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Analysis, design, and implementation of a training center for variable-speed drive assembly production Case ABB Oy

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ABSTRACT:
In manufacturing constant developments in production, processes, and layouts are required to respond towards increased production volume, quality, and customer requirements while meeting production targets and objectives. The case company of this thesis is ABB Ltd Drives Manufacturing Unit, which specializes in variable-speed drive production. ABB has recognized the need for re-designing a new and effective training center that supports One-piece flow assembly production since the old model is based on a cell production method. The training center is used for the training and integration of the company's new and experienced assemblers.

The aim of the research is to analyze the current training concept, design a new technical solution, and create a detailed implementation plan. Thus, the following research questions were developed: RQ1: How to develop and re-design a training center that supports the assembler for One-piece flow method production of variable-speed drives? RQ2: How to design and create the best possible layout and solution to guarantee safety, flexibility, ergonomics, clear flow, and the maximum utilization of space? RQ3: How to implement a training center that does not disrupt the main production lines and makes that way operations more efficient?

To achieve the objectives, the waste, bottlenecks, and issues of the current design were first identified by observing the training process and organizing focus groups and workshops with the production line and logistics (customer), and with the project team. Work-time studies were also conducted to solve the flow, outputs, cycle time, and waste time of the current process. These data collection methods aided in identifying potential improvement opportunities for the new design. The layout design process was committed by utilizing Lean principles and the Systematic layout planning procedure. AutoCAD was used to create and map various layout structures, options, and alternatives. The design process required the tendering of two layout location options, which were solved using the quantitative multiple attribute decision-making method, Weighted decision matrix (WDM), with voting based on the scoring of various criteria and features.

The result was a Flexible 6-phase U-model one-piece flow training center that allows assemblers to be trained in both one-piece flow and cell production methods. The new design's scope of work was delivered to the supplier, numerous negotiations were held to achieve the best final solution, and the new training center was ordered. In the end, a detailed implementation plan with an estimated schedule was created and a future action list was established. The new design fulfils the objectives and eliminates all issues, waste, and bottlenecks while also ensuring safety, ergonomics, flexibility, a clear flow, and a high-quality training process. With the new design, the efficiency, quality, and output of training and production operations will improve.

KEYWORDS: Manufacturing facility design, systematic layout planning, lean, One-piece flow, production and process development, training center, assembly production, variable-speed drive, AutoCAD

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ABSTRACT:
Teollisuuden alalla tuotantojärjestelmiä, prosesseja ja layouteja on jatkuvasti kehitettävä sekä modifioitava reagoidakseen kasvaneisiin tuotantomääriin sekä laatu- ja asiakasvaatimuksiin ja saavuttaakseen asetetut tuotantotavoitteet ja päämäärät. Tämän opinnäytetyön toimeksiantaja on ABB Oy Drives Manufacturing -yksikkö, joka on erikoistunut taajuusmuuttajatuotantoon. Toimeksiantaja on tunnistanut tarpeen uuden ja tehokkaamman koulutuslinjan suunnitteluun One-piece flow malliseen taajuusmuuttajien kokoonpanotuotantoon, sillä vanha tuotantomalli perustuu solutuotantomenetelmään. Koulutuslinjaa käytetään niin uusien kuten jo talossa olevien vanhojen kokoonpanoasentajien koulutukseen ja integrointiin.
Tutkimuksen tavoitteena on analysoida nykyinen koulutuskonsepti, suunnitella uusi tekninen ratkaisu ja laatia yksityiskohtainen implementointisuunnitelma. Tavoitteiden saavuttamista varten on kehitetty seuraavat kolme tutkimuskysymystä: RQ1: Kuinka kehittää ja suunnitella koulutuslinja, joka tukee asentajia One-piece flow malliseen kokoonpanotuotantoon? RQ2: Miten suunnitella ja luoda paras mahdollinen layout ja ratkaisu, joka takaa turvallisuuden, joustavuuden, ergonomian, selkeän virtauksen ja maksimaalisen tilankäytön? RQ3: Kuinka implementoida koulutuslinja, joka ei häiritse päätuotantolinjoja ja tehostaa siten operaatioiden tehokkuutta?

Saavuttaakseen tavoitteet, nykyisen koulutuskonseptin aiheuttamat pullonkaulat, ongelmat ja hukka tunnistettiin ensin havainnoimalla koulutusprosessia ja järjestämällä haastatteluja sekä työpajoja tuotantolinjan ja logistiikan (asiakkaan) sekä projektiryhmän kanssa. Nykyisen prosessin virtauksen, ulostulon, tahti -ja hukka-ajan selvittämiseksi suoritettiin myös työaikatutkimuksia. Nämä tiedonkeruumenetelmät auttoivat kehitysmahdollisuuksien tunnistamisessa uutta ratkaisua varten. Layout suunnitteluprosessi toteutettiin Lean-periaatteita ja systemaattista layout suunnittelua käyttäen. AutoCAD layout suunnittelusovellusta käytettiin erilaisien asetterakenteiden ja vaihtoehtojen luomiseen sekä kartoittamiseen. Suunnitteluprosessi edellytti kahden layout-sijaintivaihtoehdon kilpailuttamista. Lopputulos ratkaistiin äänestämällä kvantitatiivisen päätöksentekomatriisin (WDM) avulla, joka perustui eri kriteerien ja ominaisuuksien pisteytykseen. Tulokseksi saatiin joustava 6-vaiheinen U-mallinen One-piece flow koulutuslinja, jonka avulla asentajia voidaan kouluttaa sekä One-piece flow että solutuotantomallisesti. Uuden koulutuslinjan työn laajuus -dokumentti toimitettiin toimittajalle sekä lukuisia neuvotteluja käytiin parhaan loppuratkaisun saavuttamiseksi, jonka jälkeen uusi koulutuslinja tilattiin. Lopuksi koostettiin yksityiskohtainen implementointisuunnitelma arvioituineen aikatauluineen ja laadittiin toimenpidelista tulevaisuutta varten. Uusi ratkaisu täyttää asetetut tavoitteet ja eliminoi kaikki ongelmat, hukat ja pullonkaulat sekä takaa turvallisuuden, ergonomian, joustavuuden, selkeän virtauksen ja laadukkaan koulutusprosessin. Uuden ratkaisun myötä koulutuksen ja operaatioiden tehokkuus, laatu ja tuottavuus paranevat.

