? How? With these questions, it can be identified why the system is needed or wanted, what value it brings to both the customer and the company itself and how the target will be achieved. Regarding the hows, quantitative metrics should be defined. (IET, 2018, pp. 19-20)

Figure 41 - Value graph (Adapted from IET, 2018, p. 20)



4.8.1 Stakeholders of the project

Several stakeholders, whose roles and tasks are outlined in Table 7, should be engaged from the outset and included in the planning process. Stakeholders refer to parties who will be involved in robotisation in one way or another, from its design to implementation and working with it or in its immediate vicinity. As Holamo et al. (2023) state, process knowledge is the starting point for a successful solution. The purpose of robotisation is to digitise the work previously done by humans, encompassing both practical skills and knowledge. Therefore, involving internal stakeholders is of paramount importance. It is also worth discussing external stakeholders with different system suppliers. Through them, you can gain insights into the development of processes while also mapping out possible references from system suppliers for your project. (pp. 78-80)

Table 7 - Stakeholders with roles (adapted from Holamo et al, 2023, p. 80; see also Wilson, 2019, p. 105)

Role	**Task in the project**

The user of the robot	This will affect the daily usage of the robot application, such as material feeding, working with jigs, and tool changing.
Representative of safety	Needed expertise since some of the requirements are based on laws. Role in risk assessment and security.
Director of production (or similar)	Strategy, image, costs, and benefits.
Designer of the system	Social skills: development and design according to active conversations. Target to avoid suspicions and ensure that opinions are allowed and heard.
Operator of the current process	To know all the details regarding the current process, operators are flexible in solving daily problems which may not be known at the managerial level. Future users of the robot application.

Asfahl (1993) emphasises the importance of a company's staff and their representatives as key stakeholders in robotisation projects. Their acceptance and input ensure commitment and help identify potential targets for automation. Blue-collar workers, who often possess more in-depth process knowledge than engineers or managers, play a crucial role in the successful implementation. Resistance may also arise from operational supervisors, who, despite being part of management, may feel threatened by automation due to labour displacement or the technical nature of new responsibilities. However, their manual process expertise remains invaluable. (pp. 237, 259)

Launis (2011) highlights that while participation and cooperation are widely accepted principles in working life development, their application in technology remains limited. Terms like participatory design and user-centred design share the core idea that end users are the best experts in their activities. Involving end users in planning their tasks, environments, and tools enhances efficiency, flexibility, and quality while improving work content, environments, and employee well-being. (pp. 306–307)

The level of participation can range from being a test subject to active design, where the end-user designs for themselves with the help of experts. Participation becomes more meaningful the more the end user can influence the solutions that affect them. At best, the end user's usage knowledge is transmitted to the designers and solutions, ensuring that the result is suitably demanding from the end user's perspective, both physically and mentally, and is considered in the design and implementation of the user interface, instructions, and training. (Launis, 2011, pp. 309-310)

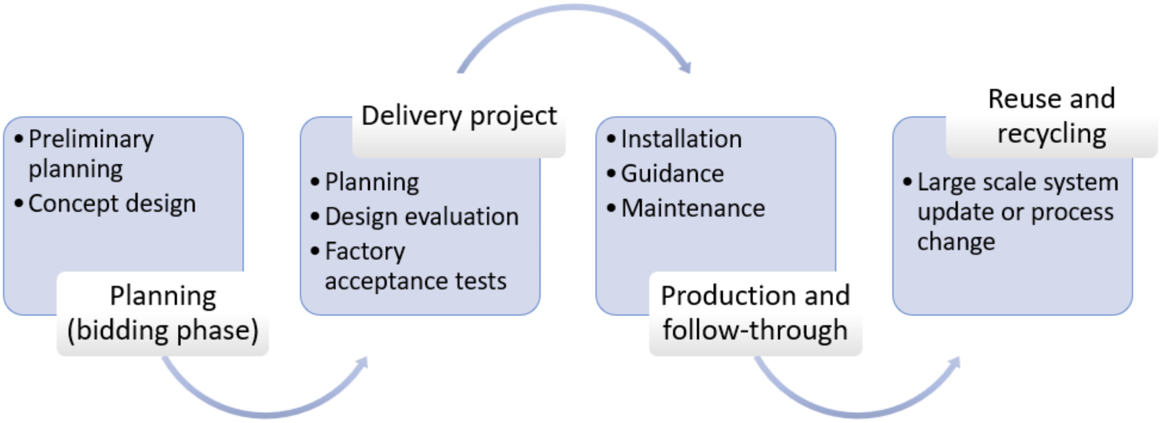
The best way to protect against problems in an automation project is to invest sufficient time, resources and expertise into the project as early as possible. Often, when a problem occurs, the root cause can be traced back to an earlier stage of the project. Investing in the early stages is also cost-effective, as the cost to fix the problem increases as the project progresses. (Wilson, 2019, p. 178)

4.8.2 Planning phase

Tarantino (2022) advises starting with one of the easiest applications, which does not have to be the highest volume or most expensive process. Common applications, such as machine tending or packing, will likely be conducted with standard tools, which allow the future usage of tooling to be utilised. At the same time, the personnel become familiar with the system, which enables possibilities to move towards more complex applications. Even with standard applications, the immediate benefits are evident in increased productivity and agility. (p. 326)

The design and implementation of a robotic system involve different phases, which are illustrated in Figure 42 and are interconnected. After each phase, you have the option to either return to the previous phase or end the project. This approach is worth considering when searching for and bidding on system suppliers. It is worth noting that there is no shortcut to success. This means that it is not a good idea to skip different phases for cost-saving or other reasons. In this case, there is a risk of overlooking some details that are only discovered during the factory acceptance test of the system. (Asfahl, 1993, p. 236) Even though each application design and integration for a robotic system is adapted to the case, requirements and equipment are based on the same or similar principles and components. The system integrator, a vendor that designs and builds the application with the robot(s) and supporting equipment and components into a fully functioning system, offers recommendations and alternative solutions according to the given requirements and limitations. The bidding phase is the phase that provides the opportunity to compare system integrators and select the most suitable vendor to conduct the project. (Blomsjö, 2023, p. 185)

Figure 42 - Robotics application implementation phases including the whole life cycle (Adapted from Holamo et al, 2023, p. 81; Asfahl, 1995, p. 236)



4.8.3 Preliminary planning

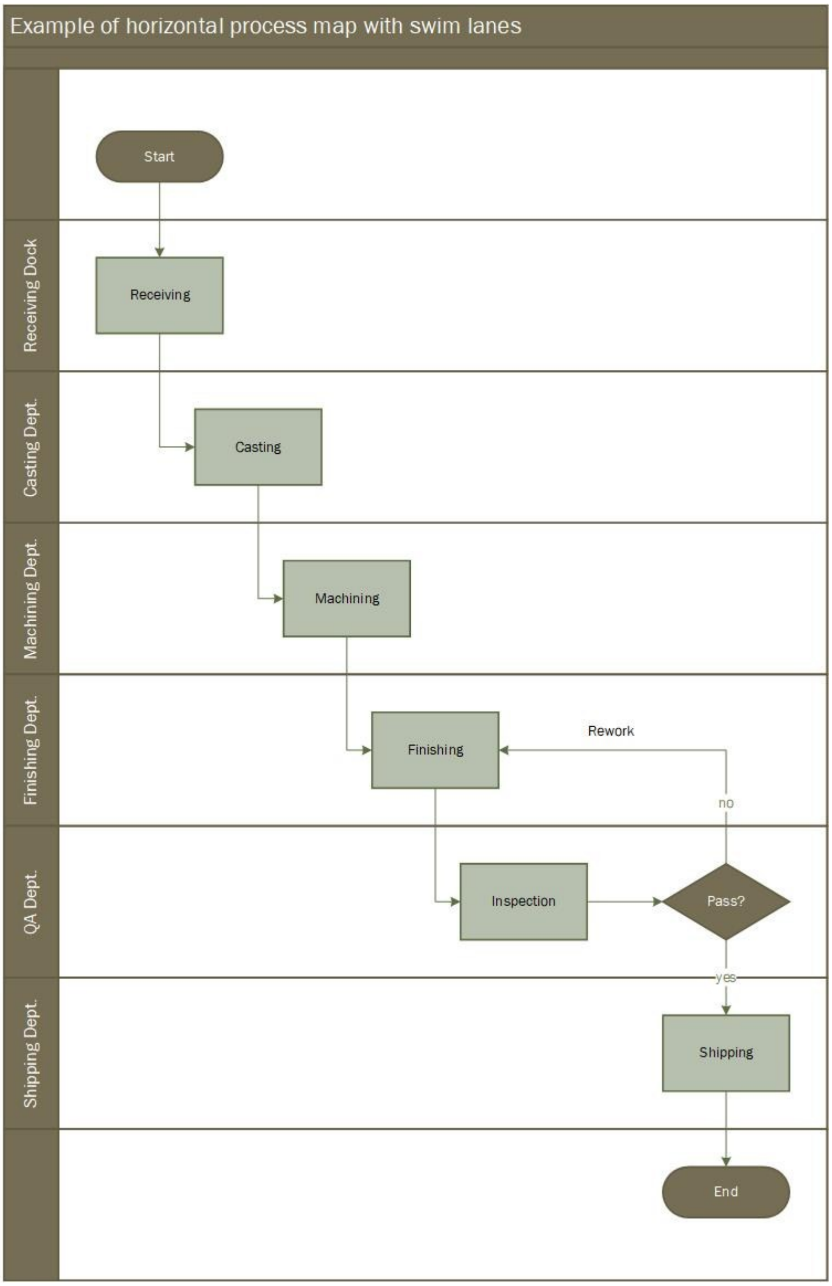
Everything begins with an understanding of the core of the robotisation project, i.e., the goal of why the project is being investigated. The motivation may be safety, customer satisfaction, strategic decisions, or the desire to be part of the robotisation wave. Next is to understand the current process, which requires more than just understanding basic process-specific figures. The fundamental analysis involves mapping the current state of the process, including the materials used, tools and machines, process steps, components to be fed, and the materials to be produced. If drawings or other documentation related to these are available, it is also worth familiarising yourself with them. One action is to verify that work instructions correspond to the actual activity, so, for example, component fit-up problems. This fundamental analysis and the documentation derived from it should be conducted independently within the company, as it supports the consideration of improving the process efficiency and its potential for utilising robotics. The target state can be described at a high level, while the process itself must be described in precise detail. However, in the target state, it is beneficial to consider the needs, boundary conditions, and future requirements, as well as the potential location of cell and material flows. If the target level includes a specific cost level, cycle time or flexibility, these should also be described. (Holamo et al, 2023, p. 83; Wilson, 2019, pp. 104-106)

Without knowing the current process, its steps and its owners, it is not easy to improve a process. The most widely used tool in continuous improvement projects is a process map, also known as a flowchart. Frank and Lillian Gilbreth introduced this in the early twentieth century. This tool helps describe and visualise the process steps and their owners. A process is constituted by several steps, events and operations, which are picturised in a flow. Besides a common understanding of the process, key inputs and outputs, as well as value-added and non-value-added steps, can be identified. An example of a process map is shown in Figure 43. (Tarantino, 2022, p. 59)

The best-known way to understand the process, create process maps, and comprehend what and how things are done is to perform genchi genbutsu. This term comes from Japan and is one of the principles of Toyota's Production System (TPS). Genchi genbutsu means going on-site to see the real situation to understand it. The term "Gemba" is a widely recognised term that originates from the combination of "genchi" (meaning the actual place) and "genbutsu" (meaning actual materials or products). These two things mean roughly the same thing, i.e. the information and what is reported must be based on a thorough knowledge of all the elements of the real situation. It is essential to understand the details of the actual process, i.e., to see behind the tables and numbers. (Liker, 2004, p. 224)

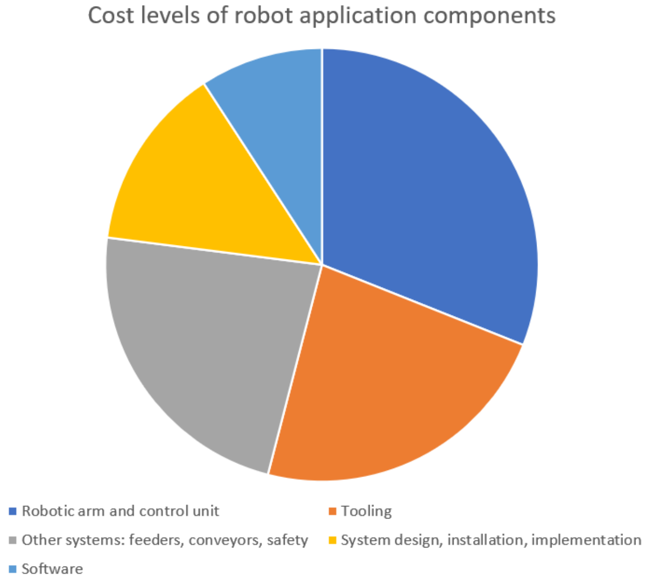
Several types of process maps can be used to gather detailed information on the process. It may be helpful to start by describing the processes using a high-level process map that only shows the core steps. One of this kind of process map is SIPOC, which can be used to describe both the current and target state and associate stakeholders with the process. As a next level, describe the process using cross-functional process maps with swim lanes. The process map visually explains the process, showing participants and their dependencies. Adding the sequences of process steps and decision points refines the process map, allowing for a clearer view of the actual process as it unfolds. One step above such a detailed process map is the value stream map, which shows material and information flows in addition to the process flow. In contrast, the value stream map includes metrics such as lead and cycle times, as well as actual work time during the processes depicted. In contrast, a standard cross-functional process map shows only actual steps with decision points. (Tarantino, 2022, pp. 60-65)

Figure 43 - Example of process map (Adapted from Tarantino, 2022, p. 59)



Holamo et al. (2023) provide a rough estimate of the costs of different robotic system components in Figure 44. The figure is indicative, as the cost of various components depends on the application and its solutions. (p. 81)

Figure 44 - Cost levels of robot application components (Adapted from Holamo et al., 2023, p. 81)



When asked, "Cost estimation of robot assembly application with screwing 5Nm torque, payload 10kg, reach 70cm, three screwing per item, target cycle time 1 unit per minute. The assembly should consist of the robot and control units, tooling, fixtures, system design, installation, and software. Comparison against traditional industrial robots and cobots. Material feeding is done on trays with cobots and feeders/conveyors on a traditional industrial robot." Copilot responds to the answers seen in Table 8. (Microsoft, 2025)

Table 8 - Cost comparison between traditional industrial robot and collaborative robot (Microsoft, 2025)

Component	Traditional Industrial Robot	Collaborative Robot (Cobot)
Robot and Control Unit	€30 000 – €50 000	€20 000 – €40 000
Tooling (End-of-Arm Tool)	€5 000 – €15 000	€5 000 – €15 000
Fixtures	€5 000 – €10 000	€3 000 – €8 000
System Design & Installation	€20 000 – €40 000	€15 000 – €30 000
Software	€5 000 – €10 000	€5 000 – €10 000
Material Feeding	Feeders/Conveyors: €10 000 – €30 000	Trays: €3 000 – €8 000
TOTAL	**€75 000 – €155 000**	**€51 000 - €111 000**

Wilson (2019) defines target cycle time as the available time with the required level of performance [total time available] / [required output]. In practice, it is advisable to use a productivity coefficient in the target cycle time calculation, which provides a conservative approach to calculating productivity. Initially, the suggested factor could be as low as 85% (meaning the output is 85% of the maximum), which can be increased as planning and understanding of the solution develop. (p. 106) Holamo et al. (2023) urge self-reliant information gathering related to understanding the nature and feasibility of different robot types and where costs and savings come from. The temptation to overplan at a detailed level for tooling or part feeding should be avoided in the early stages. The primary goal is to enhance understanding of possibilities, including which characteristics address the desired problems and in what steps and order they must be taken to achieve the preferred solution. (p. 7)

A tool to understand the technical challenges and prioritise the most critical functions is illustrated in Table 9. During the project's conceptual design and specification process, more information and knowledge are gathered, and more opportunities become visible. It may be tempting to widen the scope; therefore, it is recommended to continuously review the project's assessed goals in relation to specific opportunities and challenges. These should be reviewed against the project goal, and value-added features and priorities should be defined. Prioritisation should be based on qualitative terms, and questioning should provide answers regarding why and how an operation is automated, as well as what the expected results from the automation are. The system integrator will answer in quantitative and technical terms. Based on the most value-adding functions, the technical challenges may be identified. The approach can be investigative, involving the examination of options or challenges based on selected core functions. For example, technical difficulties can be related to processing a component that requires redesigning to improve its grip, as well as identifying the payload and workspace boundary for robot motions. The analysis can be extended to understand the impacts on, for example, product design. This step requires both understanding the current process and analysing the future process. (Blomsjö, 2023, pp. 192; 197-198; see also IET, 2018, p. 2)

Table 9 - Identifying priorities and challenges of functionalities and operations (Adapted from Blomsjö, 2023, p. 198; see also IET, 2018, p. 22)

Operation type	**Specific function**	**Priority (P) – Challenge (C)**
Handling and manipulation	Feed part	P
	Hold and seize	P
	Move tool	P
	Position and orient parts	
	…..	

Measure and monitor	Verify condition	P
	Support control	P, C
	In-process control	P
	…..	
Process operations	Integrated control	P, C
	…..	
Automatic reconfiguration	Automatic tool changer	C
	Fixture, controlled	C
	…..	

4.8.4 Concept design

Based on the first research phase and the target state, the system supplier develops a concept design, i.e., a general proposal of what the root system could be like and how the desired goal can be achieved. From the concept, the design should identify solution principles for the system's most essential functions, space utilisation, safety solutions, material flows, as well as potential limitations. (Holamo et al., 2023, pp. 83-85) At this point, Asfahl (1993) points out the vital consideration of being cautious. It may be tempting to leap into a project by buying a robot. Almost always, problems in automation projects are underestimated. Therefore, proactive planning and simulation minimise the consequences of potential pitfalls. (p. 236)

Things can go in the wrong direction from the project conception and bidding phase. The customer may have too high expectations related to pricing, delivery, and an overall unrealistic business case. These factors can be related to the customer's inexperience in robot projects. This may cause a false impression about the price and short delivery time. A factor may be the high demand for state-of-the-art or immature technology, even if the target state can be achieved with current technology. (Wilson, 2019, p. 179)

Simulation or actual testing is one part of concept development to test the first draft of the proposed solution. Concept design relies heavily on the system integrator's experience. Concept development is an iterative process, meaning that several designs and options should and can be created and tested before a decision is made. It is an excellent opportunity to run what-if scenarios for alternative solutions, equipment and resources. One good idea is to use 3D CAD tools to visualise the layout and workflow. Virtual commissioning can be carried out through simulation. This step allows all the programs and control parameters to be tested before applying them to the real world. The goal is to gain confidence that the desired results are achievable. If a real-life test is conducted, it should be as realistic as possible, meaning that actual equipment, components and fixtures are used, or alternative options may be available. The final purpose of any testing or simulation is to reduce the risk in a project (Wilson, 2019, pp. 126-128; IET, 2018, pp. 25-26)

For testing and learning purposes, some universities have robotics centres where it is possible to try out and test potential project applications without purchasing any hardware. These arrangements minimise risk while providing practical experience for college and university students. The test will utilise the company's components and central tools, as well as possible fasteners and other essential supplies. Robots can also be rented through commercial entities for a short test period, such as two months, to verify the application's functionality in a practical environment. (Asfahl, 1993, p. 253) One of these possibilities is offered by the Technology Centre TechVilla and HAMK within the robotics experiment project HELPPI (HELPPI, n.d.).

One pitfall to avoid in the supplier selection phase is the system supplier's unrealistic expectations on cost, timescale and capability. Suppose the system supplier was keen to win the business, which may have led the system supplier to place unrealistic expectations. To tackle this, multiple quotes should be obtained and compared with previous experience, as well as through visits to reference sites. It is also worth investigating and investing in the relationship with system suppliers. The relationship does not have to be friendly, but it must be open, fair and based on mutual understanding applied on both sides. (Wilson, 2019, p. 180)

4.8.5 Delivery project

When the supplier of the system is selected, the concept design will be turned into a feasible solution. Each step of the delivery project must be included in a planning phase and documented, as different stages can progress either in parallel, sequentially, or partially overlapping, depending on the interdependencies among the various phases. These interdependencies must be identified in advance. More detailed phases may include mechanical design, electrical design, safety system design, detailed process design, user interface design, basic programs, and connections to upper-level systems. (Holamo et al., 2023, pp. 85-86) The created document remains in effect during the design phase until it is frozen to initiate the procurement and construction phases. (IET, 2018, p. 26)

Blömsjö (2023) emphasises the importance of risk assessment, particularly in terms of conducting it from different perspectives. Typically, the system integrator provides an assessment from a technical perspective based on the expertise gained from previously implemented systems. The end-user of the system possesses the necessary knowledge and expertise related to the operations and manufacturing processes. Finally, it is also essential to conduct a comprehensive risk assessment from a business perspective, encompassing the entire project and its associated challenges related to implementing the robot system. In order of importance and based on EU law, the supplier of a robotic system must be able to produce a system that can be CE-marked. This requirement is placed directly on the responsibility of the system supplier, which prioritises the risk assessment carried out by the system supplier over other risk assessments. (pp. 186-188)

The implementation time offered by the vendors is clarified at this stage. Wilson (2019) includes delivery time analysis as part of supplier selection, requiring suppliers to commit to a specific time window even before the contract is signed. Cross-checking should be considered to confirm that the short-term delivery time vendors do not see issues raised by long-term delivery time vendors. Ultimately, it is optimal to create a realistic delivery plan that accounts for unforeseen problems. (p. 165) Holamo et al. (2023) approach the implementation timing from different angles. After the technical design, it is agreed that all the required components and tools to be used in the application are known. From this point forward, potential effects on the implementation timeline can be observed. Longer delivery times are required for self-made system components, such as tooling, compared to standardised solutions. If it can be agreed upon in the concept design phase which components will be used, the procurement process relating to those components can be initiated. The early start of the procurement process comes with a downside, as changes that cannot be made or will be more costly. (p. 87)

During the project, problems may occur in project planning, management or execution. Commitment from the management level should guarantee the necessary resources, time, and the internal parties' commitment to the project. For example, suppose production managers do not support the project or the change it causes. In that case, it has implications for both implementation and the commitment of operational personnel to learning new things. Clearly defined roles and responsibilities are, of course, essential in a project, but their importance increases as interfaces are built. The more suppliers are involved in a project, the more critical the roles and responsibilities become. A solution may be to appoint one lead supplier who has overall responsibility and project management, and with whom all other suppliers are in contact from a contractual perspective. (Wilson, 2019, pp. 180-181)

Both Holamo et al. (2023) and Wilson (2019) agree on the timing of FAT (factory acceptance test), which should be identified and scheduled as early as possible, even in the bidding phase. This is due to the nature of FAT, which will be conducted only as agreed. The purpose of FAT is to test the system as ready as possible, prove to the customer that the system is functional, and obtain permission from the customer for the delivery of the assembly. Not everything can necessarily be tested at the supplier's premises. At this point, there should be no rush with the delivery, as it is much easier and cheaper for a vendor to fix problems at its premises in the event of failures in FAT. What can be tested must be verified and measured in a non-sensory way. The completed and approved FAT is documented, which serves all parties related to the project. (p. 87; pp. 166, 172)

4.8.6 Production and follow-through

After acceptance of FAT, the SAT (site acceptance test) is followed. This is the time when the workforce can see and gain experience with the new automation solution. The objective is to achieve full production at the end of this period. The SAT will begin with an extended time period in case the FAT could not be fully completed. At this point, personnel training can begin. It is the system supplier's responsibility to ensure that the necessary training is provided to guarantee the proper operation and maintenance of the system. Usually, the lack of training appears when the system supplier has left the site. After the extended FAT, or in the case that FAT has already been conducted on the vendor's premises, testing will continue with production testing to confirm the system's planned functionality. The SAT may include interfaces to be established between the new automation system and the current production. This may cause some issues and delays in production. The timeline for the whole SAT may take from hours to months, depending on the scope of the system. (Holamo et al., 2023, p. 88; Wilson, 2019, pp. 166, 173, 182)

A completed and customer-approved SAT is an essential milestone in the delivery project. The supplier hands the system over to the customer, and the operation of the system is now the customer's responsibility. Depending on the project, a backup plan to provide some assistance may be negotiated. The purpose of the backup assistance is to provide guidance and aid in the operation and maintenance of the system for new operators and maintenance personnel. It is not about operating the system. Backup assistance should be considered when the system is complex or the customer's existing expertise is relatively low. After the SAT has been completed, the final documentation can be finalised, as there may be issues raised by the SAT that will lead to modifications to the documentation. The customer may request, and it might be beneficial, to have an incomplete version of the documentation. With this, the information contained may be reviewed earlier, but it also provides some backup once the vendor has left the site. (Wilson, 2019, pp. 173-174)

In general, testing milestones are essential from both a liability and financial perspective. Invoicing for the system delivery may be agreed upon on a 30/60/10 principle, with 30% due at the time of order, 60% due upon acceptance of FAT, and 10% due upon acceptance of SAT. Therefore, the procedures for the FAT and SAT should be defined and agreed upon, along with specific measures related to quality, consistency, cycle time, and unattended operation for predefined cycles. Any possible overperformance should be highlighted, and performance under the set targets should be investigated. The delivery time of the robot system varies depending on the type and complexity of the system. Typically, delivery time takes place around three to nine months after ordering the system. If the delivery project is late or is at risk of being late, the system supplier may be tempted to accelerate the project by running design and manufacture in parallel. If the consequences are known and the risk is minimal, this approach may be acceptable. Otherwise, it can be dangerous since changes in design may affect manufacturing, which is already underway. (Blömsjö, 2023, p. 203; Wilson, 2019, pp. 182-183)

The need for maintenance and other post-installation support should be discussed during the specification phase. Key considerations include warranties, both preventive and reactive maintenance, and spare parts. Even though the system integrator may be able to supply a preventive maintenance program, it is also essential to consider what can be done by the company itself and where external specialist resources are needed and utilised. The system supplier can be assisted in the beginning, but eventually be left behind. Much relies on the system supplier to convince and make people understand the importance of maintenance if the system is to be used as designed. (IET, 2018, p. 28; see also Wilson, 2019, p. 182)

Typically, the warranty period is 1 year, but in some cases, it may be extended to 2 to 3 years. At the same time, the type and the level of support should be negotiated. The more critical the system is for the customer, the more complete the service package should be. The full package may include 24-hour support and guaranteed response times for call-outs. The required service level can be partly dependent on the company's personnel and their capability to perform maintenance and troubleshooting. (Wilson, 2019, pp. 175, 178)

4.8.7 Reuse, system updates and recycling

After the vendor has met the set targets during installation, future development and adjustments are left to the company. Bigger changes are needed either for a component change, a new product, or to carry out a completely different task. Minor adjustments may be necessary to implement a throughput incentive and increase capacity. These steps are more straightforward to deliver if your personnel are committed to learning and operating with the system during the project. The company's willingness and ability to perform adjustments and further developmental actions once again highlight the importance of personnel involvement. Changes and reconfiguration may be implemented using the same steps as those taken in the original project. (IET, 2018, p. 28; see also Wilson, 2019, p. 174)

5 Research Methods

5.1 Defining the case

Defining a development task is different from defining a research problem. In a research problem, a question such as "What affects?" or "Why?" is often asked, while the development task defines precisely what the development aims to achieve. Typically, the developmental task is defined as creating or modelling, for example, a concrete product or an operating method. Product modelling involves considering the product image, quality, purpose of use, competitors, and market share. In process modelling, on the other hand, the flow of the entire process and its parts are determined with work steps and justifications. This also includes the controls and adjustments for each work step, as well as feedback systems such as problem statements and developmental proposals. (Ojasalo et al., 2015, p. 32)

The more precisely the development task is defined, the more likely the task will succeed. In terms of the success of the developmental work, the determination of the developmental task must not remain on too general a level. In such cases, practical activities will also remain without support. Metrics should be clear and measurable to enable the evaluation of the development task's results. For example, quantitative measures can include changes in throughput, the number of quality defects, and the time spent per unit produced. Qualitative metrics are suitable for measuring the quality experienced by customers and the satisfaction and well-being of personnel. (Ojasalo et al., 2015, p. 33)

In research-oriented work, research questions form the core of the research structure, while evaluation or development questions are used in connection with development activities. The meaning and nature of the questions depend on the research perspective. In terms of qualitative research methods, the questions can be general and evolve with the production and analysis of the material, in contrast to quantitative research methods, where the research questions guide the entire process more directly and are more precisely defined in advance. The relationship between the researcher and the research object is also viewed differently, depending on the research orientation. For some research orientations, the relationship is highlighted as separate, while in others, the interaction is the central starting point of knowledge and information. (Toikko & Rantanen, 2009, p. 117-118)

In this thesis, the starting point was the following questions:

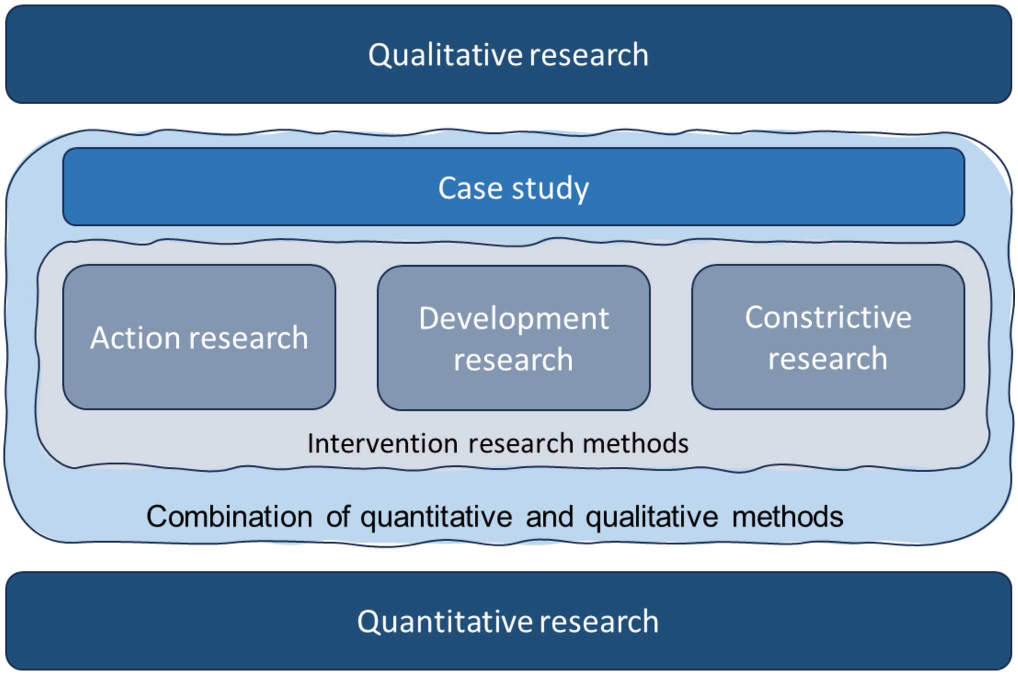
1. Can a collaborative robot be utilised in the 3PL warehouse operations?
2. If yes,
    a. In which process(es) would it be utilised, and how would the process(es) be operated after collaborative robot implementation?
    b. What would be the outcome related to cost savings and benefits?
    c. Would it be possible to get more volume if the process could be automated?
3. If no,
    a. Why can it not be utilised?
    b. What are the barriers to implementing a collaborative robot?
    c. What is needed to make it possible?