AVAINSANAT: Lean, systemaattinen layout suunnittelu, tuotannon -ja prosessien kehitys, One-piece flow, koulutuslinja, kokoonpanotuotanto, taajuusmuuttaja, AutoCAD

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Abbreviations

ABB	Asea Brown Boveri
S&M	Local Small & Medium department
LD	Local Large Drives department
DP	Local Drive Products department
Drive	Variable-speed drive
Drives	Drives Manufacturing Unit at ABB
SLP	Systematic layout planning
Lean	Lean production method
OPF	One-piece flow production method
CMS	Cellular Manufacturing Systems
DMAIC	Define, Measure, Analyze, Improve, Control approach
TPS	Toyota Production System
LSS	Lean Six Sigma
ALBP	Assembly line balancing problem
WIP	Work in progress
AGV	Automated Guided Vehicle
AMR	Autonomous Mobile Robot
FMS	Flexible manufacturing system
FAL	Flexible assembly line
MCDA	Multi-criteria decision analysis issue
WDM	Weighted decision matrix quantitative tool
FIFO	First-in–First-out sequence
MTO	Make to order
Milky-way	Material concept in which material is ordered in advance
AutoCAD	CAD software for 2D and 3D technical drawings
kit	pre-assembly kitting workstation
JIT	Just-in-time pull manufacturing method
Kanban	Pull method for material flow
SAP	Systems, Applications & Products in Data Processing
ACS880	ACS880-01 product family
ACx580	ACx580-01 product family
waste	Non-value added activities
SWOT	Strengths, weaknesses, opportunities, and possibilities analysis
IGBT	Insulated-gate bipolar transistor
PLC	Programmable logic controller
Pre-FAT	Pre-Factory-acceptance test
FAT	Factory-acceptance test
SAT	Site-acceptance test
FPY	First Pass Yield

1 Introduction

The thesis is introduced in this chapter. It includes a background of the research, research objectives, scope, and limitations, and concludes with a description of the case company.

1.1 Background of the research

The manufacturing industry has become tremendously competitive, which is why constant developments and changes in production and processes are very common and essential. Companies are able to gain a competitive advantage by implementing cutting-edge and the latest manufacturing technologies, developing efficient layout structures, and rapidly increasing automation. Companies' new operation models, increased production volumes, and requirements for customer satisfaction frequently drive these changes and developments. With constant reactions, companies can increase efficiency and quality, ensure a safe working environment, and generate savings. Especially in assembly production, re-design projects and continuous improvements of production systems and processes are crucial for meeting production targets and objectives. New products, new process methods, layout capacity changes, and increased customer requirements are typical causes of those changes. To achieve these objectives, companies must plan far into the future, prioritize the most critical investments, and continuously invest in new development projects.

This thesis focuses on ABB Ltd.'s Drives Manufacturing Unit, Drive Products (DP) department, which specializes in producing variable-speed drives for a wide range of applications. This research is carried out because the case company has recognized the need for designing a new and more effective training center for One-piece flow assembly production of variable-speed drives. The training center is used to train and orient both new and experienced assemblers of the company. Many factors contribute to the need for a new training center design and concept. The company has recently begun to use the One-piece flow method, in which the assembly process is divided into small stages in the assembly line. Thus, the current training center is still operating as a private cell, where the assembler produces the variable-speed drives from start to finish alone. Consequently, the old design, layout, and training concept require re-designing and implementing a new solution that supports the one-piece flow model. The new solution should support the one-piece flow model in terms of employee training and integration, as well as providing more efficient production operations. Unclear flow, waste, bottlenecks, safety, and ergonomic risks have also been identified in the current design and concept. The current design also disrupts the production of the main production lines, which causes losses in production volumes and waste. ABB aims to increase sustainability, innovation, and technology, in addition to achieving lift-free operations in the future. As a result, those identified risks, waste, and problems should be eliminated with the new design in order to achieve high levels of safety, effectiveness, and top-quality.

1.2 Research objectives, Scope, and Limitations

The research is a real-life production and process development project, so the main objective of this research is to design a new training center and concept that will replace the old one. The new design should support the company's one-piece flow production model. The additional objectives are to develop an efficient layout and process that eliminates the waste, problems, and risks that appear in the current design. Furthermore, the new design and concept should not disrupt the production of the main production lines, as the current concept does. Three research questions have been developed to guide and assist in the achievement of the research objectives. The research questions are the following:

- **RQ1:** How to develop and re-design a training center that supports the assembler for One-piece flow method production of variable-speed drives?
- **RQ2:** How to design and create the best possible layout and solution to guarantee safety, flexibility, ergonomics, clear flow, and the maximum utilization of space?
- **RQ3:** How to implement a training center that does not disrupt the main production lines and makes that way operations more efficient?

The scope of the research includes first the analysis and then the design of the training center, after that it finally ends with the implementation plan and detailed schedule of the commissioning. The research is limited to designing a training center only for the specific variable-speed drive assembly sector, so it excludes other types of production. To be more specific, it is a case study that focuses solely on the production of drive frames of the DP's Small & Medium department. It excludes the actual employee training process, implying that the training is handled by the factory's experienced assembly workers, whose job description includes employee training and integration. Thus, it includes a process description of the training process, as well as a description of the new training center and its technical features. It also excludes the actual commissioning, building, and installation phases of the implementation. Instead, it includes the scope of work created for the supplier, a detailed implementation plan with an estimated schedule of the commissioning.

In order to achieve the goals and answer the research questions, the literature section explores the most recent literature regarding the research topic, such as books, academic studies, research papers, and case studies. All relevant subjects that support the thesis topic and research section of the thesis, as well as perspectives and best practices that could be utilized, are examined in the literature review. This research requires a deeper knowledge and understanding of the case company's operations and current training center design and process, as well as its analysis prior to the design phase, in order to establish the research section of the thesis. Therefore, the research entails observing the current process, conducting work-time studies, and identifying problems. This allows for the identification and internalization of potential improvement opportunities. To achieve the best technical solution, the designing phase necessitates the mapping of various potential layout alternatives and the tendering of two layout location options. Furthermore, following the designing and ordering of the new training center, the intention is to create an implementation plan with an estimated timeline (roadmap). The purpose of the research is to utilize the operation principles of the case company, Lean principles, and Systematic layout planning (SLP) procedure.

The fields of science that this thesis deals with are systems design and the research is action research case study that employs a design science approach (re-design). Thus, mixed methodology is selected as a research method due to the nature of the research. As a qualitative approach, this research employs observations, workshops, focus groups, and CAD software. As quantitative approaches, surveys (weighted decision matrix) and time studies are used.

1.3 Case company

ABB (Asea Brown Boveri) Ltd. is a global corporation and a pioneer in electrification and automation technology, laying the groundwork for a more sustainable and resource-efficient future. ABB provides solutions that combine engineering expertise and software to optimize product manufacturing, movement, use, and operation. The four customer-focused global businesses that ABB is concentrating on are: Process Automation, Motion, Robotics & Discrete Automation and Electrification. ABB has a long, 130-year history and operates in over 100 countries, employing approximately 105 000 people. (ABB, 2023a).

In Finland, ABB is operating in 20 municipalities and employing 5000 people. The factories are located in Helsinki, Vaasa, Porvoo, and Hamina (ABB, 2023b). ABB Drives business line, which is part of the Motion division, is based in Pitäjänmäki and employs 1300 people. Drives manufactures and develops low-voltage frequency converters and related software tools for all applications and industries worldwide. Frequency converters, known as variable-speed drives, regulate the speed of an electrical motor. ABB pushes sustainability, and its variable-speed drives reduce electricity consumption and carbon dioxide emissions significantly. In 2015, the frequency converter base installed by ABB saved 441 terawatt hours of electricity, which is equivalent to more than 110 million European households' annual electricity consumption (ABB, 2023c).
In 2021, ABB’s revenue was 28,945$, orders 31,868$ and income from operations 5,718$ (ABB, 2022).

2 Literature review

This chapter introduces the key literature and background information of the study. The literature section contains academic literature such as books, academic journals, studies, and examples that are relevant and related to the research section and thesis topic. The information, methods, and techniques found in the literature are utilized in the thesis's results and findings section. To comprehend the thesis's starting points, scope, and research questions, it is necessary to first understand what manufacturing facility design, production development, and process development entail, as well as the methods, techniques, and characteristics required for the analyzing, designing, and implementation processes. Essential production methods, Lean production, and its subareas, such as Lean Six Sigma and DMAIC, are also covered because the case company follows these principles. Since the company's operation methodology, assembly production, structures, cell production, batch production, one-piece flow, and production automation must be reviewed. AGVs, AMRs, and flexible assembly lines will also be investigated. The production logistics are also explored, since it is essential factor for the assembly production infrastructure. The production layout design process, Systematic layout (SLP) procedure, AutoCAD, and Weighted decision matrix (WDM) are all examined because those will be utilized in the new training center's design process. The literature review ends with a synthesis, where the literature is summarized.

2.1 Manufacturing facilities design

Stephens, M. P. (2019), addresses the importance and versatility of facility design and the process in his book Manufacturing Facilities Design & Material Handling. He explains that manufacturing facility design is the arrangement of a company's physical assets in order to maximize the utilization of resources including people, materials, equipment, and energy. Plant location, building design, plant layout, and material handling systems are all part of facility design. Plant location strategy decisions are determined at the highest levels of management, frequently for reasons unrelated to operational productivity or effectiveness, and are not always considered as an engineering decision. The design and material handling of manufacturing facilities have a greater impact on the efficiency and profitability of a firm than practically any other significant corporate decision. The facility design has a direct impact on the product's quality and cost, as well as the supply/demand ratio. The construction of a new manufacturing plant is one of the most expensive projects that a company will ever undertake, and the layout will have long-term consequences for the employees. The price of the plant's products will also be affected. To keep the company current and competitive, ongoing improvements will be required.

2.1.1 Production development

The current market and competitive environment require that businesses develop and manufacture their products in a timely and cost-effective manner. Often, the manufacturing technologies used strongly influence the product concept. Against this backdrop, product and production systems must be developed concurrently from the start. This is especially important for complex products. For example, mechatronic products, which can be defined as a closed-space integration of mechanics and electronics. Today, the interdependence of a product and its manufacturing system is not adequately considered. As a result, development iteration loops are time-consuming and costly. (Gausemeier et al., 2010).

In order to fulfill the demand for an ever-decreasing length of market, development time must be reduced. The simultaneous development of a product and a manufacturing system is an optimistic approach to enhancing already designed development procedures. Furthermore, simultaneous design of the product and a manufacturing system allows for close coordination to avoid massive modifications due to overlooked production constraints. A deep interconnection between product development and manufacturing is required for simultaneous development approaches. Consequently, procedure models are already striving to incorporate manufacturing into the product development process (Javaid et al., 2022).

According to Vielhaber and Stoffels (2014), production development is defined as the improvement of the manufacturing process, factory, or manufacturing equipment. It encompasses the topic of product development as it applies to manufacturing systems and equipment, including more common terms such as layout planning, planning of production, and manufacturing equipment design. They further state the definition of product development, which is defined as the total series of activities necessary for developing a new product. It has been formalized and described for a long time, resulting in numerous process models for both scientific and industrial applications. The product development process involves four primary phases: planning and labor transparency, conceptual design, incarnation design, and detail design. Methodologies and models for the development of manufacturing equipment are not as firmly established as their counterparts in the product-oriented realm, and scientific collaboration is limited. Often, literary techniques concentrate on the details' phases, leaving out theoretical design and concept choice. Production development typically begins with an integrated systems engineering stage that includes layout planning before moving quickly into domain-specific strategy, outlining, and commissioning steps. However, it must be noted that the area of production development varies significantly, from the entire plant layout to an individual assembly station or manufacturing machine.

2.1.2 Production development process

As shown in Figure 1, the lifespan of a product and the lifespan of the corresponding manufacturing machinery intersect in the product's production phase, which also represents the use phase of manufacturing equipment. Both spheres must fit together during this phase and that’s why products and production machinery are frequently developed concurrently in modern serial production.

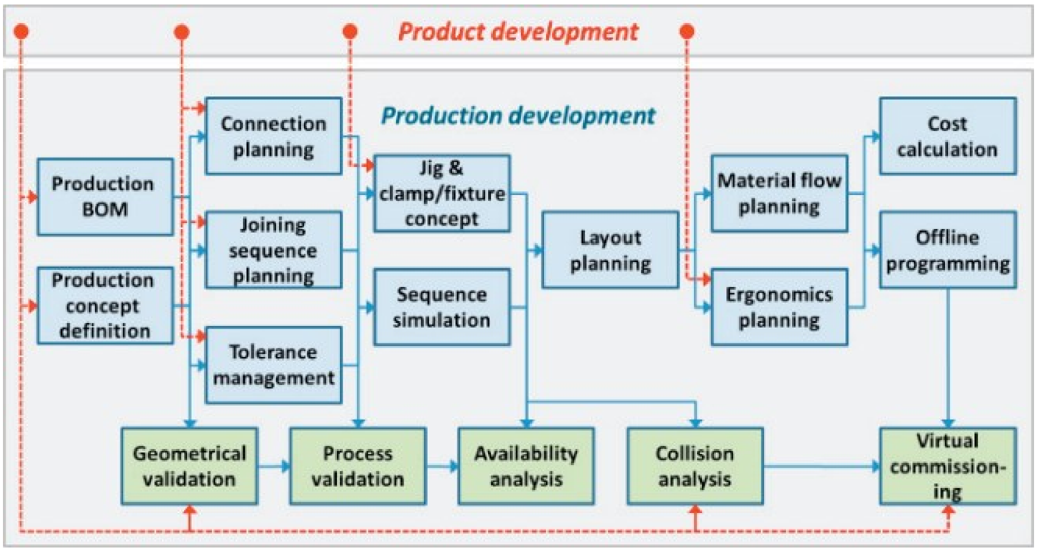

Figure 1. Example of production development of car body production (Vielhaber & Stoffels, 2014).

Since the steps in the production development process are inextricably linked to the product to be manufactured, the methods used must be evenly organized. Modification management and acceptance management are particularly sophisticated methods that must be carried out in partnership with the product development and manufacturing development domains. The product is still widely regarded as the primary input to production equipment, with product-related activities remaining mostly autonomous and possibly enriched with some "planning for production" instructions, whereas production engineering processes are designed to be much more dependent on product-related inputs or adjustments. (Vielhaber & Stoffels, 2014).