5.2 Selection of research strategy

Choosing an approach to a development task is not a matter of selecting a method or technique. The approach is related to the goal of the development work. The development task determines which approach is most suitable for the chosen development work. There are several approaches which partially overlap, and the same methods can be applied to different techniques. (Ojasalo et al., 2015, p. 36-37) The simplest division is made into qualitative and quantitative methods, but other divisions partially overlap and conflict depending on the perspective of the review. There is a heated debate about the quality and scientific validity of the research extracts. Some consider quantitative research to be more applied research because it utilises and is based on existing theories, which in turn are based on qualitative research. For that reason, others think that qualitative research is the only right one because it only produces the new knowledge required by science. In business, the quantitative method is given priority because it enables companies to develop their operations and make informed decisions. However, all research is based on qualitative research, which has been used to create an understanding of phenomena in practical life. (Kananen, 2020, p. 39-40) Puusa & Juuti (2020) state that the main difference is that quantitative research assumes the object is independent of the theory and the researcher. After all, the research approach has only an instrumental value, no intrinsic values or goals.

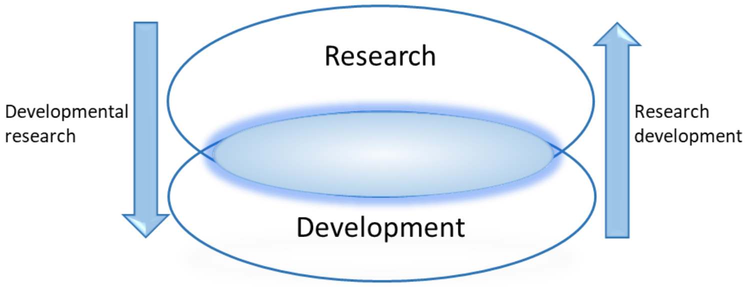
Different research methods can be combined based on the specific situation and need. The combination of quantitative and qualitative approaches includes case studies, action research, and constructive research methods, as illustrated in Figure 45. These three methods are collectively known as intervention research methods, as they involve active intervention to drive change. (Kananen, 2020, p. 40)

Figure 45 - Grouping of research methods (Adapted from Kananen, 2020, p. 39)



Between research and development arises a concept known as research and development. This is a general concept, loosely illustrated in Figure 46, that describes an aspect of the relationship between research activities and developmental activities. This relationship can be approached from either a research or a development perspective. Developmental research addresses traditional research questions to inform the development of concrete activities. In this context, knowledge is produced during the development process. In research development, practical problems and questions guide the production of knowledge. The focus here is on development actions that set definite limits to the scope of the study. Research is subordinate to development activities. (Toikko & Rantanen, 2009, p. 21-22)

Figure 46 - Crosspoint of research and development (Adapted from Toikko & Rantanen, 2020, p. 21)



Valli (2018) notes that in Finland, the action research approach has become closely associated with research and development. This approach has been embraced as a reference framework for the thesis in universities of applied sciences (p. 185). Rea Sahlberg (2021) writes in her Pro Graduation thesis about the differences between master's degrees conducted in universities and those undertaken in universities of applied sciences. According to her study, master's degrees at universities are based more on research methodology studies, while in universities of applied sciences, approaches focus on development, leadership and strategic thinking. An orientation towards practicality and the world of work is especially valued in master's degree studies at universities of applied sciences, with their basic purpose being to meet real workplace needs. (pp. 11, 64)

Action research combines investigation and modification of practices, merging research and development rather than following traditional theory-driven methods. It seeks practical, applicable knowledge to improve real-world processes, addressing how to enhance functionality, solve problems, and achieve desired outcomes. This approach prioritises active participation, focusing on internal investigation and implementing meaningful change rather than just observation. (Valli, 2018, pp. 182–186) Unlike traditional research, neutrality is not required - collaboration and action run alongside the study, involving practical workers as active participants. Researchers' observations are integral, shaping their understanding of the subject under investigation. The researcher initiates change, fostering engagement for optimal outcomes. (Heikkinen et al., 2008, p. 21) Participatory methods enable researchers to access tacit knowledge, expertise, and experience, thereby broadening their perspectives beyond official materials. Standard techniques include questionnaires, interviews, and observations, with the latter being particularly effective. (Ojasalo et al., 2018, p. 61)

Case study research is ideal for developing proposals and ideas, focusing on a specific process, job, service, or product within its real operational environment. This method provides an in-depth understanding rather than broad statistical generalisation, considering local, temporal, and social factors. Case studies begin with a defined case rather than a theory and progress according to research goals. The chosen case may be standard or unique, requiring the researcher to familiarise themselves with the subject before identifying development tasks. As research unfolds, objectives may shift, leading to adjustments in the development focus. (Ojasalo et al., 2018, pp. 52–54)

Constructive research focuses on developing practical solutions such as models, metrics, or plans based on existing research. Unlike pure innovation, it integrates theoretical knowledge with empirical findings to refine or create entirely new solutions. It aims to solve real-world problems, connecting development to established theory while ensuring practical relevance. New structures are evaluated through practical application. Constructive research invents solutions rather than merely discovering them. It involves planning, modelling, implementation, and testing, with input from stakeholders at all organisational levels. The functionality of the developed solution must be proven, which may sometimes require additional evaluation in research and development projects. This research approach is convenient, resembling innovation and service design. Like action research, it seeks to transform organisational practices, emphasising problem-solving and deriving theoretical insights from practical work. (Ojasalo et al., 2015, pp. 65–66; Lukka, 2001)

The constructive research approach allows for flexible methodologies, including observations, group discussions, surveys, and interviews (Ojasalo et al., 2015, p. 67). Evaluation can be market-oriented, tested within one organisation, multiple organisations, or through comparative analysis. The assessment can also be organisational, using a Proof of Concept (PoC) to validate feasibility. PoCs are quick, cost-effective trials that often require minimal resources. They validate the feasibility of early-stage ideas by providing concrete evidence and user feedback, enabling iterative development. PoCs help determine whether a concept should be continued or terminated. (Ojasalo et al., 2015, p. 68; Kuure et al., 2019, pp. 620-625; see also Gillis, 2023)

A comparison table of different research options is described in Table 10. The goal of this research is to conduct developmental research that employs applied methods. This means that the research builds upon existing knowledge, generating new issues for practical application.

In action research, development work is typically conducted in collaboration with those who perform the actual work. (Heikkinen et al., 2008, p. 21.) In constructive research, the output that solves the problem is constructed with a developed new way of working or a model. In a case study, one learns about one case and produces detailed information about its development. (Ojasalo et al., 2015, pp. 52, 65) In a trial culture, a new operating method or product is tested quickly with only a little planning (HUMAK). In service design, a new service is designed in a customer-oriented manner (Tuulaniemi 2011).

Table 10 - Classification of features of different research methods (Adapted from Kananen 2020, 41)

	The relationship between theory and practice	The purpose of the study	The role of the researcher	Data collection methods	Research questions
Research methods					
Qualitative research	Induction	Comprehension	External participant	Perception, interview, documents	Themes, interviews, open questions
Quantitative research	Deduction	Generalisation Divination	Outside observer	Queries	Structured questions
Combination of qualitative and quantitative methods					
Case study	Abduction with the interaction of theory and practice	Comprehension	External observer	A mix of different methods	Mostly open questions
Intervention methods					
Action research	Abduction	Change Influence	Active actor	Mostly qualitative	Mostly open questions
Development research	Abduction	Change	External participant	A mix of different methods	Mostly open questions
Constructive research	Abduction	Change	Actor	Mostly qualitative	Mostly open questions

This study adopts a qualitative research approach, emphasising the reality and subjectivity of gathered knowledge. A key characteristic of qualitative research is its focus on examining the research object through the perspectives of participants and the researcher's interaction. Rather than a traditional investigation, this thesis aims to develop practical solutions that address real-world needs. The research strategy combines intervention methods, including action research, which seeks practical insights to improve processes; case studies that analyse specific, predefined processes rather than theories; and constructive research, which integrates theoretical knowledge with empirical findings to refine or create new solutions. The developed solution can be evaluated at an organisational level using a Proof of Concept (PoC) approach. Across all methods, the researcher plays an active role, engaging directly rather than remaining an external observer.

5.3 Data collection and analysis

Constructivist and action research methods rely on the researcher's activity, intending to develop community action. The set target is impossible to accomplish if the researcher is not interested in either the subject or the environment where the development action is carried out, and which the result of this action will affect. Heikkinen et al. (2008, p. 94) also emphasise that the researcher must be prepared to collaborate with the community to advance development. The researcher has a unique community participating in the change process, eliminating the need for a traditional separate test or control group. Trust between the researcher and the community enables the collection of necessary materials and ensures their reliability.

When investigating automation or robotic possibilities, the initial reaction from operational personnel is often fear of job displacement. Will the robot take my job? People are needed in the required data collection phase, especially when comparing the automated solution to the current manual solution.

The primary data collection methods are participatory observation, interviews conducted during observation, and research diaries. Data can also be collected through other written materials, such as memos, reports, and emails. Heikkinen et al. (2008) note that since what occurs during the process is itself the object of research, these materials cannot stand alone because the process cannot be clarified through them. It should also be noted that observation is always a subjective activity. Phenomena appear differently to different people depending on the observer. Experience and presumptions guide the researcher in making observations and recording them. (p. 104)

As an observer, the researcher is simultaneously involved and detached. The degree of participation varies at different stages and as the research process progresses. In action research, the researcher aims to influence the community's activities and behaviours. It is natural for the researcher to be part of the community in generating change and experiencing its impact, while also observing the process and activities as an external participant. If necessary, the researcher could, for example, stop the process and interview participants about their experiences. In this way, the researcher can clarify their findings and seek answers to research problems. (Heikkinen et al., 2008, p. 109)

Interviews can be conducted individually and in groups and can take many different forms, which are listed as follows:

- Form interview: The structure and the order in which the questions are to be asked are predefined.
- Theme interview: The interview moves along with a predefined theme or themes.
- Open interview: The phenomenon to be discussed is pre-selected, and the interviewer proceeds to build a discussion around the phenomenon on the interviewee's terms.

(Heikkinen et al., 2008, p. 110)

A research diary was written during the research. The primary purpose of keeping a diary is to serve as a supportive tool in situations where, for example, recording a conversation is impossible. The diary helps to structure thoughts and record observations from, for example, spontaneous interviews and general observation rounds.

Volume data was collected from two sources. The primary data source for volume and BOM information was the Nordic Data Warehouse, a solution developed and maintained by DHL Supply Chain Nordics' IT department. Another data source was a locally built SharePoint form for operations, which included hourly or other additional information regarding the production of work orders. These two data sources were combined into a self-built Power BI report, where calculations and visualisations of the data were performed.

In addition to data collection and analysis, the completion of the kits was observed through work studies and work phase research, which included work time studies. During these studies, operations coordinators, supervisors and operators were interviewed. Based on these, the aim was also to consider areas for process development regardless of possible robot investment. Data and calculations for the analyses were compiled and illustrated in self-made Excel tables.

6 Investigation of possibilities for Robotic Arm solution

Although there is a slight difference between kitting and settlement services, in this thesis, 'kitting' is used as a term encompassing both packing and assembly types of kits.

DHL Supply Chain has experts specialising in robotics who act as both supplier surveyors and solution developers for these solutions. At the beginning of the research phase, the possibility of support was inquired about in the case of DSC FI. The request concerned the possibility of assisting with the test and providing general guidance during the project. During the study, the team was unable to help due to other agreed-upon customer projects in Europe. The research and pilot were conducted locally with the help of integrators and vendors, as well as an independent study.

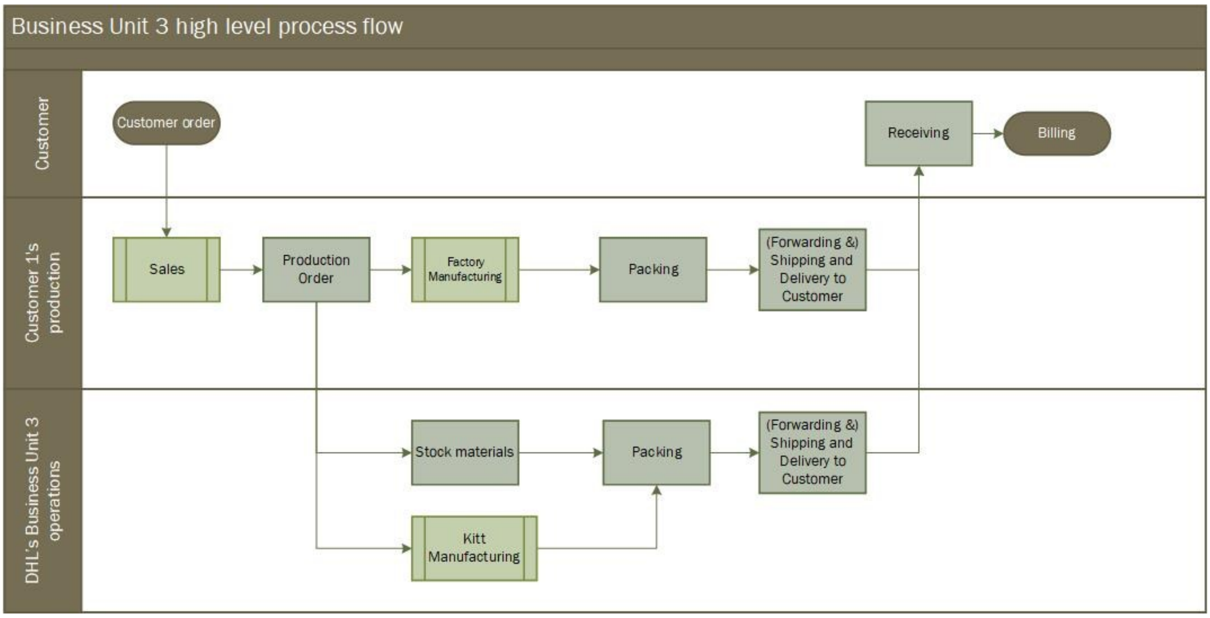
The investigation was done by mapping suitable kit configurations in terms of both data and the parts to be processed. For data, the focus is on volume and the number of components to be processed. When examining volume, both the total volume over a more extended period and the volume per production batch are considered. The purpose of this analysis was to gain a clear understanding of which kits are suitable for further research and to identify potential opportunities for automation. The aim was to find kits that were as standardised as possible, meaning that no significant variations are expected and that the volume would remain stable going forward. Additionally, the evaluation involved analysing the replicability of this kit with other kits of the same type that may be used in the future. By this, the suitability of robots for high-mix low-volume environments would be evaluated.

All volume and BOM data used in the investigation are stored in DHL's WMS system. Production time data and comparisons are based on observations and conducted time analysis. The time used for data gathering, analysis, and calculations spans from January 2022 to December 2023.

6.1 Current kitting services in the warehouse

The investigation was conducted on DHL premises, where one of DHL Supply Chain Finland's major customers is located. The customer, Customer 1, has operations that are roughly divided into two separate units, corresponding to the customer's business divisions. These units are Business Unit 1 and Business Unit 2 (hereafter referred to as BU1 and BU2), which both operations include standard order picking and delivery, as well as VAS operations. The third kitting process, Business Unit 3 (hereafter referred to as BU3), is technically part of BU1 but serves both BU1 and BU2. The BU3 is supporting Customer 1's product sales. When a customer purchases a product from Customer 1, which is produced in Customer 1's facilities, they may also order accessories to complete the system they have purchased. High-level process flow of BU3 is illustrated in Figure 47.

Figure 47 – Business Unit 3 process flow



In all kitting operations, the MTO and MTS production strategies are used. The delivery time window for MTO kits varies from same-day deliveries to delivery times of several days, weeks or even months. Occasionally, MTO kits can be produced according to standard order picking timeframes of 3 to 6 hours from receipt of the order; however, these instances are rare and require urgent attention. MTS kits are produced mainly in pre-agreed quantities and with pre-agreed minimum stock levels, where DHL is responsible for maintaining the MTS kit's stock balance within the agreed-upon upper and lower limits. Work orders are created partially automatically, utilising DHL's warehouse management system (WMS), but for some Kit types, manual control is currently required from both the customer and DHL. In every work order, the operations coordinator fine-adjusts the daily work balance according to the necessary volume and available resources. A high-level process map is illustrated in Figure 48.

Figure 48 - High-level process map of MTS and MTO processes

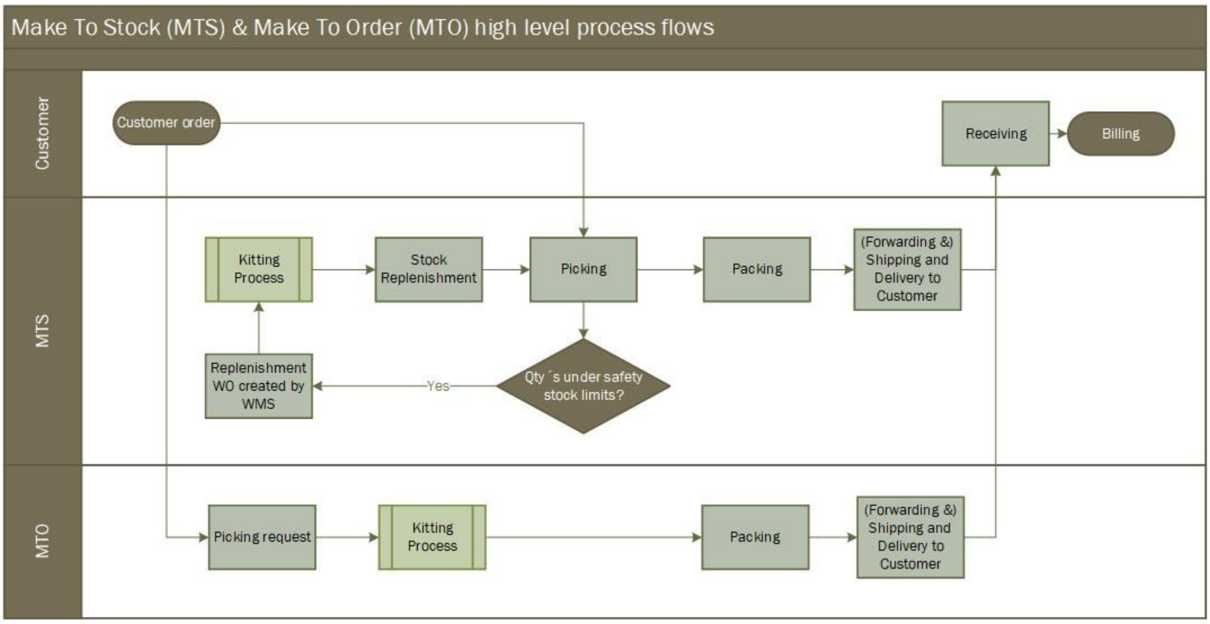


Table 11 lists key variables regarding workstations and the necessary equipment. Calibrated power tools are primarily screwdrivers with preset torque for various types of assembly kits. The used IT systems column refers to the work that needs to be done at some point in the actual kit manufacturing process. All actions related to picking and storing processes are done with DHL's WMS. The use of Customer 1's IT system is needed for releasing production orders, printing documents, and tracing. Tracing is a one-phase kitting process in which used components are attached to a specific work order for quality assurance reasons. This enables, in case of quality issues, tracking back to the element used, the supplier, and the supplier's delivery and production batches.

Table 11 - Summary of workstation requirements

Kit process	Work type	Station quantity	ESD area	Calibrated power tools	IT-systems	Components delivered with
BU2, location #1	Packing	2	Yes	No	DHL & Customer 1	Pallet, trolley
BU2, location #2	Packing	3	No	No	DHL	Pallet
BU1	Assembly	5	No	Yes	DHL & Customer 1	Pallet
BU1	Packing	3	No	No	DHL & Customer 1	Pallet
BU3	Packing	8	Yes	No	DHL & Customer 1	Pallet

A number of workstations allocated to the process do not necessarily contribute to the allocated FTEs and volume, nor the floor plan reserved for the operations. Kitting operations are carried out physically in different locations in the warehouse. Related to the current setup, and in the case of implementing a robotic solution for operations, it would require either purchasing two separate applications or centralising operations into one. A separate project would be necessary to consolidate all kitting processes into a single area.

6.2 Volume analyses

The production volume analysis covers both 2022 and 2023, with the difference that the selection of the kit to be piloted was based on 2022 volumes. The total payback calculations and evaluation cover the entire volume data range.

The different kitting processes were analysed to determine the current kitting production volumes. For each process, the total kitting volume, the quantity of different kits produced, and the number of various components processed in the manufacturing of kits were mapped. As seen in Figure 49, even BU3 comprises the most significant number of workstations that produce the fewest kits in terms of quantity. This is explained by the fact that an order for one kit involves a significant amount of work that is not directly related to the packing of the kit. In addition, special care must be taken when packaging the kits, for example, to ensure the sea freight capability is secure. Figure 49 highlights a variation in annual and monthly production volumes. As a 3PL service provider, DHL is highly dependent on the success of its customers.

During the review period, the overall production volume of BU2 packing kits decreased from 2022 to 2023. At the same time, the volume of the BU1 assembly kits slightly increased. BU3 and BU1 packing volumes remain constant.

Figure 49 - Quantity of produced kits by the process

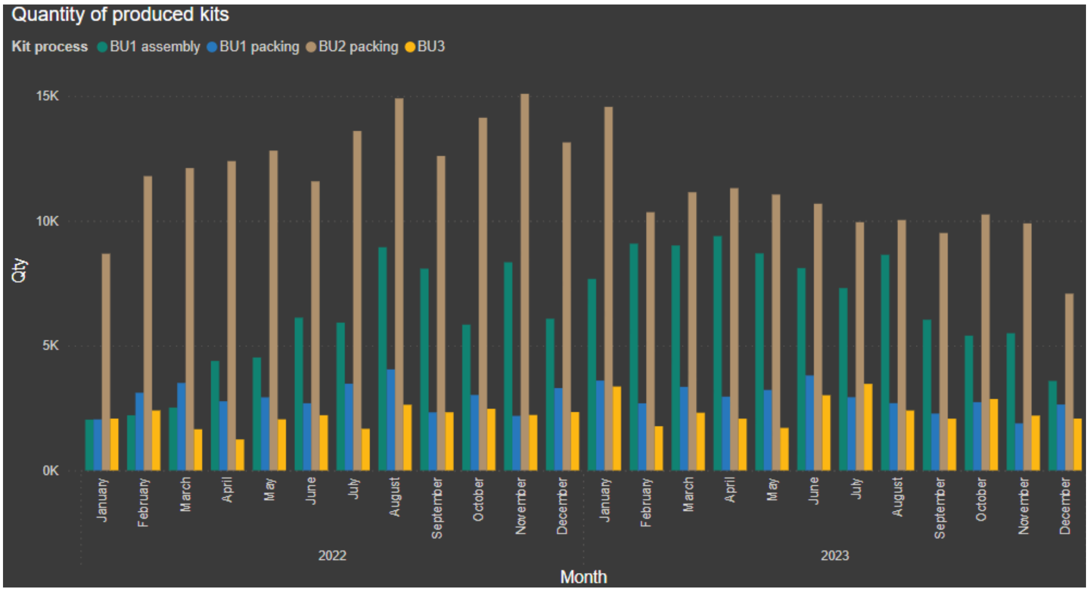


Figure 50 illustrates the distinct count of different kits produced. Although the overall volume fluctuates from month to month, with some drops and highs in production volume, the number of various kits remains relatively stable. While the highest monthly production volume occurs in the BU2 packing process, there is also the highest number of variations of kits produced. Another essential remark concerns the variations in the BU1 assembly kits. It remains stable despite the changes in production volumes, and the number of different variations is limited to a relatively low level.