Vielhaber & Stoffels (2014) propose an integrated process model (figure 2) built on a domain-spanning view of the product development framework. The following process stages are supplemented by a standard requirements procedure for management that begins with the linked product and production management (product & production system level) phase. The process then divides into domain-specific process streams (i.e., product development and production development), with theoretical and detail-level synthesis stages. Thus, these processes are connected by incorporated evaluation (i.e., verification and validation) operations on the one hand and standardized milestones on the other. Finally, the two streams are returned to the same system level and terminate with an identical production release. The project-oriented manufacturing process stream is completed by a technology-focused innovation process stream.

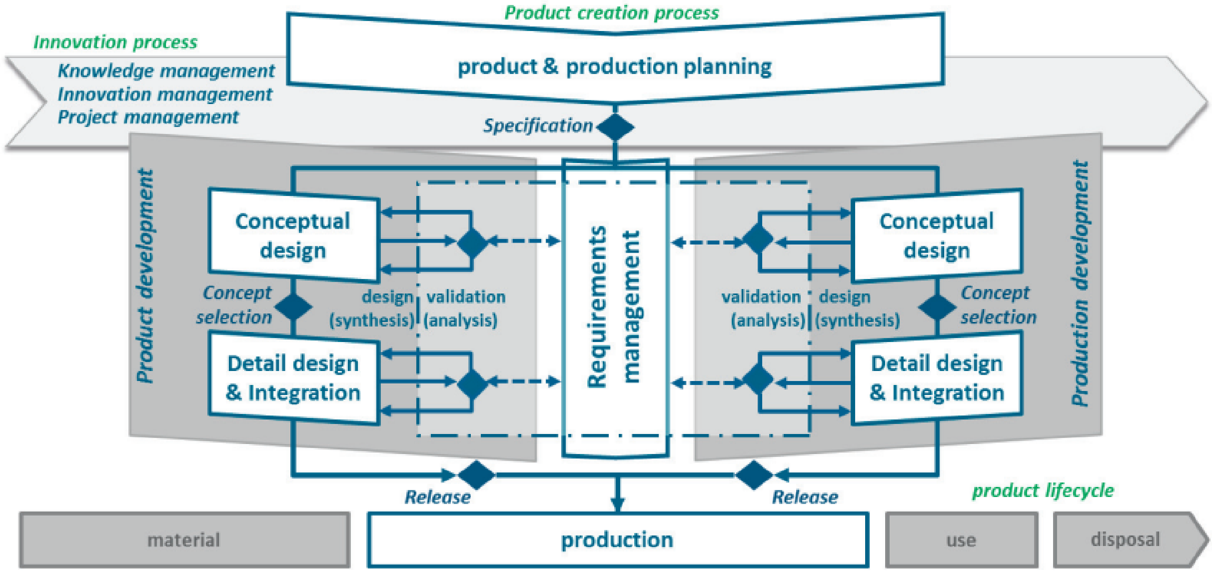

Figure 2. Model of integrated product and production development process (Vielhaber & Stoffels, 2014).

2.1.3 Process development

Process development is described as planned and methodical development largely focused on manufacturing objectives, suggesting the integration of new components into the production process alongside the goal of creating or enhancing production processes and implementing them later conveniently (Kurkkio et al., 2011). Process development takes place in the environment of production, with the goals often being internal to the firm and concentrated on cost reductions and product quality improvement. As a result, it is vital to incorporate operational employees in that process because they will be working with the new or improved process. Engagement leads to increased motivation and decreased resistance to change. Process development refers to the introduction of new input materials, assignment specifications, tasks, data flow mechanisms, or production equipment. (Kurkkio et al., 2011).

Process development is a very complicated organizational function that encompasses a wide range of functions, from laboratory environments to full-scale operations. Instead of being divided into distinct categories that range from incremental to more radical development, process development is a continuum. Process development produces a variety of outcomes, which vary depending on the aims of each individual process development proposal and project. The desired results consist of cost decreases, increased production volumes, and increased production yields. Additional benefits include improved product quality and trustworthiness, a shorter marketing time, and the ability to maintain more environmentally friendly production. The magnitude to which these results materialize is determined by a company's expertise in process development. Lager (2002) proposes a three-stage theoretical model for the "Process development process": 1. Determine internal production requirements. 2. Work in laboratories to develop processes, incorporating pilot plant and manufacturing plant trials. 3. The implementation of development outcomes into production. His findings show that experts frequently perform the initial stage and last stage with little proficiency, even though these are significant stages to achieving a well-functioning production process.

2.1.4 Lean production

Lean production is one of the most prominent modern improvement programs. It evolved from the Toyota Production System (TPS), which Toyota executives created in the 1940s (Poksinska & Swartling, 2018). According to Wickramasinghe (2017), Lean production is a management philosophy that focuses on waste elimination and value creation. Lean manufacturing 'waste' refers to everything that does not add value to the product or service from the customer's point of view. Overproduction, waiting times, unnecessary material movement, inappropriate processing, inventory, defects, underutilization of labor, environmental waste, and underutilization of facilities are all examples of waste. Value-added activities include those that are considered vital by the customer and are completed correctly the first time. They further state that, when compared to mass production, Lean manufacturing utilizes half the workforce in factories, half the production area, half the investment in equipment, and half the engineering labor to produce a new product in half the time. Furthermore, it creates a larger and constantly expanding variety of products, resulting in fewer defects, and necessitates retaining less than half of the needed inventory on-site. This definition addresses system effectiveness by considering the connection between output and organizational objectives, as well as system efficiency by considering the correlation between input and output.

According to Womack and Jones (1996), Lean implementation includes five critical elements: value, value stream, flow, pull, and the aim of perfection. Value specification enables the recognition of customer needs. Value stream analytics distinguishes between actions that must be performed to provide a product to the client and non-value-added activities. Flow indicates that products and services should move continuously and easily through all of the value-creating phases in the value stream, with no stops, delays, disruptions, flaws, or other obstacles. Pull suggests that businesses must manufacture goods or services in response to customer demands and requests. Perfection indicates the need for continuous improvement, as can be seen in the figure 3, which demonstrates the VSM process.

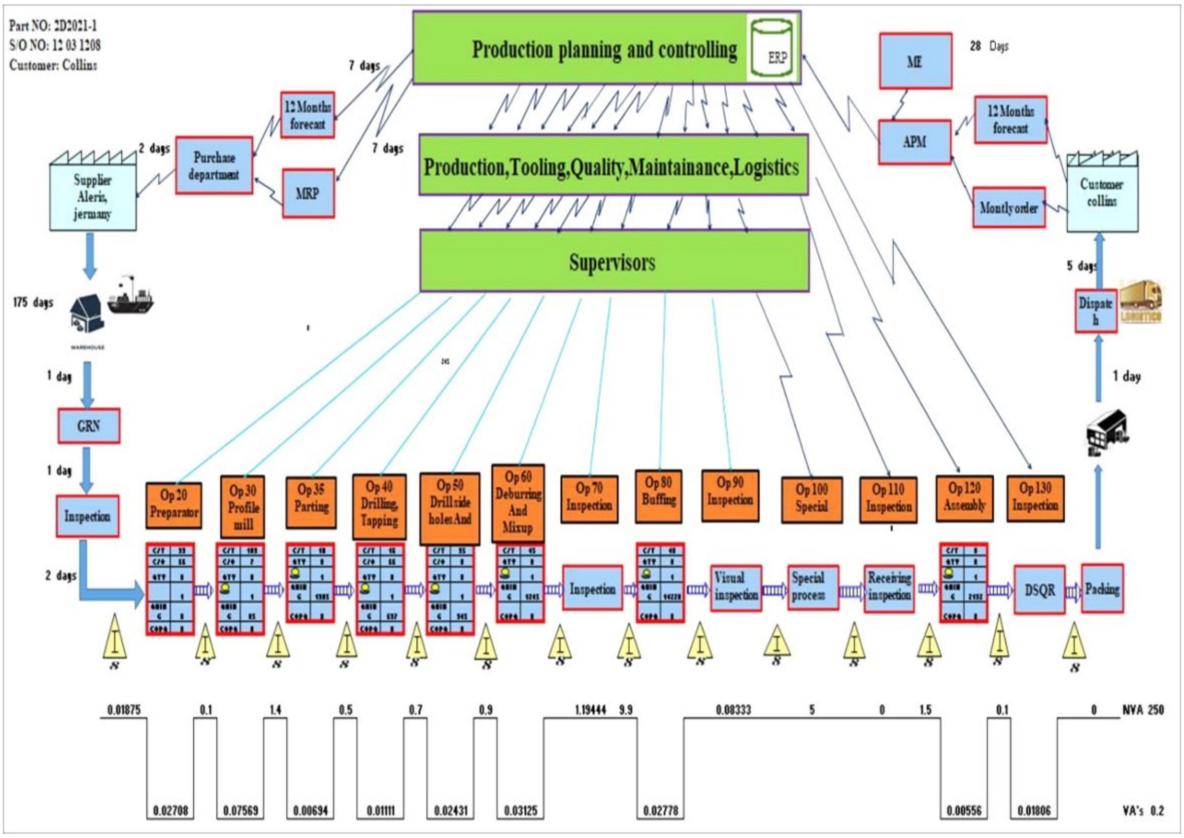

Figure 3. Example of current state VSM in aerospace manufacturing industry (Kundgol et al., 2020)

More specifically, these Lean production practices include cellular manufacturing, a multifunctional workforce, just-in-time (JIT), work allocation, total productive maintenance (TPM), set-up time reduction, total quality management (TQM), continuous flow production, Agile manufacturing approaches, safety enhancement programs, process capability measurements, and human resource management (HRM). And some effective Lean techniques that are utilized in many areas are Kanban, 5S Kaizen, and PDCA (Wickramasinghe, 2017).

2.1.5 Lean Six Sigma

Six Sigma is a methodology established by Bill Smith of Motorola in the 1980s and is now employed globally since General Electric spread the tool over the next decade. There are numerous methods to the Six Sigma theory. Six Sigma is defined as a statistical methodology for measuring the capability of a process. (Baptista et al., 2020). Six Sigma aims to reduce process variation, lower manufacturing costs, and increase customer satisfaction. Six Sigma is defined as six sigma, or six times the standard deviation of the reference value, (-6; +6), corresponding to 3.4 parts per million opportunities (DPMO), and 99.99966% of the goods are within the requirements of the customer. Six Sigma is a strategy that requires top-level support to be successful. As a result, all employees understand the importance of quality to the organization, generating the enthusiasm needed for Six Sigma projects. (Pereira et al., 2019). Six Sigma methodology can reduce process variation and unceasingly improve it in two ways: through the DFSS (Design For Six Sigma) tool, which is generally used for new projects, or through the DMAIC (Define, Measure, Analyze, Improve, and Control) approach to current products, processes, and re-designs. The effectiveness of the DFSS tool known as DMADV (Define, Measure, Analyze, Design, and Verify) has also been widely utilized. When the goal is to develop a new product, service, or process, this approach is appropriate. (Baptista et al., 2020).

In manufacturing, Lean production is usually tied to Six Sigma because there is a symbiotic relationship between Six Sigma and Lean, which means that Lean includes the appropriate tools to perform economically, whereas Six Sigma supplements the process through its statistical control tools. (Baptista et al., 2020). Lean Six Sigma (LSS) can be a powerful method when utilized alongside process improvement and shareholder value maximization approaches, with the ultimate aims of improved productivity, customer satisfaction, reliability, and overall performance optimization. LSS has been developed into a solid management process and a directed form of resource allocation that prioritizes the organization's bottom line as a result of highly organized breakthrough projects. As a result, LSS has risen in prominence as a vital quality and company enhancement methodology to achieve company excellence and competitive advantage. (Shokri et al., 2021). (Daniyan et al., 2022)

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2.1.6 DMAIC process

DMAIC refers to Define, Measure, Analyze, Improve, and Control and is a systematic Six Sigma process improvement technique. It is an effective data-driven methodology that provides an organized problem-solving process and is appropriate for rather large problem-solving undertakings. (Guo et al., 2019). According to De Mast and Lokkerbol (2012), DMAIC was initially described as a method for variation reduction, however, in organizational routines theory, DMAIC is seen as a meta routine, a routine for altering established routines or inventing new routines. DMAIC typically combines a variety of approaches and methodologies, including Lean manufacturing, the VSM tool, and constraint theory. It is also used to help with the planning and execution of Six Sigma projects. DMAIC is used in a diversity of industries, including manufacturing, healthcare, and service, because it reduces costs and improves overall process performance. (Rifqi et al., 2021).

DMAIC's five phases are as follows:

1. Define: Launch the project, identify the process, identify key process outputs, and determine what project deliverables are expected.

2. Measure: Understand the process as it is, collect data to evaluate process inputs, develop and test measurement systems, and assess current performance.

3. Analyze: Using statistical tools and charts, analyze data to highlight key input variables, identify waste, and identify root causes.

4. Improve: Problem solutions are developed and implemented. Check critical input variables, make improvements, and test the new process.

5. Control: Complete the control system and validate its long-term capability. The procedure is also documented so that future improvements can be easily replicated. (Rifqi et al., 2021).

In the "Analyze" phase of DMAIC, for instance, a cause-and-effect diagram known as a "fishbone diagram is utilized to identify the root causes of a problem. For example, in figure 4, the DMAIC approach was applied to improve the bogie assembly process in the rail-car business. The cause and effect of a decrease in process cycle efficiency and an increase in manufacturing lead time are illustrated. (Daniyan et al., 2022).