Figure 50 - Distinct count of produced kits

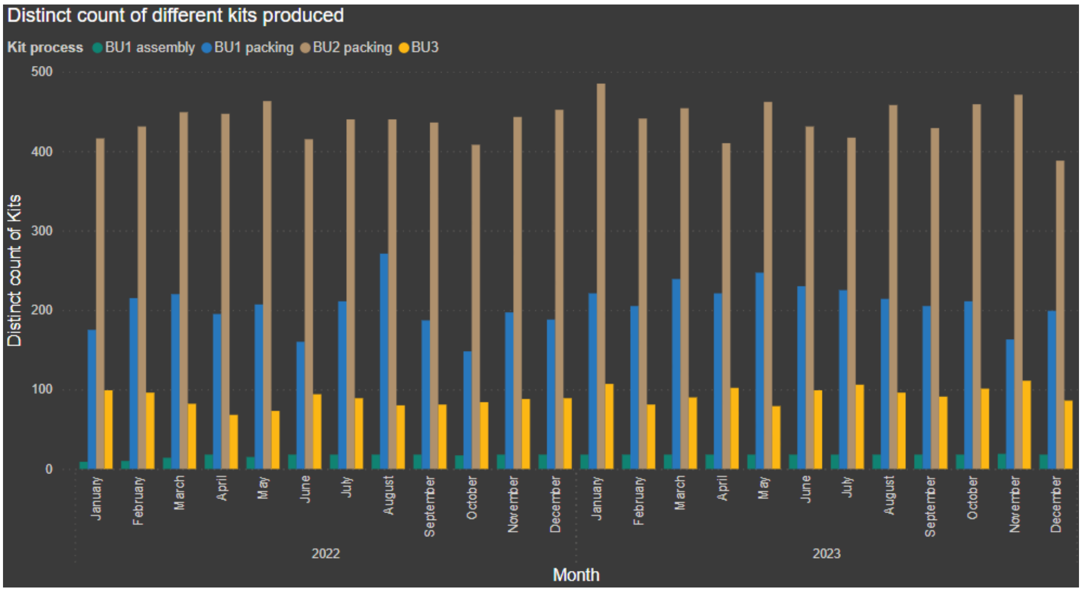
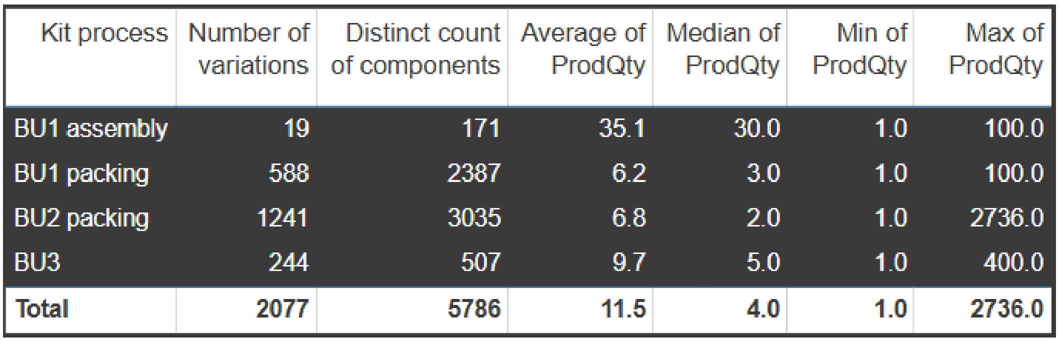


Table 12 summarises the number of kit variations produced during the entire review period for different kit processes, the number of different components used in the kits, and the average, median, minimum and maximum production quantities. BU1 assembly stands out clearly in terms of the number of different variations and the components used. A clear difference can be found in the range between the smallest and largest batch sizes, considering the average and median production batch sizes.

Table 12 - Summary table of kit processes



Kit process	Number of variations	Distinct count of components	Average of ProdQty	Median of ProdQty	Min of ProdQty	Max of ProdQty
BU1 assembly	19	171	35.1	30.0	1.0	100.0
BU1 packing	588	2387	6.2	3.0	1.0	100.0
BU2 packing	1241	3035	6.8	2.0	1.0	2736.0
BU3	244	507	9.7	5.0	1.0	400.0
Total	**2077**	**5786**	**11.5**	**4.0**	**1.0**	**2736.0**

Due to the lack of authentic master data for SKUs (components and produced kits), the weight, dimensions, adhesion, and general suitability of the components for robotics processing were first assessed through observation. If the kit and its components seemed suitable for more detailed research, the necessary data were measured after the observation. This phase was laborious and became one of the future requirements, allowing for the study, at least in theory, of the suitability of both robotic and other automation-related solutions.

Sickness absences related to musculoskeletal disorders have been the most significant cause of absences in all but one year between 2018 and 2024 in DSC FI. The data provided by occupational healthcare cannot be categorised by team or job function. Therefore, the results of the data must be evaluated at the country level of DSC FI. The collected data is shown in Table 13.

Table 13 - Sickness absences due to musculoskeletal disorders

2024	**2023**	**2022**	**2021**	**2020**	**2019**	**2018**
rank	rank	rank	rank	rank	rank	rank
#1	#1	#2	#1	#1	#1	#1

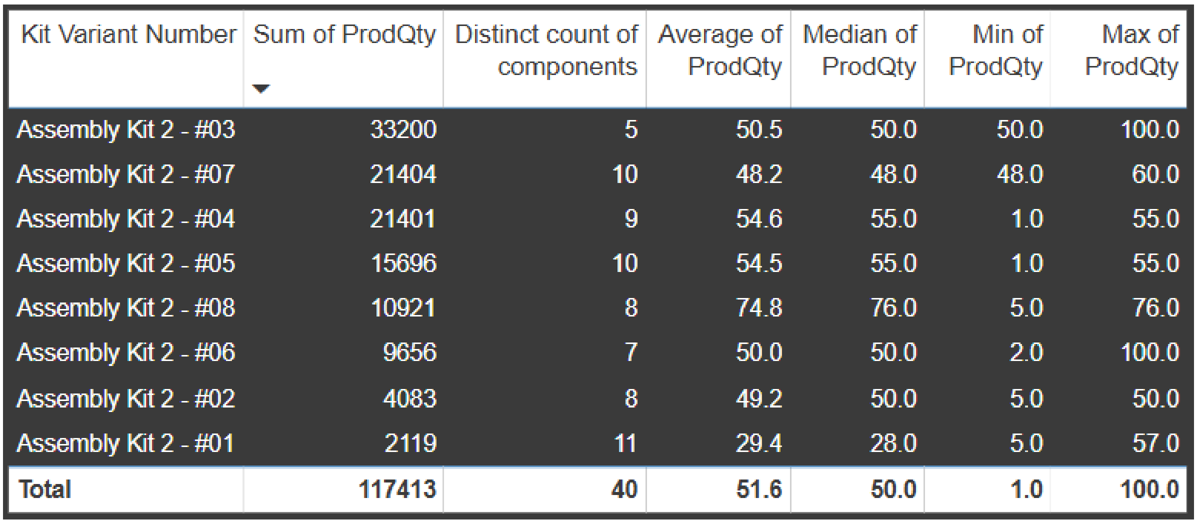
From the data combined from Figure 51 and Table 14, the first Gemba walk in the warehouse kitting operations was conducted. Based on these walks, BU3 and BU1 packing were excluded from the scope. The overall operational volume is below that of the BU2 packing and BU1 assembly operations. For BU1 packing and BU3 operations, the operational volume, combined with the number of different kit variations, did not offer an attractive production series. Observations made during the Gemba walk and verified afterwards with data revealed that the components used in BU3 contained a mixed amount and variation of different components. In BU1 packing, single components are individually packaged by at least wrapping them in paper. This increased the need to use two different tools. An observation was also made regarding packaging, where components were placed freely in the box, provided they fit and did not move around within the box. From the pilot's perspective and considering the robotised packing case from the DHL Supply Chain European warehouse as an example, a kit with pre-defined slots for components was seen as a target solution.

6.3 Case Business Unit 1: assembly

BU1 assembly kits consist of two product families that require assembly activities. Assembly Kit 1 assemblies are a product family that consists of a metal and side plate assembly, along with several smaller metal parts, to form a single unit. In addition, the kits come with a separate parts bag that the final assembler of the delivered device needs to assemble the device and make it operational. Appendix 1 shows one variation of the Assembly Kit 1. It is worth noting that one kit consists of several screws, some of which are difficult to reach, located near the side wall, while others are centrally positioned, providing sufficient operational space for screwing. Assembly Kit 2 is a fan that comes with a mounting plate for later installation and a fan finger guard. Both sides of the Assembly Kit 2 and the palletising pattern can be seen in Appendix 2. The actual assembly work for both series is done by screwing in using pre-calibrated screwdrivers to a specific torque.

Assembly Kit 2 is homogeneous in terms of the number of components used in each kit, as shown in Table 14. Assembly Kit 2 consists of two sides, with one side containing the fan component, a metal plate and a finger guard, and the other side containing a small metal clip where the fan's power cord is connected. In some versions, the finger guard is fitted with small pieces of plastic to dampen resonance. The number of fan components varies between models, from one to three, with the single-fan version being the most common. The bottom three variations in Table 13 are two and three-fan configurations. Secondly, the Assembly Kit 2 is manufactured according to the MTS strategy, which is noticeable when comparing the production batch sizes between the average and median production quantities. In this kit model, DHL is responsible for maintaining the inventory level according to the pre-agreed replenishment batch.

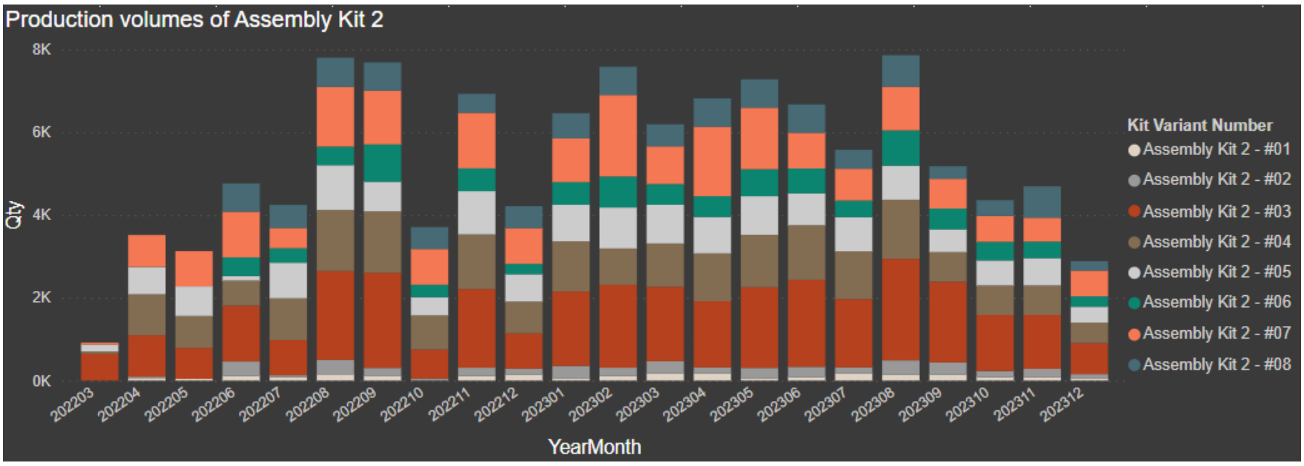
Table 14 – Assembly Kit 2 production volume breakdown



Kit Variant Number	Sum of ProdQty	Distinct count of components	Average of ProdQty	Median of ProdQty	Min of ProdQty	Max of ProdQty
Assembly Kit 2 - #03	33200	5	50.5	50.0	50.0	100.0
Assembly Kit 2 - #07	21404	10	48.2	48.0	48.0	60.0
Assembly Kit 2 - #04	21401	9	54.6	55.0	1.0	55.0
Assembly Kit 2 - #05	15696	10	54.5	55.0	1.0	55.0
Assembly Kit 2 - #08	10921	8	74.8	76.0	5.0	76.0
Assembly Kit 2 - #06	9656	7	50.0	50.0	2.0	100.0
Assembly Kit 2 - #02	4083	8	49.2	50.0	5.0	50.0
Assembly Kit 2 - #01	2119	11	29.4	28.0	5.0	57.0
Total	**117413**	**40**	**51.6**	**50.0**	**1.0**	**100.0**

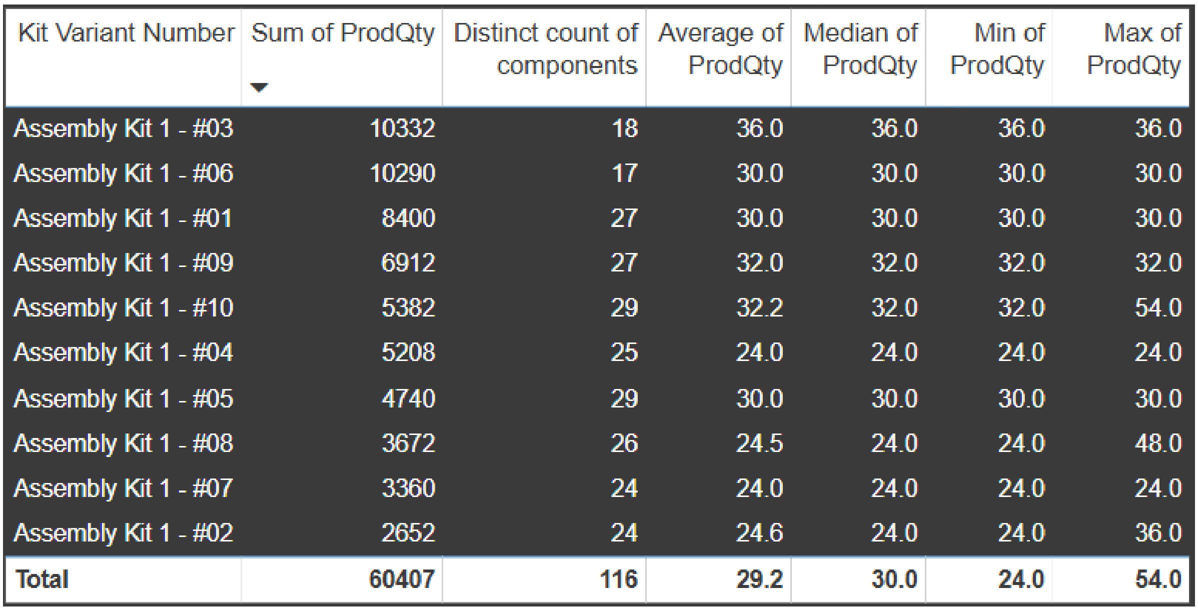
From Figure 51, the low production volume in early 2022 is evident. The production of the Assembly Kit 2 series is relatively new in DHL's production, which Customer 1 has entrusted to DHL. Volumes have increased since the beginning, but overall volumes vary by up to a third from month to month. The shares of different Assembly Kit 2 variations have remained consistent from month to month.

Figure 51 – Assembly Kit 2 production volumes



The Assembly Kit 1 product structure, as shown in Table 15, is relatively homogeneous in terms of the number of different components used in a kit. Although the number of different components is larger compared to Assembly Kit 2, only a part is installed in the product itself. The remaining parts, which, depending on the variant, are between 13 and 15 individual components, are packed in a separate bag. Two Assembly Kit 1 assemblies differ from one another in terms of the number of components. The reason behind this is in the individual parts bag delivered with the kit. For the other model, the part bag does not exist, and for the other, it is delivered pre-packed to DHL on behalf of the vendor selected by Customer 1.

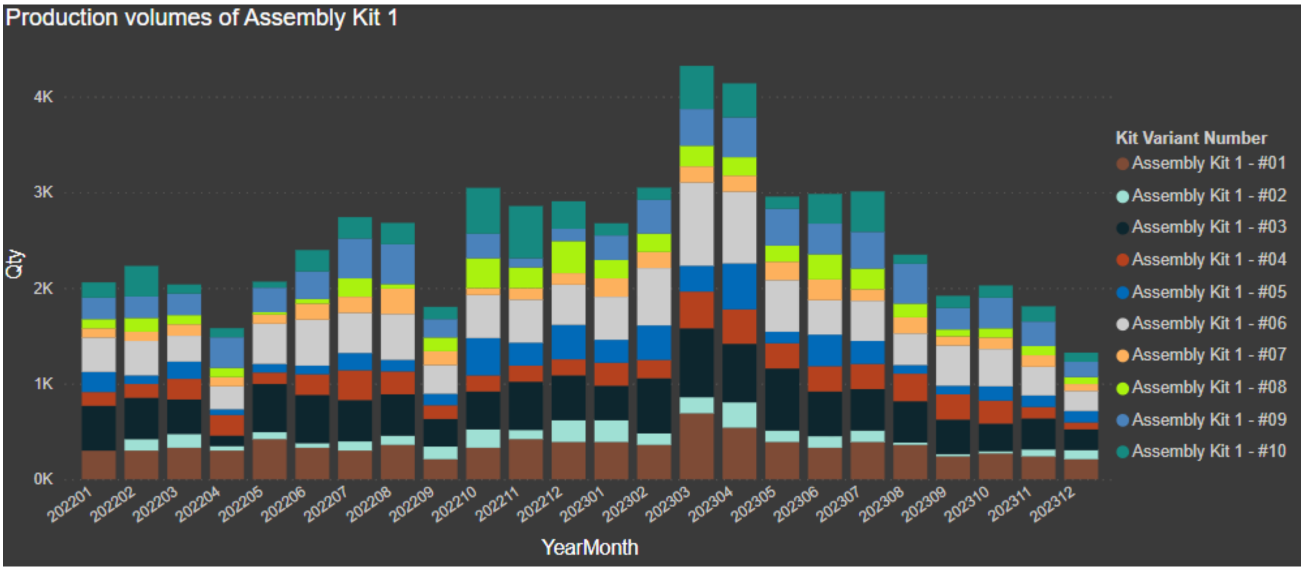
Table 15 – Assembly Kit 1 production breakdown



Kit Variant Number	Sum of ProdQty ▼	Distinct count of components	Average of ProdQty	Median of ProdQty	Min of ProdQty	Max of ProdQty
Assembly Kit 1 - #03	10332	18	36.0	36.0	36.0	36.0
Assembly Kit 1 - #06	10290	17	30.0	30.0	30.0	30.0
Assembly Kit 1 - #01	8400	27	30.0	30.0	30.0	30.0
Assembly Kit 1 - #09	6912	27	32.0	32.0	32.0	32.0
Assembly Kit 1 - #10	5382	29	32.2	32.0	32.0	54.0
Assembly Kit 1 - #04	5208	25	24.0	24.0	24.0	24.0
Assembly Kit 1 - #05	4740	29	30.0	30.0	30.0	30.0
Assembly Kit 1 - #08	3672	26	24.5	24.0	24.0	48.0
Assembly Kit 1 - #07	3360	24	24.0	24.0	24.0	24.0
Assembly Kit 1 - #02	2652	24	24.6	24.0	24.0	36.0
Total	**60407**	**116**	**29.2**	**30.0**	**24.0**	**54.0**

In Figure 52, the production volumes of Assembly Kit 1 are depicted. Production volume remains stable throughout the review period, with a few exceptions, including both volume peaks and drops. There are no dramatic changes in the share of different variations, although some variations do exist.

Figure 52 – Assembly Kit 1 kit production volumes



Gemba walks for BU1 assembly kits, both internally and with visiting integrators, highlighted the difficulty of Assembly Kit 1. The jig used for the Assembly Kit 1 assembly was more complex than the one used for the Assembly Kit 2 assembly. In addition, arranging the metal parts so that the holes of the three parts were aligned was sometimes tricky, even for the operator. An experienced operator was able to line up the screws and secure them, while a less experienced operator had to spend significantly more time to complete the task successfully. Alternatively, the separate part bags included in the assembly task were monotonous in appearance and fit the four Ds criteria for robotised work steps. Assembly Kit 1 is also packed into cartons before palletising.

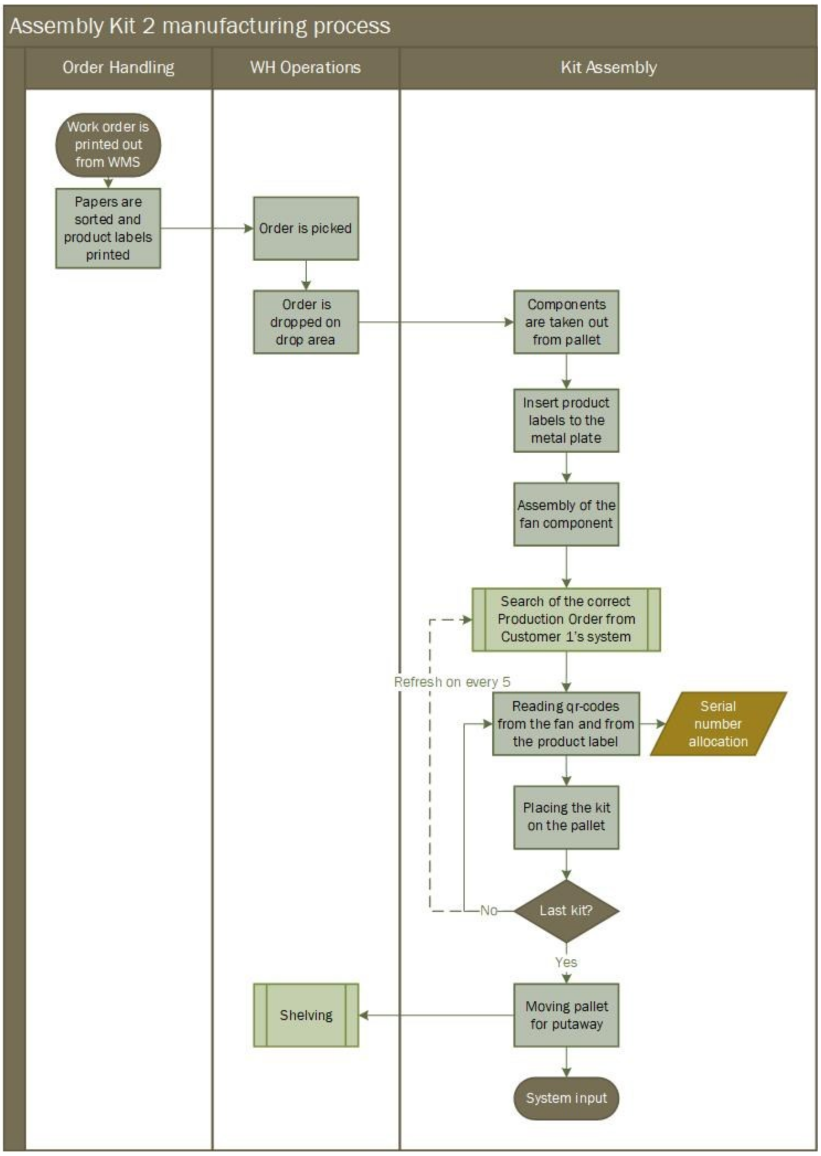
The Assembly Kit 2 was chosen as a pilot project because it was considered easier to build a pilot around it. The reason for the selection was mainly due to the screwing phase, where the screws in the fan casings were quite freely accessible without obstacles. For the protective housings and outside of this thesis, both the bagging of the components and the packaging of the completed kit phases were examined for later evaluation of robotics.

6.3.1 Process description

Assembly Kit 2 is produced with the MTS strategy. When the lower stock limit is reached, DHL WMS creates a Work Order with a pre-agreed production quantity per variation. Operations coordinators print out the work order from DHL's WMS and fine-adjust the date of manufacturing in line with pre-agreed delivery times. At the same time, the necessary product labels are printed out. When a work order is set for production, a picking request is submitted to the warehouse operations to initiate the picking process. Picked components are delivered on the pallet to the drop-down area next to the assembly stations.

The Assembly Kit 2 assembly process is illustrated in Figure 53. The kitting manufacturing operator collects the pallet from the drop-down area and unloads components onto the table. Fans are assembled utilising a jig and calibrated power tool. The components to be installed are stacked on top of each other in the installation jig in the following order (from bottom to top): fan, mounting plate and finger guard. The jig's function is to hold the fan and mounting plate in place during screwing. The size and number of screws depend on the fan model. The different Assembly Kit 2 variations feature their respective fan models, and various fan suppliers may employ different mounting methods. This means that a batch of a kit with a single work order may contain two types of fans, each with a different mounting method. The mounting process is influenced by both the location of the screws and the torque required for them. Additionally, depending on the fan model, the screwed assembly must be turned over and a small metal clip screwed onto the fan, to which the fan cable is attached. The assembled kit is moved to the table.

Figure 53 – Assembly Kit 2 assembly process chart



When everything is assembled, the next step is to label a small product label on the fan mounting plate. The product label is a small QR code that contains the product information and a pre-generated serial number. A separate label must be attached to each fan kit being assembled.

Before placing the fans into the pallet, each Assembly Kit 2 needs to be traced. Tracing is a task that involves scanning both the QR code on the mounting plate and the QR code on the fan component. For this, Customer 1's software is required to combine the two scanned QR codes. The correct production order is retrieved, and QR codes are read. The tracing needs to be done for each produced unit. After the reading, the assembled kit can be placed on the pallet.

When a work order is finished, and all produced kits are placed on the pallet, the pallet is moved to the ready-made area, and the required system inputs are made.

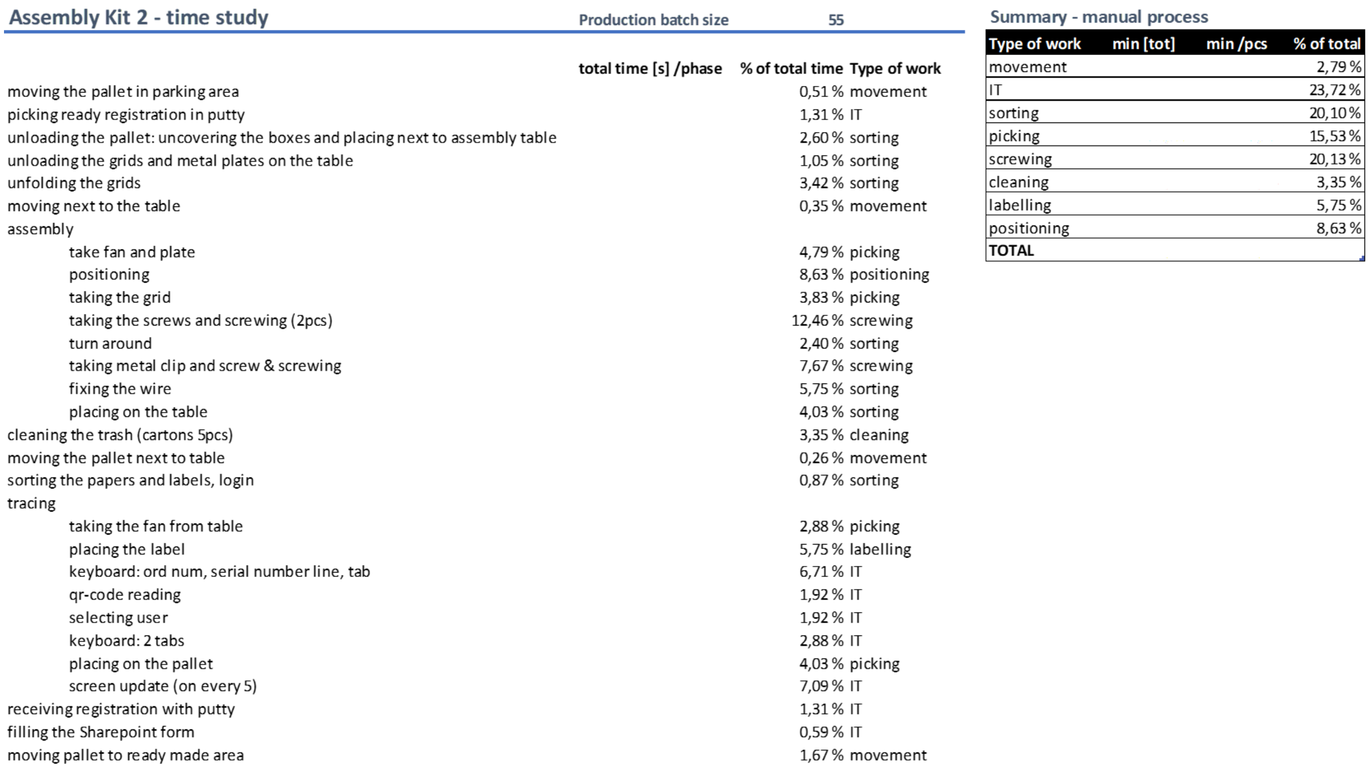
6.3.2 Time study

The selected variation for Assembly Kit 2 was variation #05. There were clear reasons to choose this variation for deeper analysis and the pilot. From the production summary table (Table 14) presented earlier, it can be observed that the selected kit represents the top 4 in production volumes. It is a one-fan assembly variation, which is the majority, and it is similar to all the top 4 kits except for the kit with the most significant volume during the review period. By these factors, the analyses cover almost half of the total production volume.