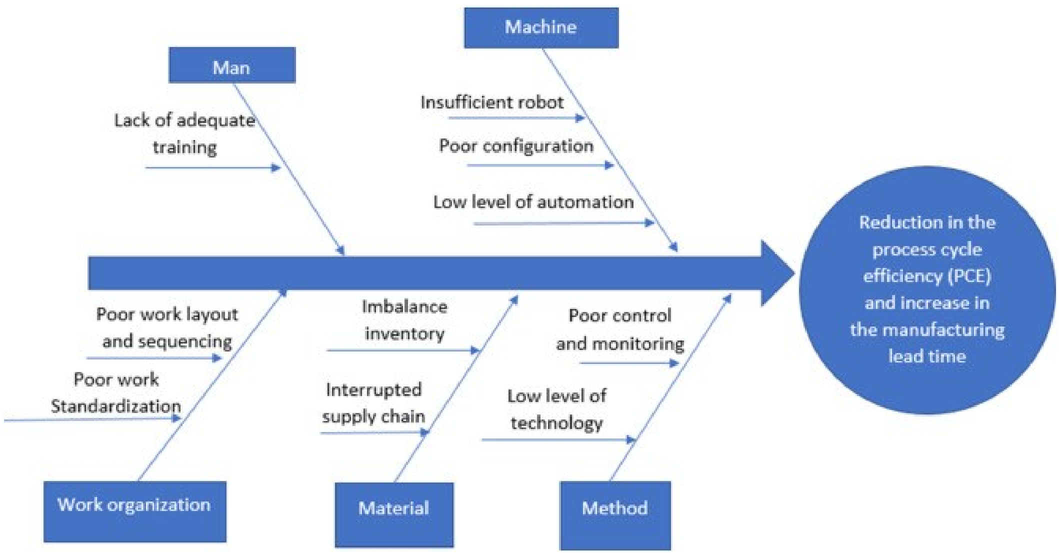

Figure 4. The cause-and-effect diagram for the railcar industry's bogie assembly process (Daniyan et al., 2022)

2.2 Assembly production

Grzechca, W. (2011) addresses in his book Assembly Line: Theory and Practice, assembly production concepts and features. Assembly production is a decade-old concept, with Henry Ford introducing the first manufacturing assembly line in the early 1900s. The assembly line was designed to be an extremely efficient and productive way of producing a particular product. The basic assembly line is made up of a series of workstations arranged in a linear arrangement and linked by material handling equipment. The following is the assembly line concept: The fundamental movement of components along an assembly line starts with an object being delivered to the first station at a predetermined feed rate. A station is any spot on the assembly line where a task on the part is completed. These jobs can be done by machines, robots, or humans. Once a part arrives at a station, it undergoes a task before being supplied with the following procedure: The process time represents the duration of time it takes to complete a task at each operation. An assembly line's cycle time is governed by a desired production rate, and the production rate is adjusted so that the desired quantity of the finished product is produced within a specific time frame. The sum of the processing periods at each station cannot exceed the station's cycle time for the assembly line to maintain a specific production rate. If the aggregate of a station's processing times is shorter than the cycle time, idle time occurs. One of the most essential elements of developing an assembly line is organizing the tasks that must be completed. This setup could be slightly subjective, but it should follow the implied rules established by the production arrangement because there are some task sequences that must be followed when manufacturing any item (Grzechca, W., 2011).

Assembly lines are used for serial production, which requires agility, high speed, and shorter cycle times. As more product models are developed in numerous variants, the number of parts required in assembly processes continues to expand. As space becomes increasingly scarce, preparing all parts for an assembly line in an effective manner is considered a critical task. Separating parts into kits or small bins appears to be a useful method for reducing overburdened assembly line workstations. Thus, costs rise when parts must be prepared in this manner. (Schmid et al., 2020). With the invention of the assembly line came the issue known as the assembly line balancing problem (ALBP). Various methods for balancing the lines have been employed over the course of the assembly line's history. There are numerous methods available today for dealing with the various forms of ALBP. (Grzechca, W., 2011).

2.2.1 Assembly production structures and layouts

According to Heilala & Voho (2001), the manufacturing system and process flow constraints limit system layout. Automated material handling systems are now widely used in modern assembly lines. Manufacturing expenses are reduced as a result of more rapid material supply, fewer space requirements, increased inventory accountability, less handling damage, and fewer workers. Installing a separate material-handling system has increased operator productivity by allowing operators to concentrate their efforts on assembly tasks that call for skill. To suit varying geographical needs, adaptability, and volume requirements, several levels of final assembly line technology are necessary.
Heilala & Voho (2001) further classify assembly production principles and strategies as follows:

1. Sequential manual assembly line.

In a sequential manual assembly line, the assembly process is separated into smaller process phases. The short cycle is easy to understand, and the operator's skill level can be minimal. The "progressive build" principle is another name for this. Because the activities are straightforward, there is plenty of space for automation.

2. Parallel manual assembly line.

On the parallel manual assembly line, one operator or cell performs all manual assembly tasks in one location. This has application in mature plants that produce small lot sizes with a high requirement for flexibility (high mix/low volume). This technique frequently has a long cycle time and necessitates highly skilled and multi-skilled workers.

3. Semi-automatic assembly line.

A segment of the process is automated on semi-automatic assembly lines. The most time-consuming, quality-critical, or ergonomically poor task stages, such as testing and screwing, will be automated in this line design. Automation has high potential if the product is assembled sequentially, and cycle times are short. The assembly procedure has already been broken down into smaller, easier steps. When the manual assembly process employs the whole build concept and volume is achieved through parallel work-places, automation becomes significantly more challenging.

4. Flexible automatic assembly line.

Flexible assembly lines automate the assembly process. This offers potential for high-volume items in relatively large batches in nations with high labor expenses.

5. Dedicated automatic assembly line.

Dedicated automatic assembly lines are employed for items that require exceptionally large manufacturing volumes, such as mass production (CAM actuated rapid machines, synchronous transfer lines, and so on). (Heilala & Voho, 2001).

According to the research of De Carlo et al. (2013), it is also possible to use a schematic classification. Workstations should be organized based on the numerous characteristics of a manufacturing process, the productive capacity, and the range of items, as shown in figure 5, which indicates the presence of four different types of layouts with a variety-quantity relationship.

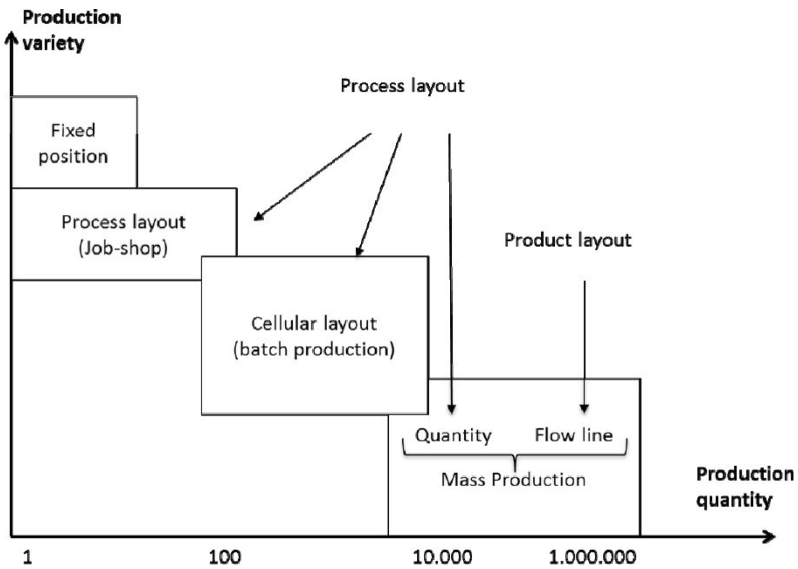

Figure 5. Different production models and the link between variety and quantity production (De Carlo et al. 2013).

1. Fixed position: this is used for creating very massive objects like ships, airplanes, and heavy machinery.
2. Job-shop: the manufacturing area is divided into several divisions, each of which specializes in a specific technology.
3. Cellular layout: This is characterized by cells (groups of separate workstations) and is used for producing things from a few different families that are related. When the scale of production does not support the choice of mass production, it is appropriate.
4. Flow line: a network of tightly connected workstations is utilized to mass produce a single product. (De Carlo et al., 2013).

2.2.2 Cellular layout

The division of production resources into smaller organizational units known as manufacturing cells, each of which independently produces a specific set of goods known as part families, is what distinguishes cellular manufacturing systems (CMS). These part families are often organized based on the required procedures, machines, and tooling. CMS's key advantage, aside from lowering setup costs, is that it simplifies material flows. Additionally, greater operator skill, shorter throughput times, and hence lower material handling and production costs have been reported (Neufeld et al., 2019).

According to a study conducted by de Negreiros et al. (2019), which focused on investigating rest times in serial and cell layouts, showed that cell layouts are preferred in situations where the products require more complexity, flexibility, and include more complex production procedures, as well as less speed and longer production cycles. Assembly lines with cell layouts allow for more diverse movements and longer cycle periods; they also allow for greater spontaneous relaxation due to the possibility of taking microbreaks. Cell layout is also known as the "full build" principle. Employees are held accountable for the product they create, which boosts their motivation, job satisfaction, and the quality of the final product. There is the possibility of capacity flexibility; a part of the workstation can be kept in backup and used only when extra capacity is needed. (Heilala & Voho, 2001).

2.2.3 Batch production

A batch is a unit of work that moves from one step of a process to the next. Working in small quantities has numerous advantages, and some of these are dependent on the product, but they are generally true. Small-batch production reduces cycle time because smaller batches move faster through the production cycle. Smaller batches reduce the possibility of a catastrophic error. For example, if you put 500 pieces in a furnace only to discover that something was wrong with the material or the procedure, you have wasted 500 parts. The error is less significant if you run a much smaller batch, such as 50 components. Smaller batches increase overall efficiency, saving money and improving product quality (Gornicki, B. 2014).

According to a book by Nicholas, J. (2018), traditional batch manufacturing (large batch size) is supported not just by the substantial setup cost, but additionally by the expensive initial investment of high-speed, specialist machinery. Producing products in large batches demands larger inventories because each batch consumes more slowly, resulting in increased costs for holding. Large-batch manufacturing at the plant level raises lead times by tying up equipment for extended periods of time and reducing scheduling flexibility. When demand is steady, the influence on lead times is minor, but it grows as demand flexibility increases. Larger batch sizes also have greater failure costs. Production issues and product faults are frequently the consequences of setup errors that impact the entire batch. The larger the batch size, the more goods are affected, because it ignores the effects of the quantity of batches on reliability and lead times, holding costs have typically been overestimated. Also, because setup cost is usually a direct function of setup time, the calculation has been skewed toward large-batch production.

2.2.4 One-piece flow

One-piece flow is a production method that converts large batch processing into single-component processing. Instead of moving batches of pieces, the goal of one-piece flow is to transport individual components from one activity to the next without interruption. In a traditional batch-production situation, parts are transferred from process area to process area in large batches, and each process step is monitored. This can lead to an excessive amount of scrap, late deliveries, long assembly lead times, and increased work in progress (WIP). One-piece flow, on the other hand, concentrates on the product and the process rather than transportation or storage. The constant flow of parts without the trouble of transit between activities is seen as a model of efficiency. In general, one-piece flow (as well as small-batch production) equates to waste elimination. This can encompass anything from labor to space to inventory. When waste is eliminated or reduced, benefits such as increased manufacturing flexibility and a safer work environment are ensured. One-piece flow will assist a factory in producing excellent components in the correct amount and at the appropriate time. It works best when combined with a plan that places all of the necessary materials and equipment in a line or cell in the order in which they are used. To function properly and successfully, one-piece flow equipment must deliver capable processes with no quality issues, repeatable processes with minimal variation, and very high uptime, which means little to no downtime. (Gornicki, B. 2014).

According to a case study by Ioana et al. (2020) that focused on establishing one piece flow by replacing traditional automotive batch manufacturing processes, the Hirschmann Automotive Romania Company saved 40 thousand production hours on a single segment. This number was calculated by subtracting the post-improvement production times from the pre-improvement value. Apart from substantial cost savings, transportation costs were minimized, and numerous resources were saved and reassigned to other projects. Insufficient bureaucracy was avoided, the work process was made more effective, flexibility in manufacturing was increased, and both facilities saved 4500 m3. Over a 6-month period, the data demonstrated a 6% improvement in productivity and a significant decrease in scrap rates.

As illustrated in figure 6, one-piece flow is usually more effective than batch production in many manufacturing facilities because it eliminates waste time and reduces product cycle time and lead time.

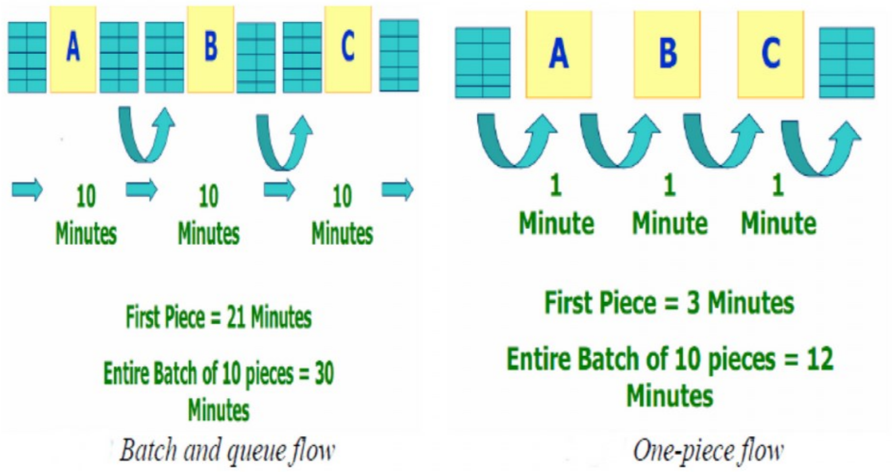

Figure 6. Example of the lead time in batch production and in one-piece flow (Accuturn, 2017).