Work steps were written, and a time study was conducted to determine the order in which the operator assembled the kit. Occasionally, the kit can be assembled in pairs, allowing one operator to start assembly work immediately after dismantling the components. In contrast, the other operator performs general work steps and begins tracing and palletising the assemblies. By working in pairs, the throughput time can be reduced to almost half of the time spent working individually. This analysis was carried out as individual work.

The detailed work phases and a summary of the types of work conducted are presented in Table 16. The actual screwing and related work steps, such as removing screws from the dish, account for approximately one-fifth of the total working time. The other time-consuming phases are arranging the parts, working with computer systems, and picking-type activity. Work phases included a lot of sorting and pick-and-place operations, as well as moving components or ready-made parts. Time-consuming phases related to IT work included keyboard and mouse work, as well as system-related slowness. Since the production batch quantities are standard for each variation, the palletising pattern is standard for each variation. As a remark, the time used in the assembly and tracing phases is measured from the whole batch as the operator manufactured it. Single-time usage of work steps inside the assembly and tracing phases was observed randomly, rather than tracking the time of each manufactured unit, where the individual work phase times are proportioned to correspond to the time used to produce the entire set.

Table 16 – Assembly Kit 2 time study



Assembly Kit 2 - time study Production batch size 55

	total time [s] /phase	% of total time	Type of work
moving the pallet in parking area		0,51 %	movement
picking ready registration in putty		1,31 %	IT
unloading the pallet: uncovering the boxes and placing next to assembly table		2,60 %	sorting
unloading the grids and metal plates on the table		1,05 %	sorting
unfolding the grids		3,42 %	sorting
moving next to the table		0,35 %	movement
assembly			
take fan and plate		4,79 %	picking
positioning		8,63 %	positioning
taking the grid		3,83 %	picking
taking the screws and screwing (2pcs)		12,46 %	screwing
turn around		2,40 %	sorting
taking metal clip and screw & screwing		7,67 %	screwing
fixing the wire		5,75 %	sorting
placing on the table		4,03 %	sorting
cleaning the trash (cartons 5pcs)		3,35 %	cleaning
moving the pallet next to table		0,26 %	movement
sorting the papers and labels, login		0,87 %	sorting
tracing			
taking the fan from table		2,88 %	picking
placing the label		5,75 %	labelling
keyboard: ord num, serial number line, tab		6,71 %	IT
qr-code reading		1,92 %	IT
selecting user		1,92 %	IT
keyboard: 2 tabs		2,88 %	IT
placing on the pallet		4,03 %	picking
screen update (on every 5)		7,09 %	IT
receiving registration with putty		1,31 %	IT
filling the Sharepoint form		0,59 %	IT
moving pallet to ready made area		1,67 %	movement

Summary - manual process

Type of work	min [tot]	min /pcs	% of total
movement			2,79 %
IT			23,72 %
sorting			20,10 %
picking			15,53 %
screwing			20,13 %
cleaning			3,35 %
labelling			5,75 %
positioning			8,63 %
TOTAL			

All top 4 work steps include functions that could also be performed by a robot, either entirely or partially. It cannot be directly concluded that, for example, sorting tasks can be completely robotised. Fixing the wire, which attaches the fan's power supply to a small, assembled metal clip, requires full hand dexterity. The same applies to the screwing activities as well. Metal clip screwing requires hand dexterity to hold the clip while inserting the screw. Some force is required from the operator to maintain the position of the clip, which needs to be aligned correctly with the power supply cord. Changing component suppliers results in different installation methods for the fan components used, including variations in screw placement, screw types, and required torque. In some fan component models, a plastic spacer must also be installed in the finger guard. The fan component supplier may change within a production batch. The required torque and the number of screws per fan component variant are necessary considerations for selecting the screwdriver for the robot application.

6.4 Case Business Unit 2: packing

BU2 packing kits were examined according to the type of kit, which is presented in Figure 54 and Table 17. From these, the largest production batches in terms of volume were for KitType #1 kits, which comprise a very mixed set of different kits. The phenomenon is evident in Table 17, where the number of other variations for KitType #1 is relatively large compared to the number of variations for KitType #2 kits. Additionally, the number of components used in KitType #2 kits is relatively small compared to other kinds of kits. The third type, KitType #3 kits, is manufactured using an MTO strategy, while inventory levels drive the production of other kinds of kits.

Figure 54 – Business Unit 2 kit production volumes

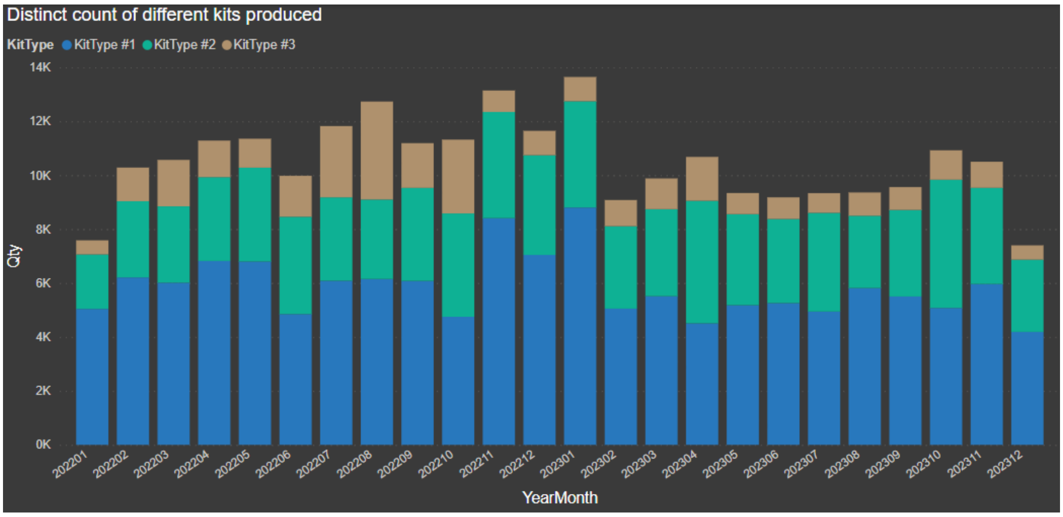
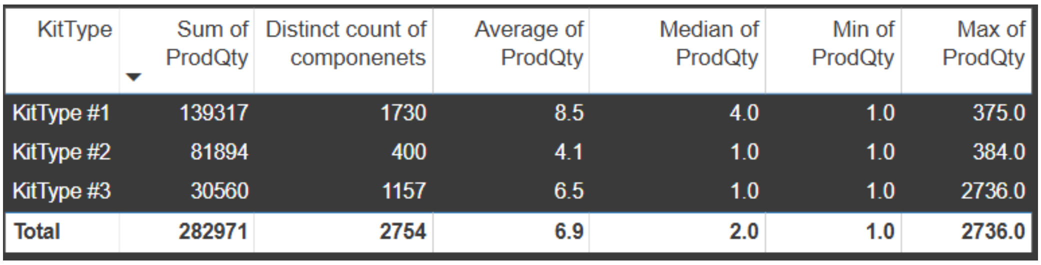


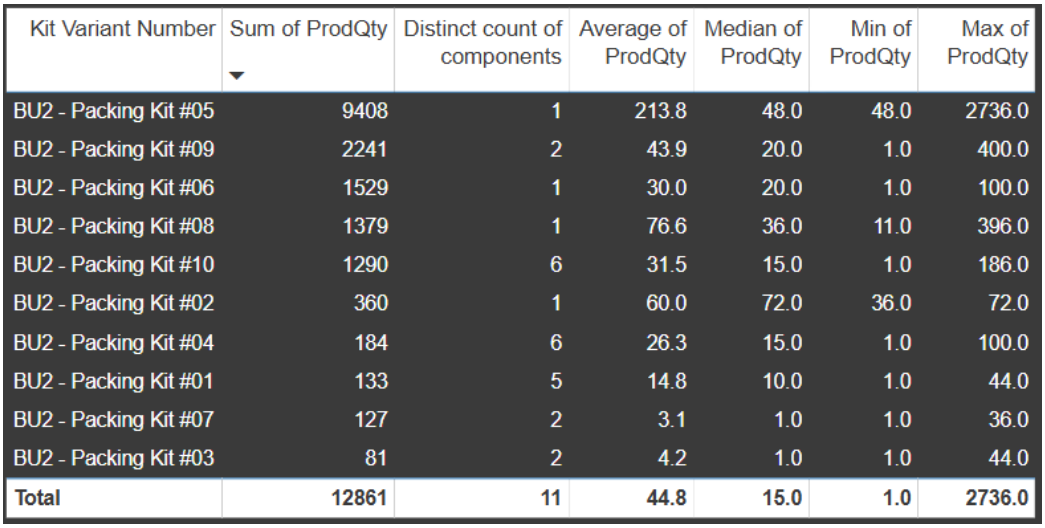
Table 17 – Business Unit 2 kit production volume breakdown



KitType	Sum of ProdQty	Distinct count of componenets	Average of ProdQty	Median of ProdQty	Min of ProdQty	Max of ProdQty
KitType #1	139317	1730	8.5	4.0	1.0	375.0
KitType #2	81894	400	4.1	1.0	1.0	384.0
KitType #3	30560	1157	6.5	1.0	1.0	2736.0
Total	**282971**	**2754**	**6.9**	**2.0**	**1.0**	**2736.0**

When conducting more detailed analyses using the built BOM and illustrated using Gemba walks, high-volume KitType #1 kits consist of assemblies with only one component to be packaged. For this reason, suitable candidates were not found in this category. From the KitType #3 kits, one kit product family, Product Family 1, proved to be ideal in terms of both volume and the number of components, as well as the size and shape of these components. The production volume and BOM breakdown of Product Family 1 kits are illustrated in Table 18. It can be observed that the number of components used per Product Family 1 kit is relatively moderate, and it is also noteworthy that the entire product family has only 11 different components.

Table 18 – Product Family 1 kit production volume breakdown

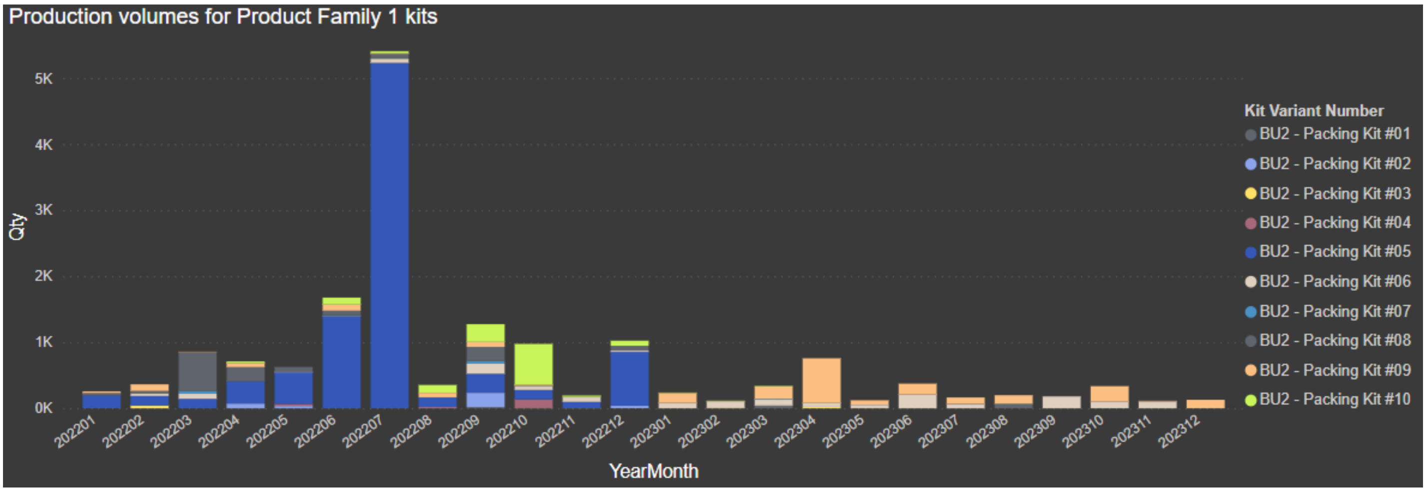


Kit Variant Number	Sum of ProdQty	Distinct count of components	Average of ProdQty	Median of ProdQty	Min of ProdQty	Max of ProdQty
BU2 - Packing Kit #05	9408	1	213.8	48.0	48.0	2736.0
BU2 - Packing Kit #09	2241	2	43.9	20.0	1.0	400.0
BU2 - Packing Kit #06	1529	1	30.0	20.0	1.0	100.0
BU2 - Packing Kit #08	1379	1	76.6	36.0	11.0	396.0
BU2 - Packing Kit #10	1290	6	31.5	15.0	1.0	186.0
BU2 - Packing Kit #02	360	1	60.0	72.0	36.0	72.0
BU2 - Packing Kit #04	184	6	26.3	15.0	1.0	100.0
BU2 - Packing Kit #01	133	5	14.8	10.0	1.0	44.0
BU2 - Packing Kit #07	127	2	3.1	1.0	1.0	36.0
BU2 - Packing Kit #03	81	2	4.2	1.0	1.0	44.0
Total	**12861**	**11**	**44.8**	**15.0**	**1.0**	**2736.0**

In terms of total volume, a one-month increase significantly increases the monthly average volume, as shown in Figure 55. Additionally, this also indicates a decrease in BU2's kit volumes for 2023, which was not known at the time of the selection in 2022.

Most of the kits are produced using the MTS strategy, but occasional MTO orders are also fulfilled, which explains the minimum batch size of 1. Despite the MTS strategy followed, a permanent and regular production batch size has not been agreed upon with the customer. One reason might be highly fluctuating demand, which applies to both total production volumes and the Product Family 1 variation type during the review period.

Figure 55 - Product Family 1 kit production volume



One factor in selecting the Product Family 1 kit was the list of packaging materials included in the BOM. In some kits, the packaging materials are not standardised, and in practice, the operator has been able to choose any packaging box for the kit. However, for most kits, a packaging box has been defined internally within DHL's WMS, which is intended to standardise DHL's operating methods and provide instructions for operations rather than a guided packing method on behalf of Customer 1. This fact was seen as a disadvantage for larger investigations and suitability assessment.

6.4.1 Process description

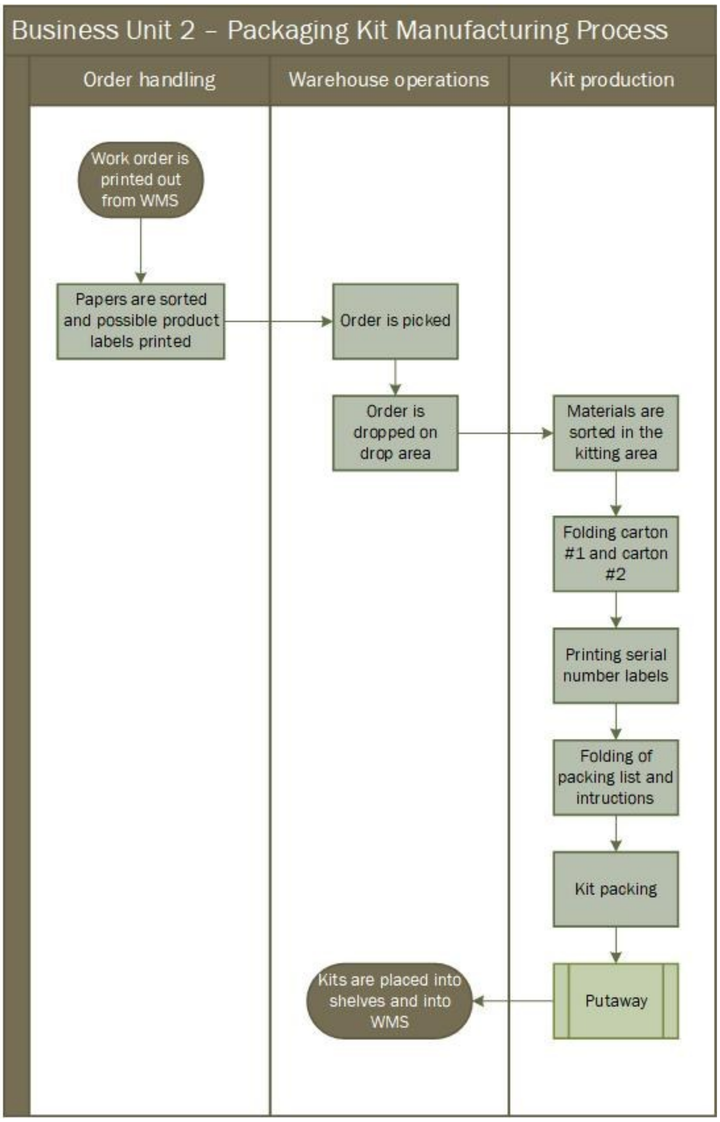
Packing of the Product Family 1 kit is performed according to the MTS strategy, where the customer releases kit orders for production. Practically, this means that the customer's representative places a kitting order in their ERP system. The quantity of produced kits is based on the current stock level and recognised and predicted orders. The final quantity and production time window are coordinated with warehouse operations to ensure a balanced workflow and optimal resource utilisation. In cases where rapid stock fulfilment is needed, a faster delivery time, including weekends, can be agreed upon.

The work order is placed under production based on the desired delivery date by printing out a picking list of the Work Order, as seen in Figure 56. The operations Coordinator issues a work order for the picking process and uses the WMS system to monitor that the picking is completed. The work order is picked from the pallet, which is then moved next to the kitting area for manufacturing to begin. The kit manufacturing operator takes the materials from the pallet and arranges them on the packing table.

The Product Family 1 kit includes two types of cartons, both of which require folding. At first, the inner carton is placed inside the second outer carton. The inner packaging provides clear places for the components to be packed. The main component to be placed in the box is the same regardless of the variation. Other possible components vary depending on the variant. These also have their place in the packaging, which is formed by the fold of the inner cardboard. However, some components are so small that they are placed under the inner cardboard and packed separately to prevent them from getting lost. In addition to the components, a pre-printed user guide and packing list are folded and inserted inside the box before the carton is closed. For each kit, a serial number label needs to be attached to the outside of the carton. This needs to be done accordingly, as the serial number on the label must match the serial number of the main component placed inside. For some variations, a separate product label is also attached outside the carton, and Customer 1's internal product label could be labelled outside the carton as well.

Packed and labelled cartons are placed on the pallet or trolley. When the Work Order is completed, the produced kits are placed either directly on shelves or in the receiving lane, waiting for shelving. The Work Order is marked finished on DHL WMS.

Figure 56 - Product Family 1 Kit Manufacturing Process

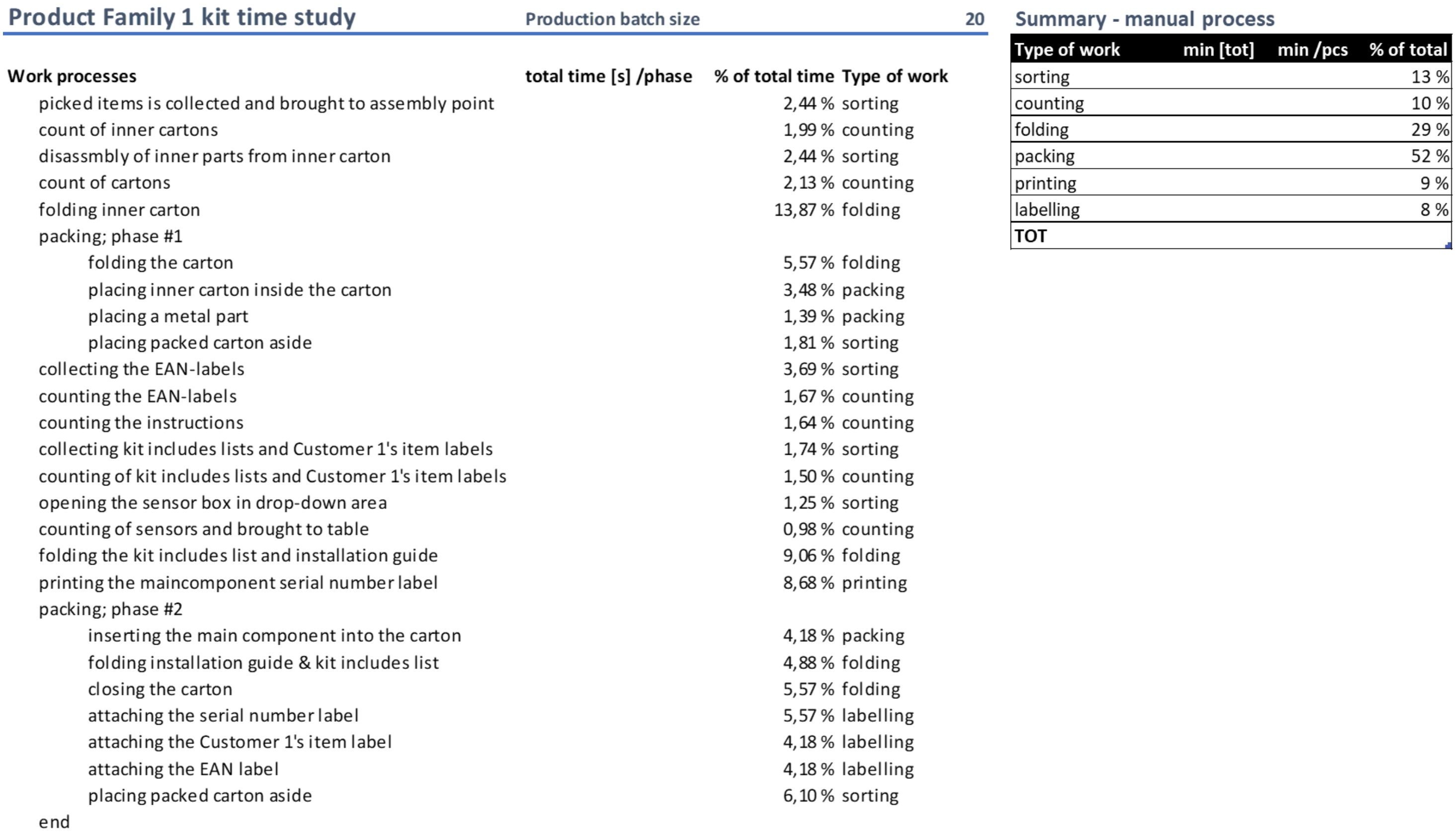


6.4.2 Time study

For the selected example, the BU2 – Packing Kit #9 was chosen. It contained one additional component in addition to the primary sensor component, as well as the labelling of the serial number and two product labels, the packing list, as well as the instruction leaflet. From a volume perspective, it represented a consistently produced variation. The two highest-volume variations were not produced during the review period until 2022.

The detailed work steps are shown in Table 19, where the work steps are written in the order in which the operator performed the production batch. Based on the work processes, the time spent was measured to determine the current situation and to assess the work steps suitable for the robot, as well as to choose the target cycle time. From work processes, a detailed process map was also created. A summary table was made of the detailed work steps, where the work steps are grouped into categories that support the overall process.

Table 19 - Product Family 1 kit time study



Product Family 1 kit time study — Production batch size: 20

Work processes	total time [s] /phase	% of total time	Type of work
picked items is collected and brought to assembly point		2,44 %	sorting
count of inner cartons		1,99 %	counting
disassmbly of inner parts from inner carton		2,44 %	sorting
count of cartons		2,13 %	counting
folding inner carton		13,87 %	folding
packing; phase #1			
folding the carton		5,57 %	folding
placing inner carton inside the carton		3,48 %	packing
placing a metal part		1,39 %	packing
placing packed carton aside		1,81 %	sorting
collecting the EAN-labels		3,69 %	sorting
counting the EAN-labels		1,67 %	counting
counting the instructions		1,64 %	counting
collecting kit includes lists and Customer 1's item labels		1,74 %	sorting
counting of kit includes lists and Customer 1's item labels		1,50 %	counting
opening the sensor box in drop-down area		1,25 %	sorting
counting of sensors and brought to table		0,98 %	counting
folding the kit includes list and installation guide		9,06 %	folding
printing the maincomponent serial number label		8,68 %	printing
packing; phase #2			
inserting the main component into the carton		4,18 %	packing
folding installation guide & kit includes list		4,88 %	folding
closing the carton		5,57 %	folding
attaching the serial number label		5,57 %	labelling
attaching the Customer 1's item label		4,18 %	labelling
attaching the EAN label		4,18 %	labelling
placing packed carton aside		6,10 %	sorting
end			

Summary - manual process

Type of work	min [tot]	min /pcs	% of total
sorting			13 %
counting			10 %
folding			29 %
packing			52 %
printing			9 %
labelling			8 %
TOT			

According to the summary table, the packing type of work is the most time-consuming phase, followed by folding of cartons, sorting, and counting activities. Work processes include separate carton folding and folding, which are included in both packing phases. The box in which the main component is packed contains a cardboard mould. This mould is stored as a sheet, from which the operator needs to take pieces out and fold the cardboard according to the pre-fold. The main component and other components are placed in this moulded cardboard. Counting is done in separate phases, which highlights the importance of quality on behalf of the customer. Part of the calculation work done by a kit assembler is to ensure that all components have been collected correctly before the operator begins manufacturing the kit.

Based on the time study and work phase analysis, as well as the general suitability of the robot, the packing phase was decided to pilot.

6.5 Mapping of the collaborative robot and tools

One target for the investigation was to conduct a practical pilot with the right components. The pilot location was established in the warehouse where the operation was conducted. The idea here was to concretise DHL's digitalisation strategy with a practical example and to show and communicate to the personnel that we are looking for alternative solutions to implement the service. Since there were no industrial robot implementations in DHL Supply Chain Finland or the Nordics at the time, no devices were available for internal use. Therefore, the solution for the pilot needed to look at robot integrators.

As part of the research, information was collected about collaborative robots, tools suitable for packaging, and screwdrivers, as well as the processes used. The work involved familiarising myself with the websites of device manufacturers, studies on the topic, articles, and other theses, as well as participating in various events related to robotics, both online and on-site. The practical applications are evident on-site, and the opportunity to program the collaborative robot independently was advantageous. Live events began to become more common in 2022 as coronavirus restrictions were lifted in Finland.

Research on utilising collaborative robots, especially for screwing, was not available on the same scale as, for example, re-palletising or packaging. Several online and live events also covered either packaging, re-palletising or welding. There was a lot of information and experiences available regarding assembly applications, especially with SCARA robots. Regarding screwing applications, marketing materials from product manufacturers were available, but these materials can be classified more as marketing materials rather than researched information.

For the robot, the possibility of utilising the collaborative robot in use at HAMK became clear in the early stages. Similarly, HAMK's proposal to commission a pilot as part of their student work offered a cost-effective solution while also providing learning opportunities for a wider group of participants. With this arrangement, it was possible to conduct the simulation and manufacture the jigs required for the screwdriving application. The procurement of the screwdriving device itself was the responsibility of DHL, while HAMK provided the vacuum lifter.

6.6 Pilot and POC

6.6.1 Setting up the pilot

Planning for the overall testing and evaluation of the pilot was started immediately after the two kit processes were selected. With the assistance of HAMK, the process design began separately for both test kits. The design phases of the packaging process included designing the robot's packaging work phase with material flows. The design phases of the screwing process included designing the screwing sequence, space planning, and reserving the necessary components for the tests. Additionally, it was necessary to plan the positioning of the components so that the screwing could be aligned correctly.

During the process design, the necessary robot tools were defined and aligned for the pilot. For the screwing process, it was quickly determined that some jig had to be made. This implementation was the fastest and most agile way to manufacture the jig as a 3D print in the HAMK laboratory. For the pilot process, two jigs for both pilot setups were printed.

Regarding the process steps for kit manufacturing, it was decided that all printing of labels was excluded from the scope of the pilot. It would have been too time-consuming to arrange the test, and it was generally stated that printing as a robotic application is a generic solution and not particularly suitable in this case. The same applies to folding activities for cartons, instruction guides, and kits, including lists used in the production of the BU2’s Product Family 1’s kit. It would have been too complex to build a solution for pilot purposes in the given timeframe. Additionally, the idea arose to approach the customer with the option of ordering a pre-folded instruction leaflet that fits into a cardboard box.

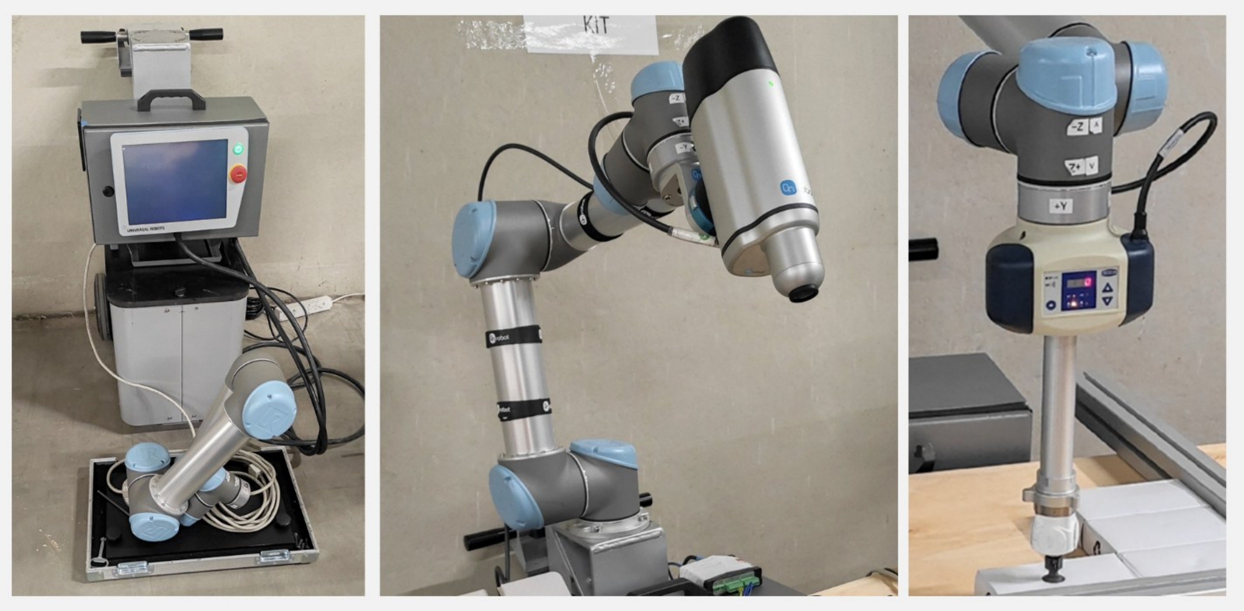
Since the used components and produced kits are not the property of DHL and will not be used by DHL, Customer 1 was naturally asked for permission to utilise the components and possibly reject them if they were damaged in any way during testing. Components were used to test vacuum lifting and screwing, serving as a model to build 3D printing jigs for both packing and screwing applications. For the packing application, a bracket was printed for the metal part, while a mounting jig was printed for the fan kit assembly.

As part of the pilot, personnel from DHL's warehouse were informed, and Supervisors identified a suitable person to participate in the pilot. The tasks of the selected person included assisting in the implementation of the pilot, experimenting, and testing the operation of the robot in practice. From the outset, the goal was to conduct a real pilot in an actual warehouse environment, and it was apparent that personnel would be involved in presenting the new technology. It is noteworthy that the person chosen had no experience in robotics whatsoever.

6.6.2 Used technology

Since DHL Supply Chain Finland has not had similar experiments and does not own any equipment, products or components to implement such a pilot, it had to rely on what was available. There were two robot options that HAMK uses. The robot models in question were Universal Robotics' UR5 and UR10. Given the weight of the pieces to be handled, the UR5 could also have been an option; however, the UR10 was chosen due to its greater reach. The robot was attached to a mobile platform, which would have enabled the robot to be moved. Other work platforms were delivered by DHL, which were made of stackable EUR pallets to suit the warehouse environment. The used robot, its control unit and the used EOT can be seen in Figure 57.

Figure 57 - The robot and the used tooling



The tooling used was a vacuum lifter provided by HAMK and an OnRobot robot screwdriver with a feeder supplied by Machinetool (Oy Machine Tool Co.). The vacuum lifter was suitable for handling the components used in the packing process of the BU2's Product Family 1. When choosing a screw-driving tool, a compromise was made between availability, cost and the achievable screw-driving result. The required torque-equipped screw-driving tool was not available for rent within the given time range. Buying could have been an option, but since it was a test and not the design of an actual application, it was decided to use a device that could be rented within a specified time frame. The used screwdriver offered torque from 0,15Nm to 5Nm, where 6Nm was needed.

In addition to this and outside of the collaborative robot pilot, another experiment that was running between December 2022 and December 2023 was utilised. DHL had suitable equipment and analysis tools for measuring ergonomics, specifically working postures and movements, in the test. The solution provided by Soter Analytics included ergonomic devices attached to either the neck or upper arm, as shown in Figure 58, the upper arm attachment. With the help of the solution, it was possible to measure and monitor 10 risks associated with back and shoulder movements. (Soter, 2025) The solution was tested in the packaging and manufacturing process of the Assembly Kit 2, among other things, and at Sites in Finland. Although the packaging processes carried out with the help of Soter differed from the packing process of the Product Family 1 kit, they involved a similar type of work.

Figure 58 - Ergonomic sensor fastening to the upper arm

6.6.3 The pilot environment

The testing environment could not be built directly as part of the selected kit manufacturing processes, as this tends to be more concept testing rather than real-world production testing. The person chosen from the operations was also not a permanent member of the staff preparing either kit; the location was able to be selected without boundaries. As a basic requirement, a suitable area with possible pallet handling, proper lighting conditions and electricity is available for the robot's control unit and laptop.

A suitable space was found near the Assembly Kit #2 assembly area, where the testing environment was constructed. No other restrictions are needed, except to close the area to forklift traffic. Tabletop and other surfaces were created with EUR pallets, and next to the stack of pallets, the robot and its unit were placed. The location highlighted the need to incorporate new technology into daily operations. The area was accessible to everyone.

6.6.4 Assembly application POC

Due to two decisions made earlier in the process, the designing phase, the Assembly Kit 2 assembly could not be fully completed by utilising a robot. The first is related to the jig and the screw of a small metal clip, which is screwed to the opposite side of the finger guard screw. Two screws are used to attach the finger guard, and one screw is used to attach the metal clip. The jigs were designed for one-sided assembly only. Additionally, a holder for the metal clip was decided to be omitted. The second decision concerned the selection of screwdrivers. The torque of the robotic screwdriver used was below that required by the fan used. Each Assembly Kit 2 completed by the robot was then handed to an operator, who performed tasks such as screwing, labelling, tracking, and palletising. The used jig is shown in Figure 59.

Figure 59 - The jig used in the Assembly Kit 2 assembly

The workstation for the Assembly Kit 2 assembly is shown in Figure 60. A work cycle was created that allowed the operator to adjust both jigs, and the robot could then screw two screws per jig. The work cycle began when the operator placed the fan and cover plate at the bottom of the jig and the finger guard in the lid of the jig. After this, the operator closed the lid and gave the robot the command to perform the screwing task, i.e. to screw two screws to attach the finger guard. During this first robot screwing job, the operator similarly equipped the second jig. When the robot had completed the first screwing job, the operator gave the robot permission to perform the second screwing job. The operator then removed the fan from the first jig, placed it on the side of the table, and reloaded new components into the first jig.

Figure 60 - Screwing assembly

The HAMK researcher had programmed the robot to return to its starting position after each screwing job, and the operator had to issue the command to screw from the control panel. In this way, it was possible to ensure the safe execution of the work, i.e. that the operator's hands were not in the robot's working area. At the same time, it was possible to ensure that the new jig was adequately equipped and that screwing could be carried out successfully.

For the assembly application, no other tests were sought.

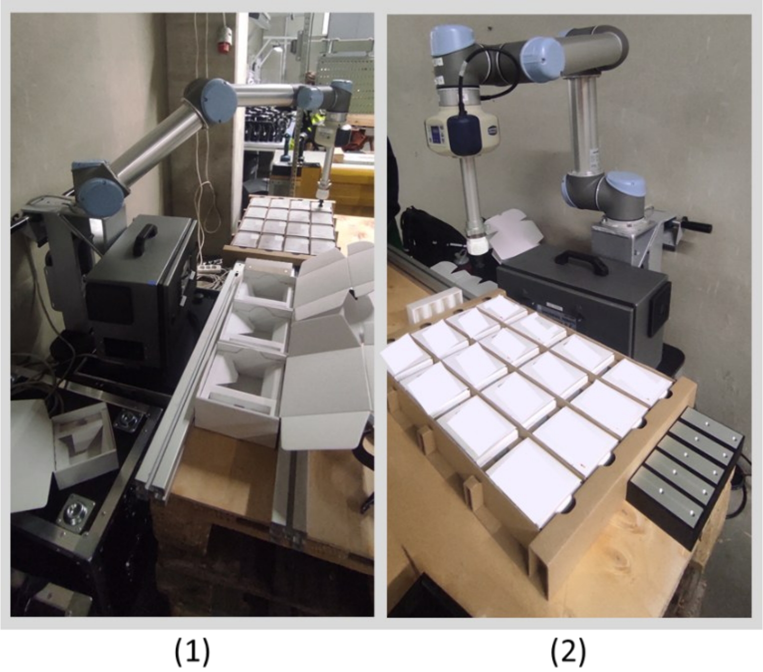
6.6.5 Packing application POC

In the packing application pilot, a decision was also made not to manufacture the kit completely. This was done because it would have been necessary to know which main component is placed on each package, as the main component's serial number label must match the main component in the package. It was decided earlier to exclude the printing and paper-folding phases from the scope of the robot application.

The conducted layout is illustrated in Figure 61. The work cycle was designed to fold the outer and inner cardboard while the robot packs two components into the carton: the sensor and the metal piece, as shown in Figure 61 (2). In addition, the operator was left with adding empty cardboard boxes to the queue and offering them to the robot, as well as removing the packed kit from the robot's working area, as shown in Figure 61 (1). After each packing cycle of the robot, the robot stopped, and the operator was required to start the second cycle from the teach pendant. By this, it was secured that the operator was not in the robot's working area, and the next package was ready to be packed. After each test cycle, the set was removed, and components were recycled as far as possible. For each test cycle, observations were made, and the robot's program was adjusted accordingly based on these observations.

Figure 61 also shows the usage of the 3D printed jigs (Figure 61 (2)) for the metal components, as well as the utilisation of the supplier's packaging solution for the sensors. The supplier packs the main components into a cardboard box, which forms several layers of similar 4*4 cell solutions.

Figure 61 – Product Family 1 kit packing



(1) (2)

At the beginning of the testing period of the Product Family 1 kit, a HAMK researcher provided programming instructions. After this, and after the kit had been packaged and tested, the program underwent further modifications and testing. The purpose of the robot program modification was to validate the claims made in the theory regarding the ease of programming the collaborative robot for testing.

Due to the limited testing of the Product Family 1 kit application possibilities, additional packaging tests were conducted. Two alternative test cases were found, both of which involved transferring material from the supplier package to another handling unit. Since the pilot was conducted in a multi-customer warehouse, it was clear from the beginning by the Site Manager that the pilot would be promoted to both major customers of the warehouse: Customer 1 and Customer 2.

Additional tests were carried out with both Customer 1 and Customer 2 products. From DCS FI's perspective, these additional tests aimed to achieve both operational savings and new business opportunities. The tests performed are similar to the bin-picking solution, with the difference that the test utilised supplier boxes in which the components are packaged in a specific manner. The components were not so-called bulk materials, which are often loose in boxes, and the material to be picked was identified using camera technology. Customer 1's test was evaluated for another possible usability application for the robot. In contrast, during Customer 2's test, the purpose was to demonstrate how the DHL Supply Chain could assist Customer 2's production by pre-packing materials in a 3PL's warehouse, thereby releasing Customer 2's personnel to perform more valuable tasks.

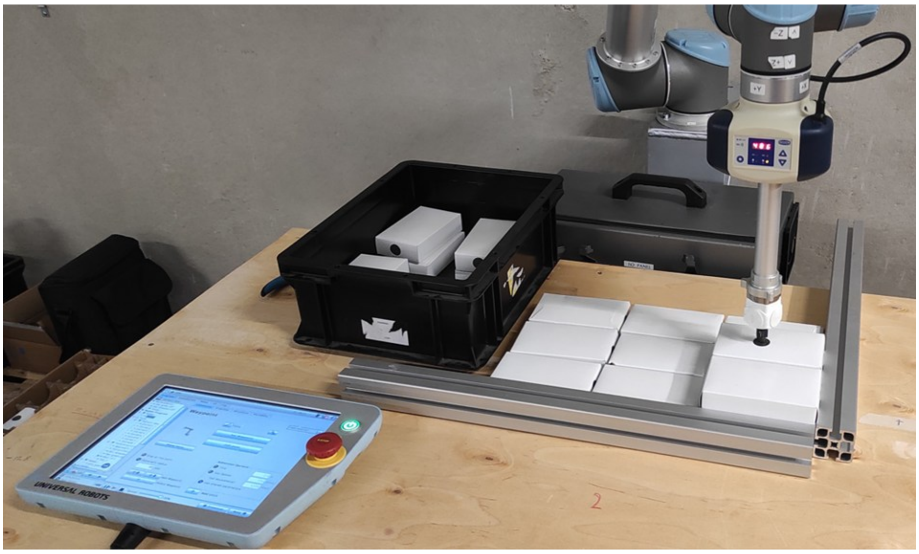
In both cases, the materials in the supplier package were transferred to a plastic box, as illustrated in Figure 62. The difference is that in Figure 62_2, Customer 2's box is replaced by a carton due to a lack of the correct box. After the items are in the box, their intended use from this point on is different. Customer 1's plastic boxes are used in a kanban cycle, meaning the plastic boxes are sent to Customer 1's factory on the production line. Currently, this is done by the operator by picking the items from the pallet shelves. At Customer 2, plastic boxes are used to supplement the automated warehouse solution in Customer 2's production, from which the materials are later collected for use in the production process. For Customer 1's kanban box filling, the required number of items to be picked is specified with the order. For Customer 2's refilling, the number of materials inserted into the box must be recorded.

Figure 62 - Unloading from the supplier's carton

(1) (2)

In addition, the programming was modified to include the following. After lifting the product, the turning of the product to be handled and its packaging in a different pattern than in the original situation were added to the program. In the experiment, the starting pattern was a 3*3 pattern, and the final problem was a 2*2 pattern. This was used to test and ensure the ease of programming the collaborative robot. The test setup is shown in Figure 63.

Figure 63 - Programming testing



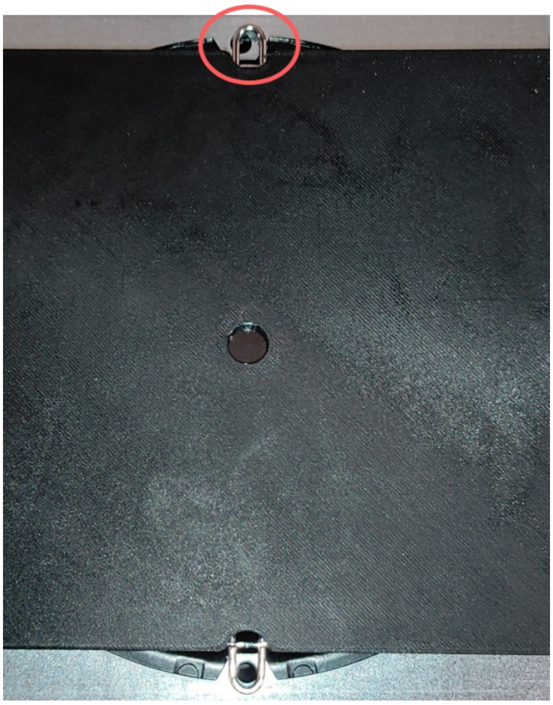
6.6.6 Insights and challenges observed from the POC testing assembly

The first days of the pilot were primarily used for setting up the environment and fine-tuning the pre-programmed application for the fan assembly on behalf of HAMK's researcher. At the same time, the test days were spent learning the programming logic of the collaborative robot, programming itself, and using the screwing tool. The use of the collaborative robot was relatively easy to learn through the graphical user interface. During the first two days, a HAMK researcher was on site, but after that, support was available remotely if needed.

The programming of the robot took unexpectedly more time than planned. A misalignment of the components was first noticed at that time; however, other issues did not become visible until the fourth day of the assembly pilot.

During the installation cycle, it was noticed several times that the screw holes were not aligned correctly, causing the screw not to go into place necessarily. In general, the fan and mounting plate aligned without any problems, but the alignment of the finger guard attachment points often became distorted after the first screw was tightened. The situation is illustrated in Figure 64. An attempt was made to correct this by, for example, adding tape to the other edge of the jig, effectively thickening the jig wall. The intention was to guide the fan cover plate more in the lateral direction. The slight gap in the lid also allowed for adjustment, but moving it affected the alignment of both holes more than adjusting the fan cover plate. As the pilot progressed, in the following days, the lid of the second jig began to lose more and more.

Figure 64 - Screw hole and fan bracket misalignment



The plan was to assemble two sets of fan kits, each consisting of 55 fans, with the assistance of the robot. Ultimately, two assembly sets were conducted without major issues: the first included 43 fans, and the second included nine fans. The measured assembly time was 2 hours 40 minutes for these 52 fans, but the total time spent was roughly three working days. Production and error tracking was cancelled during the second set because problems were constantly piling up with both the alignment of the screwing and the screwdriver equipment.

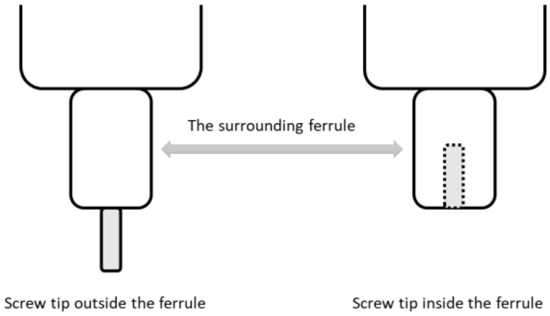
The cause of the screw holes alignment phenomenon was found to be either quality defects in the components used or with the jigs. Since the jigs were not made based on CAD design drawings, minor measurement errors could have affected the jigs' manufacturing. Secondly, the jigs' structure was not sturdy. The lid's fastening was too loose and came loose during the use of the jig. The quality of used components was found to be variable; one example of the cover plates is shown in Figure 65. The metal plates have been able to bend, affecting, for example, the alignment accuracy when the lid did not close properly. There was no locking mechanism in the lid that would have kept the lid in place and, in that way, straightened the metal plates as well. The root cause of the bent cover plates was not identified. Alternative root causes were identified as either poorly packaged plates by the supplier, or damage during transport or storage.

Figure 65 - Cover plate quality defect

Errors related to the screwdriver and screw feeder started to occur from day two onwards as programming the assembly program for the robot progressed. An error occurred for two reasons. Initially, since the screwdriver tip is magnetic, it only works with magnetic screws. However, the magnetic force may occasionally be too strong, causing the next screw catches the screw already picked up. The operation of the screw feed equipment could have been programmed with a separate program, but there was no expertise from the DHL side for this, and it could not have been done without the help of a researcher from HAMK. The operation of the screw feed equipment could have been programmed with a separate program, but there was no expertise from the DHL side for this, and it could not have been done without the help of a researcher from HAMK. The adjustment was related to the timing, as the feeder offered a new screw. There was no need to provide a new screw immediately after the one screw was picked.

A positive observation was related to the screwdriver mechanism which this model offered. Since the screw is picked from the feeder and taken inside the ferrule, the possibility of scratches to the human hand is avoided. The functionality of this is illustrated in Figure 66. The drawback to this is that it requires space, as it will thicken the screwdriver from the point where the screwing is about to happen. The use of this type of screwdriver is not possible in narrow-space assembly applications.

Figure 66 - Screw tip and ferrule positioning



The second error type was related to the ferrule, which was initially thought to be related to components and jigs. The real reason became visible on day four when a piece of magnet dropped from the screwdriver ferrule. The broken ferrule is visible in Figure 67. Based on the expertise of HAMK's researchers, most of the problems encountered during the programming phase related to the screw feeder were likely caused by a broken ferrule. It was unexpected behaviour from the screwdriver and screw feeder, which were considered reliable solutions.

Figure 67 - Broken ferrule

6.6.7 Insights and challenges observed from the POC testing of the packing

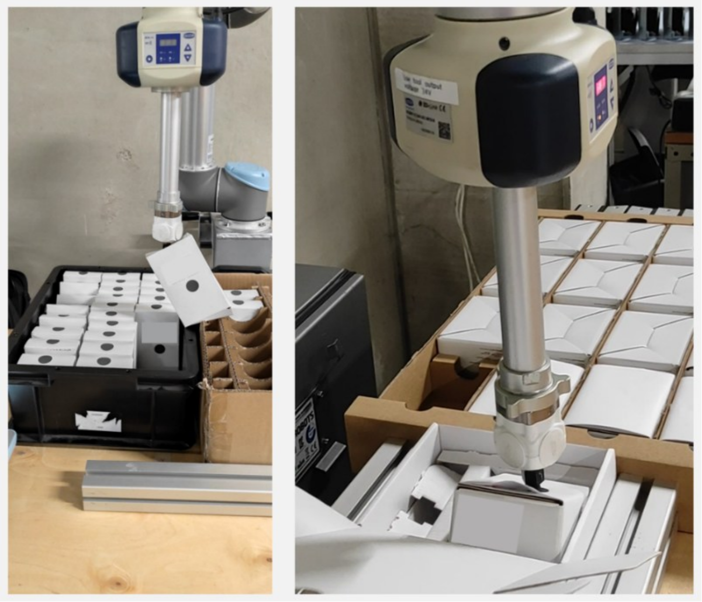
The second pilot week began with modifying the setup environment for packaging of Product Family 1 kit and programming the robot. As again, HAMK's researcher assisted in programming and teaching. It showcased how to build a program through a visualised teach pendant by utilising a program tree and adjusting parameters and sub-programs. At this point, at least for this robot model, it was eye-opening to see and understand the often-mentioned ease and speed of programming a collaborative robot. Especially when materials can be lifted and placed in a repeating pattern. In this robot model, there were ready-made programs to repeat a specific pattern, which required fixed points and the height of one layer. After this, the robot could pick from several different layers and place materials on several different layers.

Only one day was used to test the BU2’s Product Family 1 kit packaging, as most of the kit packing work was still done by the operator in this process. During the work cycle, the operator was able to fold approximately 1,5 boxes. Afterwards, the operator was still tasked with packing and placing the inner cardboard boxes into the packaging box, folding the two different papers, glueing the labels, and closing the cardboard boxes. The following days were used to program the robot without assistance from HAMK's researcher to pack capacitors and small carton boxes.

Packaging errors occurred. These were related to either the robot's trajectories or positioning. The operator moved the actual packaging box. Two reasons could have caused this error. Either the packaging box had not been moved correctly to the position where the part to be processed should have been placed, or the robot base or the robot had moved slightly out of place. The poor fixation of the robot base and the workbench used could have contributed to this issue, which is why even a slight movement could alter the position of both in the robot program. A similar situation is illustrated in Figure 68_2. The misunderstanding or lack of knowledge and experience related to robot trajectories resulted in an error, as shown in Figure 68_1, where a small carton box packed from the supplier's carton to the Kanban box collided with the supplier's carton.

For movement paths where the trajectory is not essential but the target positions are, the preferred movement type is joint movement, also known as MoveJ, as Universal Robotics (UR) refers to it. MoveJ means that a robot, moving from its current position and pose to the target position and pose, simultaneously rotates its joints from its current angles to the target angles. In the world where humans live, the space is defined by linear axes X, Y and Z, which correspond to the Cartesian coordinate system. Trajectories that require linear, straight-line movement are defined by linear movement, or MoveL, called by the UR. Typically, MoveJ is used in applications such as pick & place and packing & palletising, which corresponds to the Smart Sensor packing application. MoveL, on the other hand, is typically used in assembly, polishing, and dispensing applications. (Universal Robotics, 2025)

Figure 68 - Misalignment of packaging



(1) (2)

In pick-and-place applications, both movement types were used. Initially, the robot approaches the object to be picked up using MoveJ. Then, the object is picked up with MoveL in a vertical motion. Depending on the situation, either MoveL or MoveJ can be used to move the robot to a position above the desired one. Usually, MoveJ is used because it is faster. Finally, the MoveL movement type is performed again, where the object is left in the desired position with a vertical motion. The error illustrated in Figure 68_1 was caused by using MoveJ and not paying attention to the height of the movement.

7 Conclusion

The purpose of the research was to determine whether collaborative robotics can be utilised in 3PL warehouse operations. The goal was to find a suitable process that enables the utilisation of collaborative robotics while identifying potential barriers to its adoption. DHL Supply Chain Finland Oy also aimed to highlight new technology to support the visibility of Strategy 2025 in practical work as part of warehouse operations. Therefore, the goal of the study of the application of collaborative robotics was set at the initial stage to organise a pilot in the warehouse, enabling the strategy to be concretised.

The most important value of the study was the pilot. It was generally known and recognised that warehouse operations are a set of repetitive tasks, especially in kit manufacturing, where different kits are manufactured repeatedly over a specific period. It was also known that variations in kit production, in terms of weekly volume and the number of different kits, can be high, and both MTS and MTO strategies are employed based on the Customer 1's decisions. VAS operations represent a significant portion of the operations to be performed in the warehouse for both Customer 1's business units. By combining kit production and identifying similarities between the kits of both business units, further development possibilities can be identified both internally and in cooperation with the customer.

Before the pilot, it was necessary to find a suitable process and kit variant to be piloted. For this and stronger robot application possibilities, it was necessary to understand the robotic processes at a general level, as well as conduct data analysis and work studies in production. For a deeper understanding of robot application implementation and potential payback, it was necessary to study both the literature and actively engage in various events, company visits, and networking with suppliers. The opportunity to participate in these events served both the thesis and the mapping of other processes to be robotised in this warehouse in question and other DSC FI warehouse operations.

7.1 Conclusions of the PoC

7.1.1 Assembly Kit 2 PoC conclusions

Based on the results and observations of the pilot experiment, it can be stated that no entire production batch could be manufactured at once. The most important observation during the first days was the positioning accuracy of the jig and the three components of the Assembly Kit 2: the fan, cover plate and finger guard. This problem occurred from the beginning to the end of the assembly pilot, making it the primary error type. Other error types that occurred and were observed during the pilot are listed in Table 20. The second highest error type was related to the screw feeder of the screwdriver solution. When the robot was retrieving a new screw from the screw feeder and rising, the screw feeder offered a new screw to the pick-up point, which caught the robot's screw in the rising phase. The second screw sticking to the first screw was due to the magnetic operating mechanism of the screw tip. The last two error types are also related to the screwdriver and alignment of the screw. A rough conclusion can be drawn that half of the errors were related to the components and the jig, and the other half to the screwdriver.

Table 20 - Error monitoring of Assembly Kit 2

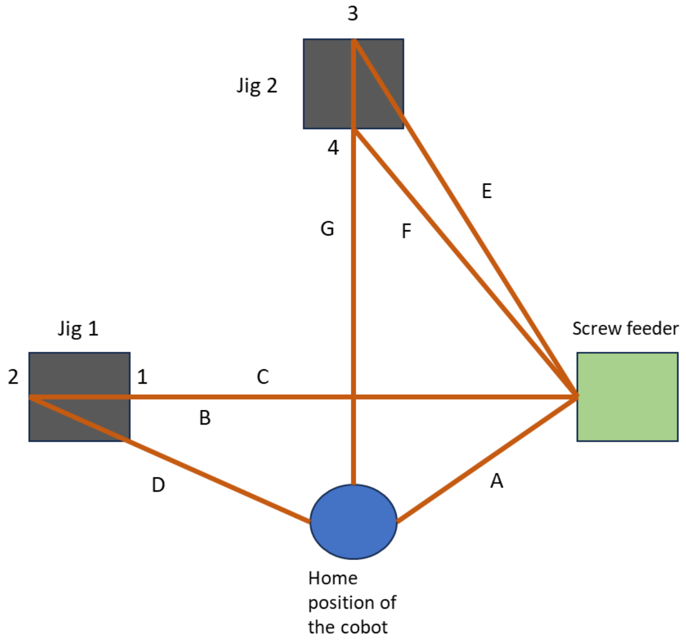
Error type	# of appearances	% of total
The screw holes were not aligned	26	54 %
Two screws when taking the screws	11	23 %
The screw was aligned poorly on the bit of the screwdriver	8	17 %
The screwdriver bit did not come out when taking the screw.	3	6 %
TOTAL	**48**	

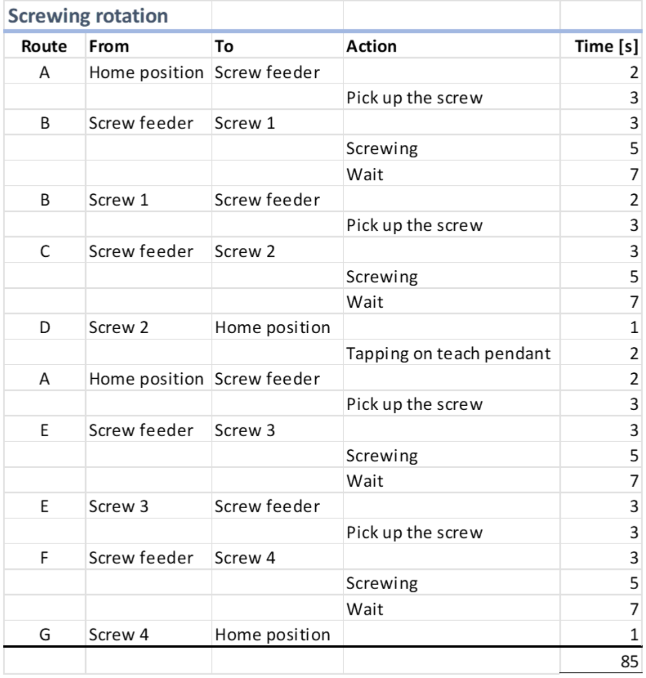
The error observation tracking was interrupted on day three because most attempts failed, and no expertise was available to solve the problem. Roughly speaking, all of the issues occurred at the beginning of the screwing process, i.e. when the screw was placed in the hole. Since the broken ferrule was noticed at the end of the pilot period, it may have affected the earlier-occurring errors and made error monitoring more controversial. Even though the misalignment of the components was observed, the screwing was able to conduct successfully. The question arises of whether the results would have been better if the ferrule had been intact. It may also be possible that screwing into a misaligned hole caused the breakage of the ferrule.

In this research, the target was not to build an optimal environment or solution which could be utilised directly as a complete assembly application. The primary objective was to test the robot and a concept built around it. The feasibility of the selected approach was tested and monitored against assumptions. Therefore, the placement of the robot with the movable platform, and partly because of that, the layout was built based on the robot's technical specifications, which did not necessarily correspond to the actual application. Due to the movable platform requiring space from the front part of the robot, it was not possible to use a depth-oriented trajectory, but the layout had to be spread in the width direction.

For one work cycle of the robot, it took 85 seconds to complete the screwing of 4 screws in two jigs. The robot's trajectories with disassembled times are presented in Figure 69. The layout turned out to work fine, allowing combined moving and screwing times to be aligned with each other. For jig 1, the total used time was 42 seconds, and for jig 2, the total used time was 43 seconds. The tested work cycle allowed the operator equal time to perform the change of components after each screwing of the jig.

Figure 69 - Robot trajectories with moving times in the Assembly Kit 2 assembly





Screwing rotation

Route	From	To	Action	Time [s]
A	Home position	Screw feeder		2
			Pick up the screw	3
B	Screw feeder	Screw 1		3
			Screwing	5
			Wait	7
B	Screw 1	Screw feeder		2
			Pick up the screw	3
C	Screw feeder	Screw 2		3
			Screwing	5
			Wait	7
D	Screw 2	Home position		1
			Tapping on teach pendant	2
A	Home position	Screw feeder		2
			Pick up the screw	3
E	Screw feeder	Screw 3		3
			Screwing	5
			Wait	7
E	Screw 3	Screw feeder		3
			Pick up the screw	3
F	Screw feeder	Screw 4		3
			Screwing	5
			Wait	7
G	Screw 4	Home position		1
				85

A notable action is waiting, which was programmed to show the precise sequence of the robot after each screw attachment. Additionally, the move to the home position in the middle of the sequence was created for safety reasons, ensuring the operator can be certain that the robot will not malfunction during component replacement. The forces used by the robot would have allowed a collision with the operator, as well as with the screwing tool, where the screw is inside the ferrule during transfer. By enhancing the process by removing these steps, one screwing rotation would be improved by 31 seconds, lasting 54 seconds (an improvement of 36%)

Data generated by the ergonomic sensor pilot can also be used to estimate the benefits. Figure 70 presents data regarding the assembly of Assembly Kit 2 and an explanation of different hazardous move types. In the ergonomic sensor pilot, the sensor was placed on the operator's shoulder during the assembly of the fan kit. According to instructions from Soter Analytics, the sensor was attached to the dominant hand, which is determined by the handedness. When the device was put into use, it was ensured that the devices were attached to the operator's hand with which the screwing work was performed. On the top right, the hazardous movement types measured by the device are presented. At the bottom left of the figure, the average movement per category is shown daily when the device is in use. On the bottom right is an example of daily data, categorised by hour. In that example day, Jan 25th in 2023, the operator's shoulder was targeted on average 10,8 hazards per hour, with a range of 0 (hour starting at 11:00) and 25 hazards (hour starting at 07:00). The most common type of hazardous movement was arm elevation, second everyday repetitive arm movements and overextension was the third most common which can be seen from the top left doughnut chart. The highest number of hazardous moves in one hour occurred on Feb 6th 2023, when a total of 59 hazardous moves were measured in an hour. The lowest number of hazardous moves per hour, measured between Jan 28th and Feb 2nd, is not related to fan kit assembly. Jan 28th and 29th were weekends, and no assembly of Assembly Kit 2 was performed during that time. The operator, for the following week, has been performing other work according to the planned work rotation.

Figure 70 - Ergonomic sensor pilot data and measured hazard move types

Arm elevation Elevation of arm in any direction **>90°**

Pushing & pulling With arm elevated, jerky pushing & pulling, pulling with an open shoulder *(Based on RAPP tool health and safety executive)*

Overexertion Cumulative arm elevation of **>90°** for **>20%** of working time wearing the device *(Based on WISHA checklist guidelines)*

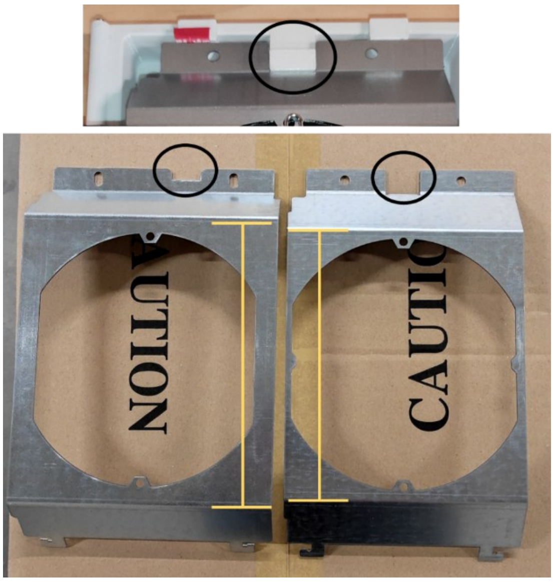
Static arm elevation Elevation of arm in any direction **>90°** and held for **>30** seconds

Repetitive arm movements Elevation of arm in any direction **>90°** performed more than 2 times a minute

According to the operations Coordinator and Supervisor of Assembly Kit 2 production, the fan assembly places a particular strain on the shoulders, resulting in some employees taking sick leave.

In addition to the observed deviations in component quality, their dimensions vary depending on the supplier. In Figure 71, you can see cover plates, which come in a variety of shapes and dimensions that must be considered when designing the application and jigs. However, due to differences between suppliers, the possible positioning points used in the design of the jigs differ from each other, even though the outer dimensions and screw holes are the same. In the pilot, the notches circled in black were used for alignment. When designing the final application, the use of these must be re-evaluated, as they vary depending on the component supplier. The use of bend points (yellow lines) may also need to be evaluated, as their dimensions also vary depending on the supplier.

Figure 71 - Cover plate variations



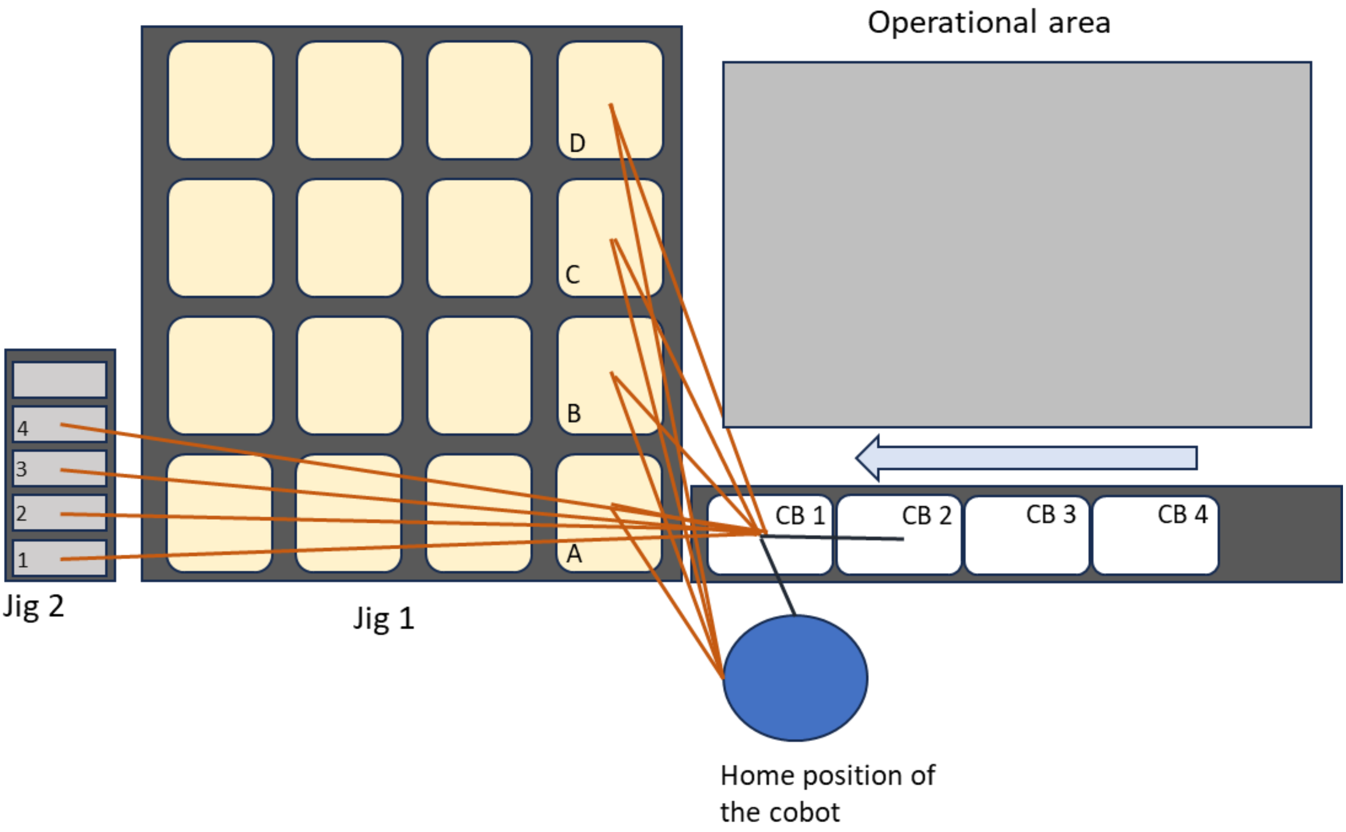
7.1.2 Product Family 1 packing PoC conclusions

Due to the nature of packaging, it was clear from the beginning that a complete production batch would not be assembled during the packaging pilot. This was due to the structure of the inner cardboard of the packaging box, which required a considerable amount of time from the packaging operator, the adjustment of the folding papers to the packaging box, which also had to be done manually, and the attachment of three different shaped labels to the cardboard box, which requires the use of three different printers, label bases and data sources for the information on the label. The pilot helped illustrate, understand, and partly measure the concept more precisely.

The packaging pilot provided the most significant benefit in the programming of the collaborative robot. The operator, as well as the researcher, were able to implement changes to the robot program with a very short orientation without prior study. The changes were tested in different packaging options that were mapped during the pilot phase. Due to the nature of the operators' operations, the mapping focused on finding products that could be moved from supplier packaging to kanban boxes for Customer 1’s production. The potential expansion of Customer 2's operations was also mapped, where products are also transferred from supplier packaging to boxes used in Customer 2's automated warehouse solution.

For the BU2’ Product Family 1 kit packing pilot, the layout was built in a disadvantageous way due to the robot platform and the distance it needs to the working surface. Therefore, all the lifting and dropping points used by the robot were placed linearly without utilising the vertical space, as illustrated in Figure 72. According to Figure 72, Jig 2 was the 3D-printed jig on behalf of HAMK, while Jig 1 utilised the supplier's box. The line system on the bottom right for empty carton boxes was built from aluminium profiles.

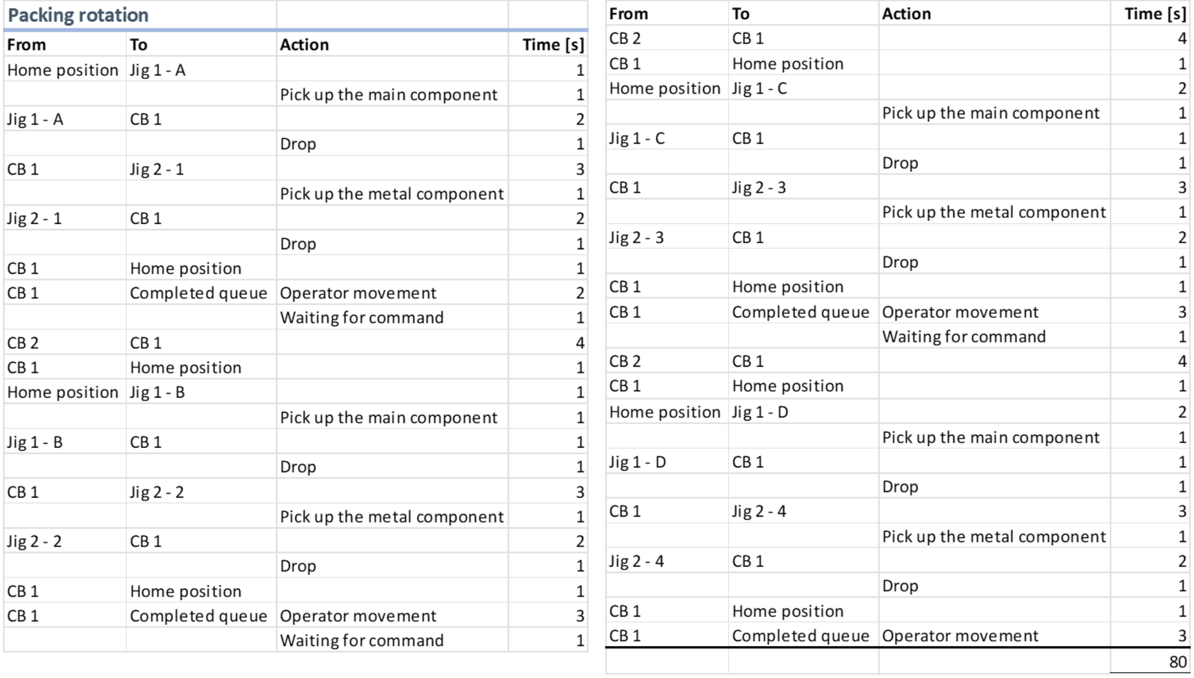
Figure 72 - Robot trajectories in Product Family 1 kit packing



The pilot application was designed for the robot to pick and pack, first the main component from Jig 1, and secondly, the metal component from Jig 2. After placing those parts in the folder carton box (CB), the robot returned to the home position to receive the signal from the teach pendant, as instructed by the operator. Before allowing the robot to continue the program, the operator removed the packed package from the CB 1 location. After the program continuation commands, the robot moved the next empty box to be packed from location CB 2 to location CB 1, and the operator moved the line of empty boxes towards location CB 1.

The phase times of the robot's work movements are in Table 21. The above-mentioned work cycle was conducted four times, resulting in a total time of 80 seconds. Notably, if the main component packaging is divided vertically into four parts according to the supplier's packaging layout, the first quarter is the fastest. After that, the robot's path lengths increase in each quarter. In the robot program, two motion types were used for demo purposes. After placing the main component, the motion path from the packing point to jig 2 was MoveL, while after the metal component was gripped, the movement from jig 2 to the packing point was MoveJ. The difference between the movements is 1 second.

Table 21 - Robot moving times in Product Family 1 packing



Packing rotation

From	To	Action	Time [s]
Home position	Jig 1 - A		1
		Pick up the main component	1
Jig 1 - A	CB 1		2
		Drop	1
CB 1	Jig 2 - 1		3
		Pick up the metal component	1
Jig 2 - 1	CB 1		2
		Drop	1
CB 1	Home position		1
CB 1	Completed queue	Operator movement	2
		Waiting for command	1
CB 2	CB 1		4
CB 1	Home position		1
Home position	Jig 1 - B		1
		Pick up the main component	1
Jig 1 - B	CB 1		1
		Drop	1
CB 1	Jig 2 - 2		3
		Pick up the metal component	1
Jig 2 - 2	CB 1		2
		Drop	1
CB 1	Home position		1
CB 1	Completed queue	Operator movement	3
		Waiting for command	1
CB 2	CB 1		4
CB 1	Home position		1
Home position	Jig 1 - C		2
		Pick up the main component	1
Jig 1 - C	CB 1		1
		Drop	1
CB 1	Jig 2 - 3		3
		Pick up the metal component	1
Jig 2 - 3	CB 1		2
		Drop	1
CB 1	Home position		1
CB 1	Completed queue	Operator movement	3
		Waiting for command	1
CB 2	CB 1		4
CB 1	Home position		1
Home position	Jig 1 - D		2
		Pick up the main component	1
Jig 1 - D	CB 1		1
		Drop	1
CB 1	Jig 2 - 4		3
		Pick up the metal component	1
Jig 2 - 4	CB 1		2
		Drop	1
CB 1	Home position		1
CB 1	Completed queue	Operator movement	3
			80

The robotic packaging system, tested across various products and processes, was not quantitatively measured; however, it effectively demonstrated the seamless programmability of the collaborative robot for both new applications and modifications to existing workflows. This was validated through practical testing. The tests involved developing a packaging application for new products using pre-programmed packaging configurations. The user is required to define the edge coordinates of the starting points, the shape of a single layer, and the number of components per layer. Additionally, the height of each layer was specified. Once these values were entered, the robot autonomously generated the application through repetitive motion sequences. For instance, this functionality enabled the conversion of a four-layer 8×2 packaging pattern, initially provided by the supplier, into a six-layer 4×4 pattern that met the customer's requirements.

When mapping suitable products for testing robot programming and demonstrating kanban picking, the importance of the tool used in the robot was emphasised. Although it was a simple suction cup lifter that took up considerable space, it was not suitable for handling all products. The reasons were the excessive weight of the products, the lifting capacity offered by the suction cup gripper, the packaging solutions provided by the product suppliers, and the shapes of the products. The lifting capacity offered by the suction cup gripper had been mapped to be suitable for the actual pilot project, so other possible uses were not considered when selecting it. The packaging solutions provided by the product suppliers enabled the use of various types of grippers. Both suction and finger grippers can be used for several products, while for some products, such as wire harnesses, picking is only possible with finger grippers. A magnetic gripper could be used for several metal parts, but the strength of the magnet would have to be adjustable so that only one piece is lifted at a time.

Cylindrical capacitors highlighted the importance of precise alignment. If the pick-up point were not perfectly centred, the product would come out of the supplier's packaging at an angle, causing the item to hit an adjacent item. The collision resulted in the capacitor being lifted off the vacuum gripper. Additionally, while the cylindrical base surface area of some capacitors would have allowed the vacuum gripper to grip, the pins on the capacitors prevented the suction cup from thoroughly engaging. With a three-finger gripper, even smaller capacitors would have been possible for the robot to handle.

Some products were disorganised in the boxes and pallets provided by the supplier. A camera-assisted bin-pick solution is also required to pick up these products with the robot.

7.2 Payback calculations

The payback calculations and estimation of overall suitability were made based on the time used to complete one set of the kit. Manual operational times are based on a work study conducted. The operational time for the robotised solution is observed during the pilot. The duration of the tasks performed by the robot has been determined based on videos recorded during the pilot. The screwing time per screw is calculated from the number of screwing's, and the screwing time for the third screw is assumed to be the same as the average screwing time calculated with two screwing's. In the BU2’s Product Family 1 kit packing, the average time used to pick and pack one component is also calculated as an average from the total duration. In a real-life application, the component placement determines the final application time for the robot.

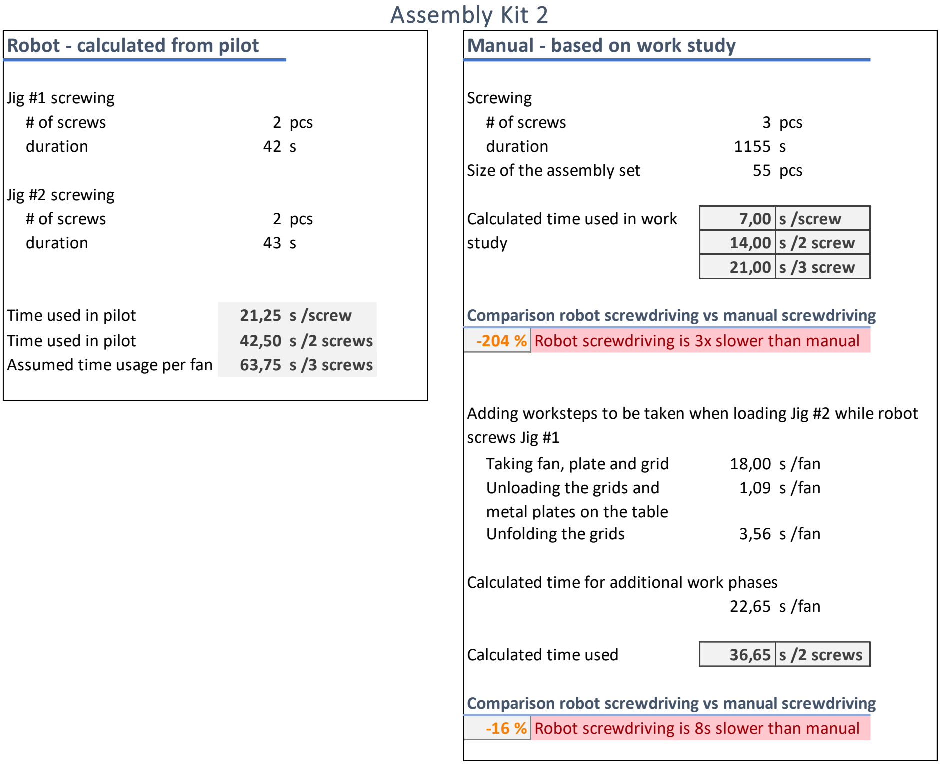
In this research, there was no attempt to optimise all conditions to the point of producing the most advanced solution possible. The purpose was to investigate and verify, using a rough concept, whether collaborative robotics could be utilised in this type of operation. This also resulted in the robot speed being set too slow, with intermediate steps in the programs that had to be acknowledged by the operator via the controller. In addition, the structure of the robot's movable platform led to placing the robot more firmly than optimising the space available. The decision resulted in unnecessarily long trajectories by the robot.

7.2.1 Assembly Kit 2 calculations

The comparison of the calculations for the Assembly Kit 2 is presented in Table 22. The time used by the robot for screw driving is relatively constant between the jigs, indicating that the robot's positioning was successful. It did not matter from the operator's point of view which jig the robot was working on. The operator had the same amount of time on the tasks regardless of the jig. On average, for two screws, the robot used 42,50 seconds per fan. In the manually operated assembly, the average time required for two screws is based on observations from a work-study; the average time used for two screws was 14 seconds per fan. When comparing only the time spent on screwing itself, manual screwing is approximately three times faster than screwing done by the robot.

During the robotised screwdriver, the operator was able to unload the screwed fan from the jig a re-load the jig with new components. By incorporating these work steps into the manual assembly calculations, the calculated time required for manual assembly increases to approximately 37 seconds per fan. As a result, robotised screwing is only 8 seconds slower per fan than manual screwing.

Table 22 - Comparison calculations of manual and robotised scredriving



Assembly Kit 2

Robot - calculated from pilot

Jig #1 screwing		
# of screws	2	pcs
duration	42	s
Jig #2 screwing		
# of screws	2	pcs
duration	43	s
Time used in pilot	**21,25**	**s /screw**
Time used in pilot	**42,50**	**s /2 screws**
Assumed time usage per fan	**63,75**	**s /3 screws**

Manual - based on work study

Screwing		
# of screws	3	pcs
duration	1155	s
Size of the assembly set	55	pcs
Calculated time used in work study	**7,00**	**s /screw**
	14,00	**s /2 screw**
	21,00	**s /3 screw**

Comparison robot screwdriving vs manual screwdriving

-204 %	Robot screwdriving is 3x slower than manual

Adding worksteps to be taken when loading Jig #2 while robot screws Jig #1

Taking fan, plate and grid	18,00	s /fan
Unloading the grids and metal plates on the table	1,09	s /fan
Unfolding the grids	3,56	s /fan
Calculated time for additional work phases	22,65	s /fan
Calculated time used	**36,65**	**s /2 screws**

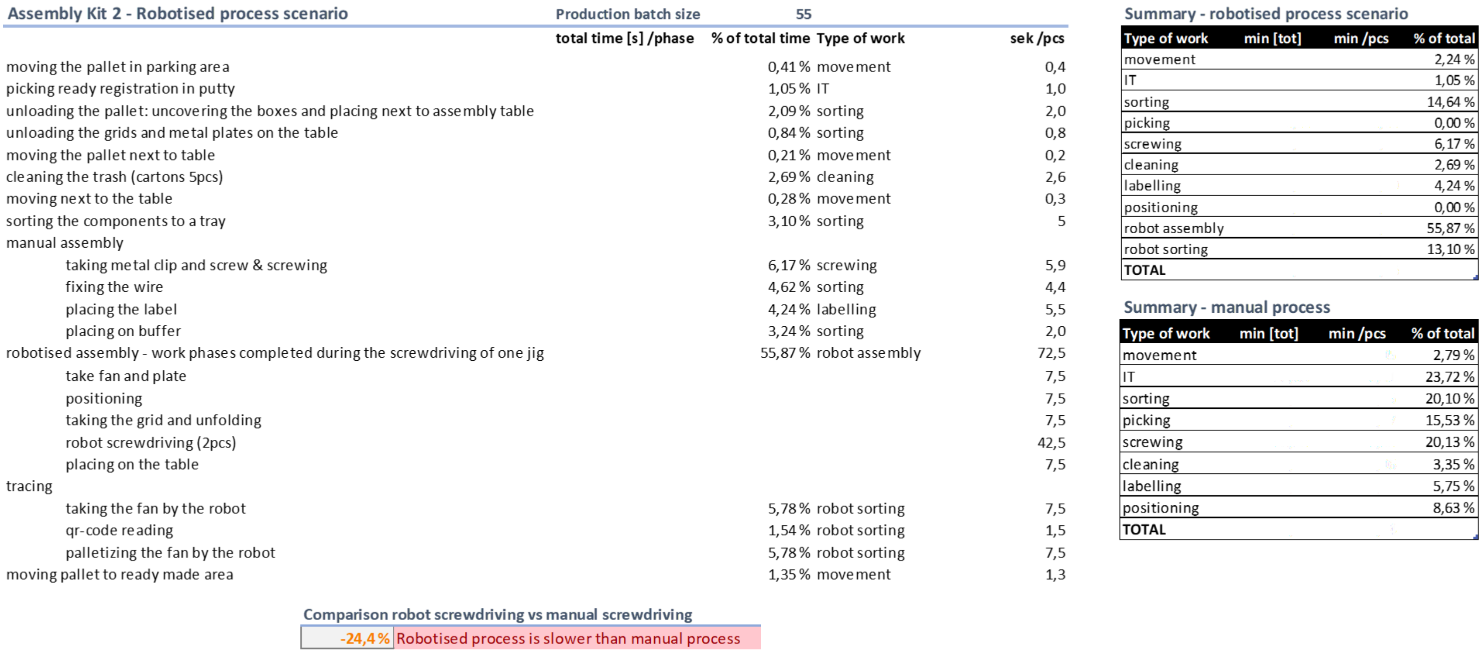
Comparison robot screwdriving vs manual screwdriving

-16 %	Robot screwdriving is 8s slower than manual

The work steps followed after screwing in the Assembly Kit 2 assembly are very similar to the steps in Bu2’s Product Family 1 packaging. In the manual process, the operator places all the screwed kits on a table. The next step is followed by the tracking step, where a QR code label is inserted into the cover plate and read with the scanner to combine the cover plate's QR code with the QR code from the fan component. After the reading, the Assembly Kit 2 is palletised. This work phase involves modifying the customer's IT system to select orders related to this, which could also be automated.

An alternative scenario was estimated and calculated based on the time used in the conducted pilots, as well as on certain assumptions. The created robotised scenario is presented in Table 23, which includes a summary table from the manual process. In the robotised process scenario, the operator's tasks include unloading components from the pallet and placing them in a tray or having them picked up by the robot. After unpacking and sorting, the operator screws the metal clip to the fan component, attaches the power supply wire to the metal clip, and places the fan component into a buffer. Also, the QR code label is inserted into the metal plate. The process would continue as a robotised one, where one robot picks the components from the trays and a buffer and loads the jigs. A second robot would do the screwing of the fan component, cover plate and finger guard. When the screwing task of one jig is finished, a third robot would unload the screwed fan, perform the tracing, and palletise the fan kit to the pallet. Alternatively, one robot would do the loading and palletising while the second robot would perform the screwing.

Table 23 - Robotised process scenario for assembly of Assembly Kit 2



Assembly Kit 2 - Robotised process scenario Production batch size 55

	total time [s] /phase	% of total time	Type of work	sek /pcs
moving the pallet in parking area		0,41 %	movement	0,4
picking ready registration in putty		1,05 %	IT	1,0
unloading the pallet: uncovering the boxes and placing next to assembly table		2,09 %	sorting	2,0
unloading the grids and metal plates on the table		0,84 %	sorting	0,8
moving the pallet next to table		0,21 %	movement	0,2
cleaning the trash (cartons 5pcs)		2,69 %	cleaning	2,6
moving next to the table		0,28 %	movement	0,3
sorting the components to a tray		3,10 %	sorting	5
manual assembly				
taking metal clip and screw & screwing		6,17 %	screwing	5,9
fixing the wire		4,62 %	sorting	4,4
placing the label		4,24 %	labelling	5,5
placing on buffer		3,24 %	sorting	2,0
robotised assembly - work phases completed during the screwdriving of one jig		55,87 %	robot assembly	72,5
take fan and plate				7,5
positioning				7,5
taking the grid and unfolding				7,5
robot screwdriving (2pcs)				42,5
placing on the table				7,5
tracing				
taking the fan by the robot		5,78 %	robot sorting	7,5
qr-code reading		1,54 %	robot sorting	1,5
palletizing the fan by the robot		5,78 %	robot sorting	7,5
moving pallet to ready made area		1,35 %	movement	1,3

Comparison robot screwdriving vs manual screwdriving

-24,4 %	Robotised process is slower than manual process

Summary - robotised process scenario

Type of work	min [tot]	min /pcs	% of total
movement			2,24 %
IT			1,05 %
sorting			14,64 %
picking			0,00 %
screwing			6,17 %
cleaning			2,69 %
labelling			4,24 %
positioning			0,00 %
robot assembly			55,87 %
robot sorting			13,10 %
TOTAL			

Summary - manual process

Type of work	min [tot]	min /pcs	% of total
movement			2,79 %
IT			23,72 %
sorting			20,10 %
picking			15,53 %
screwing			20,13 %
cleaning			3,35 %
labelling			5,75 %
positioning			8,63 %
TOTAL			

From the Summary table, the time distribution is visible. Robotised assembly and sorting work constitute about two-thirds of the total time. The most time-consuming type of work is sorting, which in a robotised process is placing components into a tray or similar. By comparing total used time, the manual process is approximately 24% faster with 55 pieces set than the robotised solution.

The calculation described above is based on the basic assumption that a robot replaces a human and that the speed of a human and a robot is compared. However, during the pilot, the operator was easily able to unload the screwed jig and load new components onto the jig while the robot screwed another jig. By reconfiguring the process to screw the metal clip and attach the power supply wire manually, the need for designing a jig or other fixtures to hold the metal part is reduced. Additionally, the most challenging part of automating, i.e., attaching the power cable, can be done simultaneously. In the modified work cycle, the operator can also label the QR code.

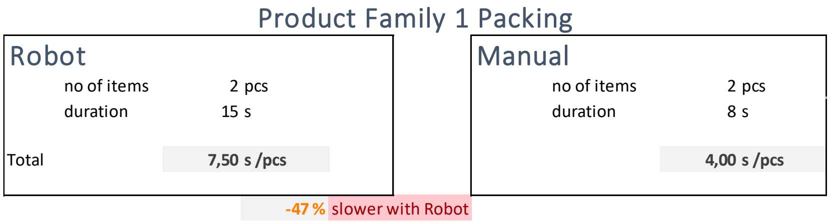
Assuming that the operator first unloads the components from the pallet and places them on the tray. After this, the operator screws the metal part, attaches the power cable, glues the QR code label, and places the fan component in the buffer. While the first fan components are ready in the buffer, the robots can be programmed to start working. After sorting the components, screwing on the metal clip, and labelling the QR code, the operator can proceed with other tasks. While the robot completes its program, the operator can, for example, shelf the pallet from the previous batch and collect the components for the next batch. By making the line 2-sided, the operator can prepare the second batch to start immediately after the first is finished. Alternatively, the operator can manually install other fan kit variations that do not lend themselves to automation due to their low volume.

Another cost-saving opportunity relies on enhanced ergonomics in the process. Based on the data from the ergonomic sensor pilot, it can be observed that repeatable movements occurred, occasionally quite heavily. Another significant issue not reflected in the sensor data is the jerk produced by the current screwdriver when the desired torque is reached. This jerk is directed at the operator's arm when the hand is in a raised position, and the hand is tense.

7.2.2 BU2 Product Family 1 packing calculations

A manually packed Product Family 1 kit and a robotised comparison can be seen in 24. Based on the work-study, the operator used 4 seconds per piece for packing, while the robot took almost twice as long. The robotised duration is an estimated value based on pilot findings, supplemented with additional time resulting from the lengthening of the robot's motion paths. The pilot setup for the Product Family 1 kit packing was not ideal due to the placement of the mobile robot platform. The platform needed to be positioned so that the central unit acted as a weight, preventing the robot from tilting forward. Due to the positioning, the robot's attachment point was far from the actual working area, which used most of the robot's reach. As a result, the components had to be placed unfavourably to the work to be performed, which partly contributed to the relatively long time the robot spent processing each part. Other components, which are packed and inserted inside the package, could not be filled by the robot.

Table 24 - Comparison calculations of manual and robotised Product Family 1 kit packing



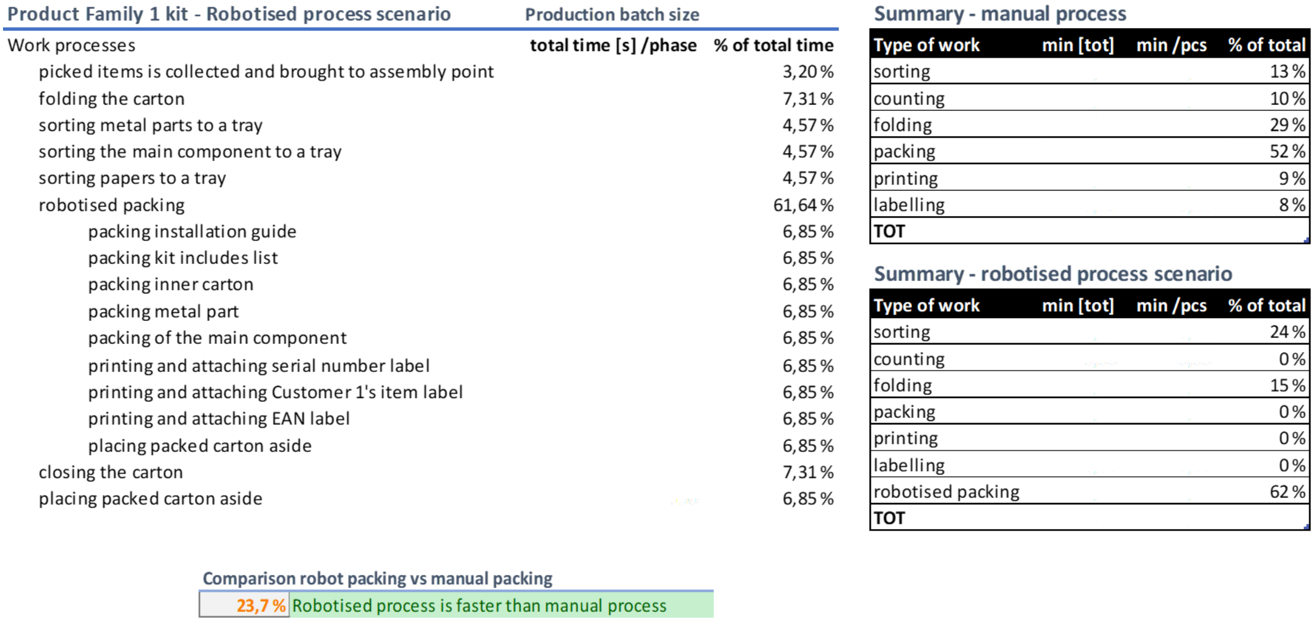
Product Family 1 Packing

Robot			Manual		
	no of items	2 pcs		no of items	2 pcs
	duration	15 s		duration	8 s
Total		7,50 s /pcs			4,00 s /pcs

-47 % slower with Robot

An alternative scenario was also created, which is illustrated in Table 25. Based on the example from DHL Supply Chain Europe operations, leaflets and other general accessories were already folded into the shape of the package's bottom. The used method allowed, for instance, instructions and other papers to be placed on a rack from where the robot could pick them up, just like any other component from a tray. By assuming that this approach can be applied to this application, the robot's processing time would increase. The same applies to labels, which would be printed and attached as a robotised solution. Based on these assumptions and comparing these activities to those conducted by the operator, adding extra steps for the robot results 23% time reduction in packing time per Product Family 1 kit.

Table 25 - Robotised process scenario for Product Family 1 kit packing



Product Family 1 kit - Robotised process scenario — **Production batch size**

Work processes	total time [s] /phase	% of total time
picked items is collected and brought to assembly point		3,20 %
folding the carton		7,31 %
sorting metal parts to a tray		4,57 %
sorting the main component to a tray		4,57 %
sorting papers to a tray		4,57 %
robotised packing		61,64 %
packing installation guide		6,85 %
packing kit includes list		6,85 %
packing inner carton		6,85 %
packing metal part		6,85 %
packing of the main component		6,85 %
printing and attaching serial number label		6,85 %
printing and attaching Customer 1's item label		6,85 %
printing and attaching EAN label		6,85 %
placing packed carton aside		6,85 %
closing the carton		7,31 %
placing packed carton aside		6,85 %

Summary - manual process

Type of work	min [tot]	min /pcs	% of total
sorting			13 %
counting			10 %
folding			29 %
packing			52 %
printing			9 %
labelling			8 %
TOT			

Summary - robotised process scenario

Type of work	min [tot]	min /pcs	% of total
sorting			24 %
counting			0 %
folding			15 %
packing			0 %
printing			0 %
labelling			0 %
robotised packing			62 %
TOT			

Comparison robot packing vs manual packing

23,7 %	Robotised process is faster than manual process

Based on the Product Family 1 volume data from 2022 to 2023, a total of 23079 kits were produced, with a yearly average of 11539. Assuming a time reduction of xx seconds per piece and an internal cost of the operator of yy €/h, annual savings would be estimated at around zz €.

$$\mathrm{zz}\,€ = \frac{11539\,pcs * \mathrm{xx}\dfrac{s}{pcs} * \mathrm{yy}\dfrac{€}{h}}{3600\,\dfrac{s}{h}}$$

As shown in the volume figure (Figure 56), there is a significant annual difference in production volumes between 2022 and 2023. Therefore, the annual production volume of over 11000 units used in the calculation is not realistic. It should also be noted that these assumptions and calculations apply to only one package. If the package is robotised, the suitability of several different packages for robotised packaging must be assessed.

7.3 Results and project assessment

At the beginning of the study, guiding questions were established, based on which the research was conducted, and answers were sought. The answers to the research questions were obtained from the results of the study. The answer is reviewed in their chapters.

7.3.1 Assembly Kit 2 results

The first question of the research design was:

1. Can a collaborative robot be utilised in the 3PL warehouse operations?

Based on the study's results, experiments, and observations, it is entirely possible to utilise a collaborative robot in the 3PL environment. As Latokartano et al. (2023) state, the best-fitted assembly work for the robots is a sub-assembly task that serves to reduce the throughput time in the final assembly. When it comes to the use of collaborative robots in assembly tasks, they are ideally suited, as human labour can be shifted, depending on the case, to handling materials or removing the finished piece. During the assembly process, human effort may not be needed. (p. 53) During the pilot, it was observed and verified that without significant changes to the layout, a collaborative solution can support the human operator. As Braun et al. (2016) point out, with fixed-fenced robot applications, significant changes to the layout may be required. The relatively low investment cost of a collaborative robot is in favour of using collaborative robot applications. In addition, savings in investment are achieved by not having to make necessary investments in security or material handling equipment. (p. 13) Collaborative robot application offers greater benefits for the operator to work alongside the robot.

The manufacture of Assembly Kit 2 is specifically designed to meet the production needs of Customer 1, which requires one fan kit for each device manufactured on Customer 1's production line. PoC showcased the overall functionality of the process, as well as the cooperation between the robot and the human during the process. The Assembly Kit 2 is produced based on the MTS strategy, which offers standard set quantities and palletising patterns.

Based on interviews conducted in operations and data collected using ergonomic sensor pilots, a high level of repetitive movements is observed at times during the assembly process. This research and observation are supported by Latokartano et al. (2023) and Wilson (2019), who justify the use of robotics in assembly applications. Assembly tasks are labour-intensive and require both high precision and production speed. The weight of the components used and the final product is usually light, making them difficult for humans to handle. A second and more important argument is that using a robotic assembly solution is ergonomically challenging and monotonous for human operators. (pp. 100, 121; p. 53)

The PoC provided a good experience with the robot screwdriver and its selection. Although the desired torque was not achieved, the functionality of the screwdriver was tested. From a safety perspective, it is recommended to use a screwdriver when inserting the screw into the sleeve during robot movement. This allows the operator to perform tasks during the robot's movement without needing to ensure that the screw does not scratch the operator's hand or fall off if it is struck. A disadvantage observed, which needs to be tested and proven in the future, is the functionality and reliability of the magnetic grip in such an application. The number and quality of problems observed indicated that the screwdriver bit holding magnet was either already damaged or damaged during the screwing pilot. Another benefit of the piloted solution is the screw feeding system, which allows the use of several different screws, provided that the screwdriver bit remains the same.

An alternative to a system that holds the screw in place is a screwdriver, where the screw is fed directly through a tube into the screwing tip. This type of solution can also provide efficiency benefits because the back-and-forth movement required by the robot to the screw feeding station is eliminated. After screwing the screw, the robot can proceed to the next screw, and the screw is delivered along the hose. In general, however, it can be stated that the measured screwing phase times may serve as a guide for system sizing in the future. Screwing will probably take 1-2 seconds longer per screw, as more time is required to achieve a higher torque.

The process used, where the operator performed the unloading and loading of the fan from the jig and the placement of new components into the jig during the robot screwing, was functional. The measured 42 seconds per jig was enough for the operator to perform the unloading and loading. An observed fact related to the jigs was their loosening during use, which may also have contributed to the observed quality problems. The process included the commands necessary for the robot to move from one jig to another, which the operator executed via the control panel. The process can be slightly accelerated by also making it a partially forced cycle when the jigs are equipped with a mechanical relay. The relay is released when the jig cover is open, and the relay closes when the jig's handle is pressed closed. A simple mechanical relay could serve as a signal for the robot to perform a screwing task in a possible application. A mechanical relay is a cheap and straightforward solution, the maintenance and repair of which can be done completely independently.

Based on the conducted research and the PoC pilot, it is not possible to unequivocally state the suitability of the fan assembly for robotisation, but no fundamental obstacles were identified. The answers to the follow-up questions support the continuation of robotisation as well as further research. It is essential to choose the proper work steps that will be robotised and those that will remain the responsibility of the operator.

If collaborative robotics is to be utilised in the process, the follow-up question was as follows:

2. If yes,
   a. In which process(es) would it be utilised, and how would the process(es) be operated after collaborative robot implementation?
   b. What would be the outcome related to cost savings and benefits?
   c. Would it be possible to get more volume if the process could be automated?

The speed of human and robot performance should not be compared. As Armstrong & Shah (2023) point out, a direct comparison between humans and robots often leads to a "lights-out dream" that should be avoided. Creating a comparison of direct input costs ignores other improvements related to the process. It is about the team and improving its performance. The key question is: Can the team perform better with an automated process? Although in many robotic applications, the robot performs the task more slowly than a human, the investment can still be justified by the higher productivity it enables. (pp. 88-89) Apunen (2016) highlights the role and possibilities of collaborative robots. These robots are designed to work with humans. When automating processes, an either-or situation should be avoided; instead, adopt a both-and approach. In this way, part of the processes can be automated, and robots can support humans by creating situations where humans and robots produce more than humans or robots alone. (p. 6)

Calculations based on the pilot test support the aforementioned notion that, in a direct comparison of screw-driving performed by a robot and a human, the robot is slower than the human. Moreover, it was also verified by considering the operator's work with the jig, including unloading and loading tasks. As an alternative calculation, a process was created where the operator fastens a QR coded label, screws a metal clip onto the fan, and inserts the fan's power cord into the clip. After this, the process would be robotised with a corresponding robotised screwing, and a second robot would enable the follow-up steps. After the screwing, it is a matter of reading two QR codes and placing them on the platform according to a predefined, repeating pattern.

When comparing the direct throughput time done by a human and the robot-human combination, the process is still faster when done by a human alone. However, by placing the work steps on a timeline, as shown in Figure 73, we see that by slightly modifying the process, a situation can be created where, after a human does the sorting and assembly of the most challenging steps to automate, the rest of the Assembly Kit 2 assembly and process can be automated. With this approach, a free period (marked in dark grey) is allocated for each produced batch for the operator to perform other tasks. With a modified process, new functions for the assembler would involve assembling kits of two or three fans, shelving the previous batch, and collecting components for the next batch, which other warehouse operators currently perform.

Figure 73 - Robotised screwing work timeline

A robot vs human calculation would be based on savings, meaning how much time would be saved if a robot were to do the job. Based on the production volume during the review period, an average of three batches of single-fan fan kits are manufactured per day. The robotised solution can achieve annual savings of zz € at the hourly rate of one worker. It can also be seen from Figure 73 that although the duration of the robot installation is longer than that of a human installation, the overall throughput time remains unchanged.

$$zz\,€\,/year = yy\frac{h}{d} * 250\frac{d}{year} * xx\frac{€}{h}$$

The benefit of the productivity improvement achieved by the robot can be seen, for example, through increased billing. Currently, Customer 1 is billed for xx hours per produced Assembly Kit 2 batch of 55 pcs at yy € per hour. Invoiced time includes all activities, such as picking, assembly, and shelving. Based on the conducted work study, non-assembly-related activities account for 15% of the time per batch. When the price per unit is calculated from this, it can be stated that if the operator can be assigned a task for which more than zz € per performed action can be charged, the human does work which would generate more revenue. The robot can handle less valuable, repetitive work that has been reported and measured to be burdensome for humans in places. Usually, investments are justified through savings, but they can also be justified through additional revenue.

$$zz\,\frac{€}{\mathrm{pcs}} = \frac{\mathrm{xx\;h} * \mathrm{yy}\frac{€}{\mathrm{h}}}{55\;\mathrm{pcs}}$$

It is not yet possible or economically viable to robotise two or three fan assembly lines due to their low volume. However, by robotising one fan assembly line, a labour-intensive work step can be relieved by following Dinwiddie's (2019) four D's (dull, dirty, difficult, dangerous) principle. (p. 35) Westcott et al. (2024) note the shift in emphasis in robotisation from productivity thinking to flexibility and quality thinking, where productivity thinking is considered short-sighted due to the additional costs incurred by robotisation. (p. 9) Hänninen (2022) highlights the overall progression of robotics, where a robotic arm with six degrees of freedom represents a pivotal advancement in the evolution of industrial robots. Despite historical resistance to the integration of robotics, operational workers are more likely to accept robotised solutions, as they will take over tasks in hazardous, monotonous, and unclean environments, improving both safety and efficiency. (pp. 59-61, p. 74)

Improving human ergonomics by robotising part of the manufacturing process can also affect the flexibility and quality of production, as well as the costs. Collaborative robot applications with movable platforms offer greater flexibility for changing between products and production types. Productivity improvements are achieved by reducing the number of sick leaves and by enabling the operator to perform a manual fan kit assembly set while the robotised assembly is in progress. By improving the staff's working environment with a robotic solution, the amount of potential resistance caused by the robot can be positively influenced.

It is known that Customer 1 has similar sub-assemblies to those of Assembly Kits 1 and 2. By robotising part of the manufacturing process for one product family, DSC FI showcases its capability to robotise assembly operations and serves as an alternative manufacturer for Customer 1's sub-assembled units. Simultaneously, DSC FI differentiates itself from other 3PL service providers by also being a viable option for new customers whose logistics outsourcing needs cover logistics from inbound to production.

The third question examines potential barriers to using a robotic application.

3. If no,
    a. Why can it not be utilised?
    b. What are the barriers to implementing a collaborative robot?
    c. What is needed to make it possible?

Some limitations and notes need to be considered. The screwdriver used in the pilot did not achieve the desired torque; the used jigs were qualitatively insufficient, and there were component quality defects and deviations. As mentioned earlier, although the used screwdriver solution appears to be a positive option, the actual solution has not yet been fully developed. The solution also affects the total cost of the investment, as the costs of screwdriving tools operating on different operating principles can vary. Additionally, the need for fans for various screw types must be considered.

For jigs, additional studies are needed to consider the variations in different fan and cover plate configurations, including how they can be positioned in the jig and how to ensure the alignment of screw holes for the screwing process itself. This also affects the choice of tool and its properties. The solution presented by Asfahl (1995) for tolerance management can be implemented using the RCC (Remote Centre Compliance) feature of the tool. In this, the tool "gives a little", allowing for better alignment of the component. (p. 155) For the developed robotic process to free the operator to perform other tasks, the application must be able to both unload the finished fan and load new components into the jig. Lifting the finished fan and placing the components is a relatively easy pick-and-place type task, but the functionality of the jig must be solved. If a similar jig with a lid is used, ensuring functionality means considering how the lid is opened and closed, as well as how the sign is given to the robot to indicate the next screwing task. If it requires the use of multiple tools, it might be cost-effective to use an operator for switching the tools, as the operator is always present at the beginning of each production set.

The observed quality defects in components and variations between cover plates, even when using the same fan, can cause problems. Since the components used are not the property of DHL and DHL does not influence component suppliers, the customer must be committed to the change. The study could not completely unambiguously verify whether the alignment problems that occurred were due to the components or the jig. Warped sheet metal sheets were observed in the pilot, which affected the positioning.

The billing basis used for this activity does not provide DHL with a basis to invest in automation solutions. The current billing basis for assembling fan kits is hourly, although most other activities and kit production are based on performance. The used contract model means that, without any other agreements made with Customer 1, all actions towards process enhancement primarily aim to reduce the used time and, therefore, the DSC FI's revenue from the customer. As Jalanka et al. (2003) state, the accrual basis principle is the easiest charging criterion when the service to be performed can be defined with sufficient precision in terms of content and workload. An hourly-based pricing model could be used for invoicing temporary works whose scope is difficult to predict. Generally, hourly based pricing should be minimised and used to supplement other work and contract types. (pp. 49-50). As fan kit production started in 2022, it is no longer possible to justify it as fixed-term work, nor is the scope difficult to predict.

As the 3PL study (2024) reveals, contract lengths and the lack of clear business benefits are cited as the primary reasons why 3PL operators are unable to invest in automation (3PL study, 2024). Robots are traditionally investments that are directed at a company's assets. The growth of RaaS (robot-as-a-service) lowers the threshold for robotics applications. RaaS enables companies to lease robotic applications as a subscription service, thereby avoiding the burden on the company's balance sheet. It also allows for easy scaling options, such as those used by warehousing industries. (Marr 2020, p. 147)

It is challenging, if not impossible, to accurately evaluate the total costs of the project due to open questions regarding the jigs, tooling, and other accessories to be used. Neither the calculated savings nor the potential additional sales that could be achieved are significant enough to make this investment immediately profitable. The practical challenge is the time freed up by robotisation, if it is intermittent. From a risk management perspective on behalf of DSC FI, it also makes sense to involve the customer in the project, as the product manufacturing process and component contract management are under Customer 1's control. DSC FI does not influence any possible changes or shortcomings related to the used components.

7.3.2 BU2 Product Family 1 Kit Packing Results

1. Can a collaborative robot be utilised in the 3PL warehouse operations?

Pick-and-place applications, particularly for 3PL providers, benefit from plug-and-produce collaborative grippers, which enable easy replication and flexible redeployment with EOAT amid changes in product or contract (Tarantino, 2022, p. 326). Collaborative robots, which can move without guarding, enhance labour savings and throughput, particularly in multi-shift operations. They also improve ergonomics by automating heavy loads and reducing repetitive tasks. Robots can handle varying package sizes and standardise pallets, with simple solutions relying on preset patterns, while complex implementations require machine vision or AI. (Wilson, 2019, pp. 98-99; Latokartano et al., 2023, p. 58)

As a PoC for the collaborative robot Product Family 1 kit packaging, the robot is possible to utilise, easy to use, and easy to change the program when the product changes. Observations made are a prerequisite feature for 3PLs of the high-mix low-volume operation type. Packaging of kits is a monotonous and repetitive task, where most of the components and finished kits handled weigh less than 10 kg, which enables the use of a lighter payload and, at the same time, cheaper robot usage.

As was already known at the start of the pilot, a complete set or even an individually packaged product could not be manufactured during the pilot. The decision was related to Customer 1's packaging solutions for the kit product, where folding the inner cardboard was too difficult for the robot to solve in the given time. In addition, the packaging contained A4 or A5 size paper prints, which the operator had to fold by hand to fit them into the box. Third, there were labels to be printed, of which there were three in this variation, each on a different label base.

When testing the packaging of other products in used storage and delivery boxes, the claim about the ease and rapid programming of collaborative robots can be confirmed. Two different people could change the robot's program with no prior experience in robotics or programming. Programming and its ease were based on the utilisation of ready-made software components. It is reasonable to assume that programming robots will continue to be accessible in the future and, with general software development, will offer new possibilities.

Similarly, the general readiness to utilise ready-made programmed components will grow in the future.

One apparent downside has occurred since the review and research period. Volumes have decreased tremendously in 2023 compared to 2022 levels. However, this is particularly evident in Customer 1's operations, especially in the manufacturing of the Product Family 1 kit. Volume fluctuations are part of the 3PL business, but at the same time, they reduce the opportunities to utilise robots.

Based on the conducted research and the POC pilot, it can be stated unequivocally that the Product Family 1 kit is not suitable for implementation using robotics. The solution itself and the use of a robot are entirely possible, but it requires more volume, clear packaging standards and a redesign of packaging and packaging methods. The answers to the follow-up questions support the continuation of the study on enabling robotisation, identifying those that are robotised and those that remain the user's responsibility.

2. If yes,
    a. In which process(es) would it be utilised, and how would the process(es) be operated after collaborative robot implementation?
    b. What would be the outcome related to cost savings and benefits?
    c. Would it be possible to get more volume if the process could be automated?

One clear benefit of collaborative robots is their capability and ease of repositioning between various tasks and processes. On a general level, packing similar kits to the Product Family 1 kit and bagging bulk materials might be a possible combination to utilise the same hardware, extended with sorting and feeder equipment. Repalletising occurs in most operations in every warehouse, at least in DSC FI's operations. It is about improving both quality and picking efficiency, which is achieved by eliminating the possibility of selecting the wrong product from the correct location. Performing quality-related activities, the receiving stage is one of the best options available.

There is potential for robotics around the return and picking processes of Kanban boxes, which would directly improve the efficiency of DSC FI's operations. From a value production perspective, this is partly wasted and partly necessary work. The volume of Kanban boxes consists primarily of 5 standard-sized boxes and several non-standard boxes. Currently, the returnable boxes are manually unloaded from the transport unit and transferred to their designated stacks. When a picker sets out to collect work according to the picking list, they must first collect a certain number of boxes of a specific size in the picking unit, as specified in the picking list. According to the work-study conducted during the process, unloading and arranging returnable Kanban boxes take about xx seconds per Kanban box, and equipping the picker's picking unit takes about yy seconds per Kanban box. On average, the daily volume of returning boxes is zz.

Tämä kohta poistettu

To fully utilise these steps, several concerns need to be considered.

3. If no,
    a. Why can it not be utilised?
    b. What are the barriers to implementing a collaborative robot?
    c. What is needed to make it possible?

To utilise robotics in the Kanban process, both the tool to be used and the identification method for identifying the boxes should be studied first. The size of the boxes varies between the smallest and the largest in terms of standards, so that the largest weighs almost 10 times the weight of the smallest, while the volume is approximately 16 times larger. In return, the boxes can be both nested and stacked, in which case the weight of the stack is not constant. When picking, the kanban boxes can be grabbed from above and handled individually from their respective stacks.

Repalletising, picking, and placing items from the supplier's boxes into the Kanban boxes presents one clear obstacle. The lack of proper master data. Although used components are not the property of DHL, utilising the data is necessary for productivity increases. This was observed during the mapping of practical examples. In addition to the incorrect weight information for the products, it was not possible to detect at the system level how the product can be gripped, what material the product packaging is made of, or how many pieces of the product are in the supplier packaging. Although this was a pilot and the tool to be used was selected based on availability, a significant amount of background work needs to be done for larger-scale utilisation and tool selection. Even though the robot is equipped with a tool changer, it still needs to determine which tool to use for each product.

The use of robotics in kit manufacturing depends on production volume, the number of components, and how they can be lifted and placed in packaging. During the pilot, items such as papers, instructions, and labels often required manual insertion unless they were pre-folded to fit the carton. The pilot setup included the maximum number of labels in various sizes, necessitating the use of three different printers for automation. While collaborative robots are viable for high-mix, low-volume operations, productivity gains are realised when robots run extended cycles, allowing operators to focus on other tasks.

7.3.3 General suitability for 3PL service provider operations

To evaluate the general suitability for 3PL service provider operations, the same research questions are answered.

1. Can a collaborative robot be utilised in the 3PL warehouse operations?

There are no barriers to why collaborative robots would not be appropriate or should be avoided in 3PL operations. The conclusion applies to both the 3PL's warehousing operations and the 3PL's internal operations performed at the customer's premises. The questioning is more closely related to the selected partnership-level strategy, both from the 3PL's and the customer's perspectives. Does the customer seek an operational, tactical, or strategic partnership? As Ståhle (2000) describes the partnership levels, in the operational partnership level, the target is on cost reduction, and added value is purely financial. The strategic partnership level aims to identify and capitalise on significant strategic advantages through innovation in products or services. The added value relies on the opportunity to raise the business to a new level. A tactical partnership targets joint processes and learns more effective ways of working. Through this, the target is to streamline processes and improve competence. (p. 103)

Concerning this Thesis, in particular, the implementation of new technologies and value-added services is a key point that the 3PL service provider is investigating and could develop to bring new solutions as part of customer operations. As Branch (2009) highlights, new technological implementations are a subject that continues to grow due to innovation and cost efficiency in supply chain management (p. 70). Christopher (2011) notes that robotics has been utilised in manufacturing for a considerable time. Now, with the new technological hype, robotics in warehouses is growing at a remarkable pace. (p. 293) One of the main points is the relatively low cost and flexibility. This will also enable the increase of localised manufacturing and offer the assembly of customised products.

From the 3PL service provider's perspective, is it necessary to determine whether the 3PL provider is seeking functions that require a deeper understanding of the customer's processes than simple pallet-in, pallet-out type of operations? Where in the customer's value chain does the 3PL operator want to be? 3PLs are increasingly linked to both the supply and value chains of their customers. Active participation in the value chain creates opportunities to offer a range of services for both pre-and post-manufacturing. As Rushton et al. (2014) and Haapanen et al. (2005) describe these actions as value-added services. Pre-manufacturing activities support the customer's just-in-time manufacturing operations by pre-assembling products directly on the production line, thereby optimising the manufacturing process. This can be done either on the customer's premises or the 3PL's premises. Post-manufacturing services refer to the final modifications made to a product before it is dispatched to the end-user or market. (pp. 577-599, p. 251) By outsourcing pre-manufacturing outside the company's premises, it frees space for its core activities.

As Jalanka et al. (2003) note, the primary reason for outsourcing a company's logistics operations is to focus on its core business. The role of logistics is increasingly viewed as a key factor in determining a company's success in the market. The goals of outsourced logistics have been stated to be flexibility, cost savings, and the release of capital tied up in logistics. Furthermore, Jalanka et al. (2003) mention that investment in logistics is not seen as competitive in the short term. A selected logistics partner can either have these solutions ready or they can take advantage of their economies of scale. (p. 10)

The effort and investment required in a 3PL service provider's operations remain the same, regardless of whether the provider operates in its warehouse or as an in-house service provider at the customer's premises. Investing in robotics may be easier to justify and implement when the provider operates on-site at the customer's location. When competing for outsourcing contracts, the typical agreement lasts for three years. Within this period, it is challenging to develop a robotics application that not only covers its costs but also generates savings for the 3PL provider. However, if operations are based at the customer's premises, they are likely to continue beyond the initial contract term. In the context of robotics applications, the crucial factor is not which 3PL service provider controls the application but rather how effectively the application performs.

As Branch (2009) notes, a 3PL provider should not be selected solely based on cost or daily operational performance. Instead, a provider's development strategy plays a key role in distinguishing it from competitors. A good 3PL operator has a built-in proactive approach rather than a reactive one. (pp. 71-72) When competing for service providers, customers could also select a 3PL operator capable of implementing robotic solutions.

There are several reasons and outcomes why and where collaborative robot applications can and should be used.

2. If yes,
    a. In which process(es) would it be utilised, and how would the process(es) be operated after collaborative robot implementation?
    b. What would be the outcome related to cost savings and benefits?
    c. Would it be possible to get more volume if the process could be automated?

According to MIT (2020), five supply chain technologies deliver a competitive advantage. Robots are one of them. (MIT Sloan) Colestock (2004) suggests that fixed automation solutions are best suited for applications where speed is crucial and batch sizes are large. In contrast, when speed is less critical and batch sizes can be smaller, an industrial robot becomes a more suitable option (p. 193). If a collaborative robot is used for implementation, its execution speed will likely be slower than that of a human.

Tarantino (2022) highlights the ease of deploying and redeploying pick-and-place applications in 3PL operations using plug-and-produce collaborative grippers, enabling replication for similar tasks. The initial application should prioritise simplicity, allowing personnel to familiarise themselves with the system before progressing to complex solutions (p. 326). Collaborative robots offer a key advantage: they enable deeper human-robot interaction without requiring separate safety devices. However, effective collaboration depends on two factors. First, technical standards do not explicitly define "collaborative robots"; instead, the term refers to the nature of interaction. Second, a robot designed for safe interaction does not automatically make an application collaborative. A thorough risk assessment is essential, as external factors like welding sparks or heavy loads can still pose safety risks.

According to Harvard research (Armstrong & Shah, 2023), the primary reason for investing in automation is to increase productivity. Other key motivations include eliminating tasks that pose risks to human workers and enhancing process flexibility (p. 94). To identify suitable projects for robotic automation, Dinwiddie (2019) recommends focusing on tasks that fall into the four D categories: dull, dirty, difficult, and dangerous (p. 35). Automating and eliminating these types of tasks not only improves workplace ergonomics but also reduces sick leave. Even if direct performance efficiency gains are minimal, productivity can still be enhanced by reducing indirect costs.

Even partial automation in processes would bring efficiency benefits, improve ergonomics, and thereby reduce sick leave and the associated costs. For processes operated at the customer's premises, it would be an even easier situation to start robotisation. If the customer decides at some point not to continue cooperating with DHL, the operation and the work task in question will remain at the customer's premises. DHL would still introduce a new solution during its contract period, thereby creating value and enhancing the customer's supply chain efficiency. As Santalainen (2014) notes, the added value produced by expertise should be measurable in a way that enables the customer to understand the expert service received and be willing to pay for it (Santalainen, 2014).

For operations located in DHL's warehouses and processes that aim to reduce DHL's costs, RaaS offers possibilities to allocate costs according to the current service agreement and transfer the cost to variable costs. This arrangement offers several benefits: the investment does not burden the company's balance sheet, the service agreement can be tailored to 3PL's customer agreement, and it involves less risk than a direct investment.

3. If no,
    a. Why can it not be utilised?
    b. What are the barriers to implementing a collaborative robot?
    c. What is needed to make it possible?

Obstacles to not investing in robots are related to targeting higher automation levels, which increases the complexity and, thus, the costs of hardware, software, and implementation. The target setting for automation and robotics is based on productivity and comparison between robots and humans. As Westcott et al. (2024) highlight, increasing productivity and reducing costs are seen as short-sighted reasons for automation. The cost of automation and the shortage of qualified workers to manage and maintain it have raised obstacles. In practice, the financial contribution required for programming may become a barrier to implementing a robotics project. (p. 9, p. 402)

During the Second Industrial Revolution, Edison invented the light bulb, making night seem like day. (Schön, 2013, p. 78) Now, the dream is turning day into night by building lights-out factories. People are needed in production to achieve productivity and flexibility. General Motors' "factory of the future" and Elon Musk's Tesla mass production failed. The automation strategy should be based on enhancing human capabilities and value rather than replacing humans with automation. It is a combination of the strengths of intelligent machines, managers, engineers and production line workers. (Armstrong & Shah, 2023, pp. 90, 95)

The robotics implementation should begin with smaller steps instead of aiming for fully automated production. Enhancing ergonomics and minimising hazardous tasks performed by humans lays a solid foundation for exploring possibilities in robotics. Logistics operations, both in warehouses and production facilities, often involve monotonous tasks that robots can replace.

Although the DFM is more commonly used in assembly applications, it is also applicable to packing operations. As observed in the pilot, the papers included in the kit needed to be printed or pre-printed in sizes corresponding to the dimensions specified at the bottom of the carton to be packed. In the pilot, the paper sizes used were too large to be placed directly in the packaging. The same applies to the product labels used, of which three different types were printed in the packaging pilot. If the documents used were standardised through packaging design, they could also be components that are packaged using a robot in the future. For assembly kits, the possibilities of robotisation can be influenced through product design in terms of screw placement and screw direction. A crucial aspect is the suitability of the quality level of the purchased products for robotic installation. Humans are more creative solvers in parts allocation problems.

As a general rule of thumb, it is not easy to improve a process without knowing the current one. When looking for suitable sites for robotisation, it is essential to have a clear understanding of what is being done and why. As Holamo et al. (2023) and Wilson (2019) emphasise, a mapping of the current state of the process should cover the machines and equipment used, materials, and the manufacturing process, including work instructions. At the same time, it is worth assessing current obstacles, future needs, and the location and space requirements of a possible robotics cell. The assessment of future needs should include the necessary goals for both the desired cost level and the pace and flexibility. (p. 83, pp. 104-106)

Even a good robotisation project idea may not come to fruition if the 3PL service provider is unable to win the customer over, and the future risks caused by the continued uncertainty of possible product or supplier changes become too great. When evaluating robotisation opportunities, external partners or system integrators can provide valuable insights. Interviewing solution providers helps assess feasibility and profitability, offering diverse perspectives on implementation. Preliminary planning, essentially a bid for the project, is a crucial stage, especially for 3PL operators. Three key considerations apply: (1) Robotics implementation is iterative, meaning fixed pricing and solutions are rarely possible. Each stage influences the next. (2) After preliminary planning, supplier recommendations begin to take effect and incur costs. (3) Since 3PL providers handle customer products and processes, financing, cost distribution, and future process changes must be considered. A concept plan, based on initial research and target objectives, outlines space usage, safety measures, material flows, and limitations. Simulations are typically included. The plan remains universal, allowing supplier flexibility and serving as a tender document for potential re-competition.

8 Discussion and future research

The study's results indicate that the screwing of the Assembly Kit 2 can be carried out using a collaborative robot; however, achieving the optimal result still requires further research into selecting a suitable screwing tool and technical modifications related to the assembly. The UR10 was a suitable robot based on its payload capability and reach. More research activities are needed regarding the selection of the proper screwdriver and jigs. For jigs, the number of different die models and backplate variations must be determined to ensure that the components are secured and that the screwing process produces a high-quality result. At the same time, the operating principle of the jig must be determined when the screwing operation in one jig is complete: whether the lid of the jig opens automatically or whether a robot opens it, for example. This decision has a bearing on the lead time.

When selecting a screwdriver, the primary consideration is the required torque and how the screws are fed into the screwdriver. The used screwdriver was a good selection regarding safety aspects, as the screw was inside the ferrule during the movement. If the screw is fed directly to the tip of the screwdriver via a tube, it offers the same safety aspect. The research should also be expanded to the production of other screw-on kits if the purchase of several different screwing tools can be avoided.

The alternative process includes robot-assisted tracking (reading QR codes) and palletising according to a predefined pattern. The latter of these work steps is easy to implement based on the experiences of the second part of the pilot. The successful implementation of tracking requires Customer 1's input to enable the selection and input of various data.

The BU2 Product Family 1 kit packing pilot reinforced the importance of maintaining accurate product master data when alternative SKUs were mapped for packing. Master data includes precise details on the dimensions of the SKU, the delivered carton, and the pallet. Additionally, if the SKU is packed or bundled in any way, relevant material information must be documented. When a single SKU has multiple suppliers, this data must be collected separately for each supplier. In addition, the packaging materials and methods used must be standardised wherever possible, together with Customer 1. Master data is used in every automation solution, regardless of whether the products are transported, stored or otherwise handled.

The trend towards more sustainable packaging is driven by both the materials used and the space efficiency of the packaging. The direction of packing development may lead to changes in both the packing methods used and the actual pack used in the packing process. The possible change will also involve modifying packaging to be more suitable from a robotisation perspective and utilising the DFM principle.

Several other possible processes for utilising a pick-and-place type application are recognised during the project across multiple Sites in Finland. The possibilities are:

- Bagging bulk materials such as screws, nuts or other similar parts.
- Assembly Kit 1 pre-assembly: Can the robot and tooling be used together with the Assembly Kit 2 assembly?
- Re-palletising upon receiving in almost any DSC FI operations.
- Unloading the Kanban transportation unit returning from Customer 1's factory into the warehouse and placing Kanbans into the buffer.
- Providing empty Kanbans in sets according to the picking list for use by pickers.
- Unloading suppliers' delivery boxes from the pallet and sorting them into shelves by production line.

The solution for bagging bulk materials would be based on either a bin-picking application or the use of different feeders. Kanban box handling offers a clear opportunity for efficiency improvement. The boxes are handled at a daily volume of approximately zz boxes.

For DHL Supply Chain Finland, it is recommended to invest in smaller-scale industrial robots, particularly for collaborative solutions. As this research shows, robotics will shape the future, and companies that adopt and utilise robotics will succeed. From a 3PL perspective, the risk is greater because the products and suppliers are not directly under the 3PL license, and the service provided typically continues in three-year cycles.

A couple of years ago, kitting jobs were performed in four different locations within the warehouse; however, they are now managed in three. Upcoming changes in the warehouse create possibilities to centralise kitting operations. This change possibility offers both flexibility in resourcing and centralising the volume as well. This development project would require changes to the layout and renovation of ESD areas to enable the operation of all kitting types. Currently, some of the kitting operations run in one shift, while others run in three shifts, and occasionally, weekends are also worked. The necessary layout changes create the possibility of integrating a manufacturing cell into the kitting process. The cell is familiar with electronic factories and lean thinking. With cellular manufacturing, material flow is smoothened, internal transportation is minimised, and a smaller floor area is needed. Additionally, if the robot and screwing tool can also be used to produce other screwable kits or parts of those, it increases the robot's volume.

There is a moral question of whether welfare is or should be shared. The public, in general, will benefit significantly from the acceleration of digital technology in terms of lower costs. All innovations are indeed based on existing products and services. However, there is a difference, especially between traditional industries and information technology. The latter can scale machine intelligence across organisations, which will lead to the substitution of workers. Secondly, the IT industry creates monopoly situations everywhere. Thirdly, a tiny elite captures the ownership of the accumulated technological capital.

As history has shown, the Industrial Revolution shaped the worldview and influenced people. There has been resistance to innovation due to the fear of job loss. The fact is that innovations have affected jobs in all terms, decreasing, increasing and changing. There are disagreements on how the future will look during the ongoing Industrial Revolution, as this Industrial Revolution is more related to virtual development rather than materialistic development.

Preparing for future changes can be considered at the company level. PESTEL, also known as STEEPLE, is a good starting point for examining the strategic position. It does not create value on its own and should be used in conjunction with other environmental analyses. PESTEL helps to highlight the forces of change that affect the structure and competitive situation of the industry. These themes are an essential part of SWOT analyses. PESTEL stands for Political, Economic, Socio-cultural, Technological, Environmental and Legal. The analysis is conducted on macro-environmental factors that may influence the operations or further strategic decisions.

The results of the thesis can be linked to several of the United Nations' Sustainable Development Goals (SDGs). The goal of the UN Sustainable Development is to secure the conditions for a good life for current and future generations. The focus is on three key issues: the environment, the economy, and people. The program is guided by the principle that no one is left behind in the development process. (Suomen YK-liitto, n.d.) The subject and target are related to good education, which would guarantee everyone access to open, equal, and high-quality education, as well as lifelong learning opportunities. This target is fulfilled both in the workplace and in the educational institution. The pilot was carried out in cooperation with the University of Applied Sciences, utilising the work of both permanent staff and students. The results of the work are also partly linked to enabling economic growth, promoting decent work, and fostering innovation. Production has been relocated to East and Southeast Asia in search of lower costs, which does not reduce the emission reductions associated with production. Robotics has the potential to drive economic growth and facilitate the transfer of production back to countries with higher educational standards and lower production costs. Additionally, this is achieved by increasing productive employment while ensuring a safe and decent working environment.

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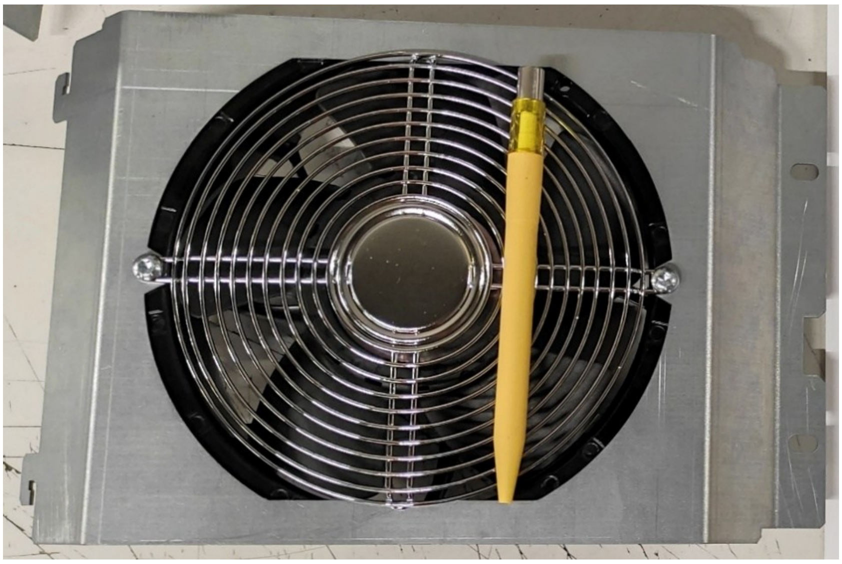
Appendix 1. Assembly Kit 2

Fan kit from the bottom side. Metal clip with the power supply wire on the left-hand side.

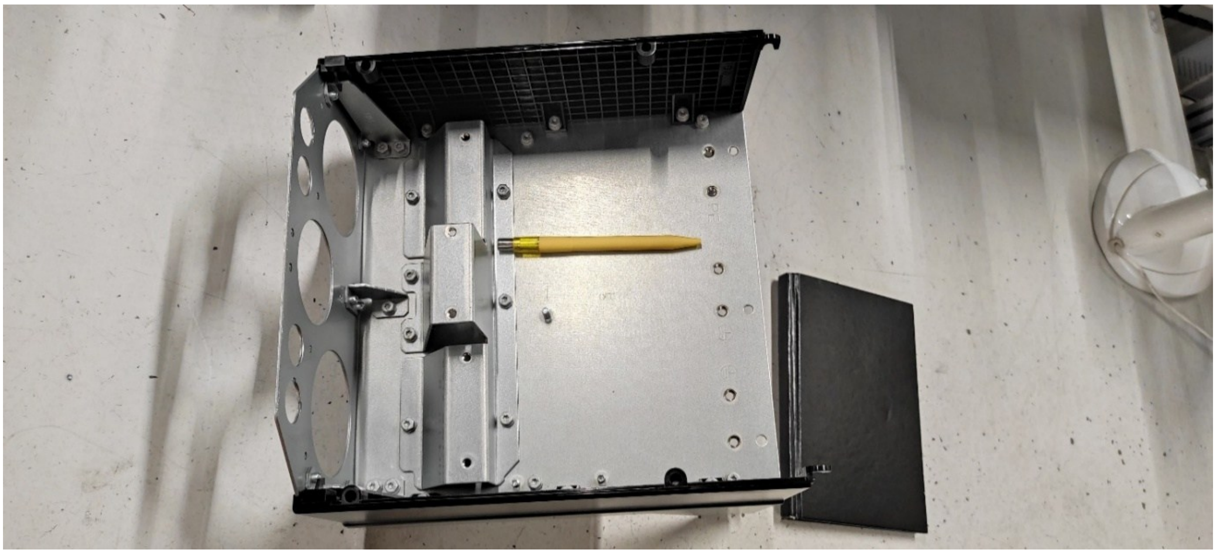
Fan kit from the top side.



Fan kit on a pallet.

Appendix 2. Assembly Kit 1

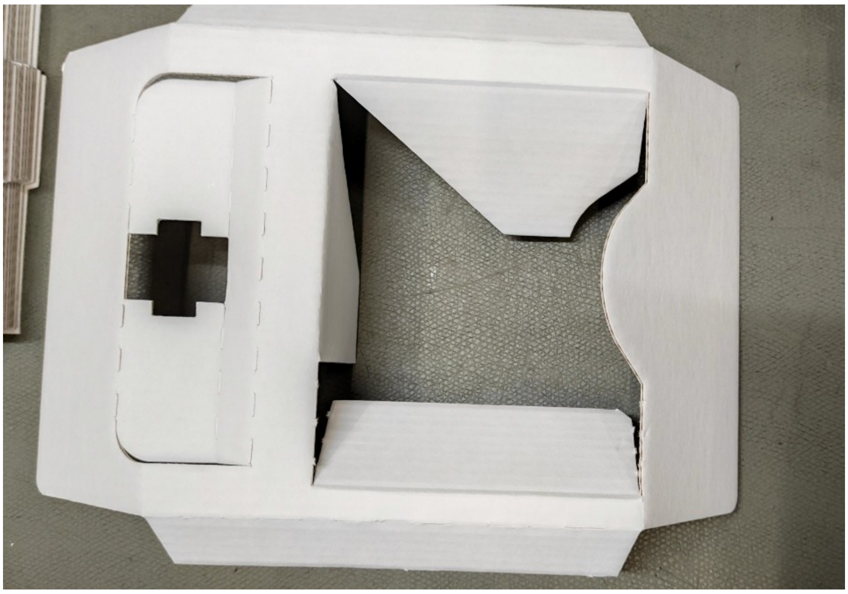
One Assembly Kit 1 variation



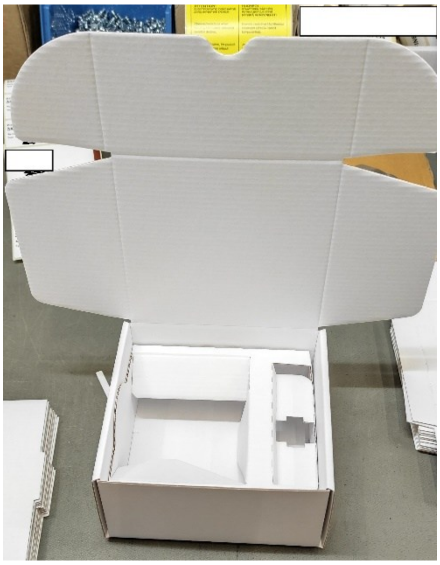
Spare parts to be packed. Packed kit and spare parts.

Appendix 3. Business Unit 2 – Product Family 1 Kit

Folded inner carton



The inner carton is placed in the outer carton.



Components packed and papers folded inside the carton