2.2.5 Automation of production

According to a book by (Collan & Michelsen, 2020) Industry 4.0 technologies possess the ability to eliminate the labor shortage by replacing human labor with various robots, automated methods, and algorithms. Industry 4.0 deals with the concept of integrating traditional manufacturing and industrial processes with digital technologies such as artificial intelligence, the internet of things, data analysis, and big data. Its primary objective is to automate production processes so that all operations can be handled in real time. This is true for both semi-skilled and skilled people who need to compete with clever machines and intelligent systems. Machines and automated production systems are called "collaborators". Robots will replace humans in difficult, dangerous, and attentive activities. However, ultimate authority will remain under the control of qualified employees and management. Automation improves productivity and safety while increasing the technological complexity of industrial assets. and requires a greater reliance on production systems, emphasizing the importance of reliable and effective maintenance. Autonomous mobile robots (AMRs) and automated guided vehicles (AGVs) have recently been broadly used to tackle numerous engineering challenges in logistics, production, and high-risk jobs. (Zhang et al., 2023).

2.2.6 Autonomous Mobile Robots and Autonomous Guided Vehicles

Automated guided vehicles (AGVs) and Autonomous mobile robots (AMRs) are used in numerous industries to replace human labor and solve various engineering issues. There has been a substantial development in recent years, and the usage has been growing exponentially. An AGV is under control by an industrial computer and autonomously follows a predetermined route. It can navigate barriers on its own and perform a sequence of handling duties to transport goods to specific destinations. Its structure is built on a mobile robot with wheels. AGVs perform three primary tasks and have three distinct features: 1. Materials handling. 2. Automation of manual labor. 3. A mobile workbench. (Zhang et al., 2023).

The use of AGVs has four advantages: 1. Reducing the number of trolley-related events that occur while cargo is loaded and unloaded 2. Labor savings in goods loading and unloading, handling, and other processes. 3. Monitoring of products and decreasing loss rates 4. Lowering pollutants and energy consumption. Based on those advantages, AGVs are widely utilized in manufacturing, storage, power inspection, medicine, and other industries (Zhang et al., 2023). Due to their high investment costs and limited applications, AGVs are controlled by wire, tape, or magnetic tracks and have largely been used in high-volume industrial operations. (Jun et al., 2021). Figure 7 displays an illustration of ABB AMR.

Figure 7. ABB autonomous mobile robot (ABB, 2022).

AGVs typically require human monitoring and rely on paths or predefined routes. AMRs, on the other hand, represent the next step in the development of AGVs. AMRs are robots that can understand and move freely in their surroundings. AMRs are commonly defined as mobile robots that consist of non-remote-control drones and self-driving vehicles. With significant autonomy, they are able to respond to diverse dynamic changes in the environment in a reasonable, accurate, and timely manner. AMRs can automatically navigate from one location to another in order to complete specified activities. To navigate indoors, mobile robots employ floor layouts and inertial measuring units. An AMR must typically have a variety of intelligent environmental sensors in order to perform its tasks. These sensors are mounted on the robot or as external sensors at specified points in a dynamic environment, and the variety of sensors used on mobile robots makes overall system design highly complicated. Mobile robot fundamentals include mobility, perception, and navigation. (Zhang et al., 2023). AMRs are expanding rapidly as a result of their scalability, adaptability, and lower costs. In the context of Industry 4.0, which includes networked devices, dynamic reconfiguration, and enormous amounts of data, AMRs can also be extensively used to perform extra jobs during travel, such as collecting information. As a result, even small to medium-sized factories can reap the benefits and opportunities provided by AMRs. (Jun et al., 2021). Table 1 compares the main functions between AGV and AMR.

Table 1. Comparison of the main functions of AGV and AMR (Adapted and modified from Zhang et al., 2023 and Jun et al., 2021).

Function	AGV	AMR
Localization	Magnetic bar, wire, QR code,	Reflective strips, Visual and Lidar SLAM,
Navigation	Predefined route	Free route navigation
Avoidance	Stops and waits to avoid obstacles	Can avoid and cross obstacles
Features	No intelligence	High environmental tolerance, ability to locate in complex dynamic situations, accurate tracking, and trajectory prediction
Payload	High (> 1500 kg)	Low (100–500 kg)
Speed	3 km/h	5–10 km/h
Costs	Higher costs, requires regular maintenance and update	Low costs of camera, low maintenance costs for later replacement

2.2.7 Flexible assembly line

There are various definitions and different points of view on flexible manufacturing systems (FMS) and flexible assembly lines (FAL). According to Javaid et al. (2022), a flexible manufacturing system incorporates manufacturing lines that can change the type of product produced quickly and flexibly. Industry 4.0 is having a big impact on flexible manufacturing systems. Changing product types is typically entirely automated in flexible production processes. Machines in the manufacturing line can interact, gather data, and issue instructions autonomously, utilizing sensors and communication technology. The activities are linked to supply and delivery networks, allowing for the integration of other business units and the realization of efficiency gains. FMS is a computer-controlled numerically managed machine tool, automated material and tool handling, and automated measuring and testing machinery capable of handling any product in a particular product family to its stated capability and on a predetermined timetable with minimal user intervention and rapid change over time. FMS is a technique for dealing with huge product changes and short product life cycles while providing consistent, top-notch, and cost-effective outputs.

Flexible manufacturing systems are able to cross the gap among fully automated lines and CNC machines, enabling effective mid-volume production of a diverse part mix with low work-in-process, short turnaround times, rapid manufacturing, high utilization of machines, and excellent quality. FMS is especially attractive to businesses with medium and low capacity, such as aerospace, automotive, and technology. FMS is intended to be adaptable, allowing the system to respond to changes. This system utilizes numerous technologies, but its main elements are at least two automated manufacturing centers connected by the controller, a traditional load station, and a pallet pool system. A large investment is required to design a production line, but FMS is thought to be adjustable enough to respond to tiny batches of market demand. As a result of the increased frequency of new product ideas, the existing production line was rearranged. It provides accurate customer value by producing higher-quality items in amounts and kinds determined by demand, and with exceptional precision. Although FMS requires a significant initial investment, it results in less space consumption, less human labor, lower component inventories, enhanced system reliability, shorter lead times, higher production rates, and lower manufacturing costs than traditional mass manufacturing systems. (Javaid et al., 2022)

Complete build assembly is often characterized by a long cycle time and extensive equipment at the workstations. A pallet, extra workpiece carriers, and a conveyor can all be employed in the same system to mix human and automated activities. The orientation and position of the part are known, which improves automation. The primary problems are how the workstations are connected to the conveyor system and the type of pallet that the conveyor system utilizes. (Heilala & Voho, 2001). To remain competitive in the market, organizations should adopt flexible assembly lines to achieve outstanding productivity and respond to continuously changing customer requirements. Robots and numerically controlled machines, for example, can do more complex and precise assembly jobs in less time. Flexible assembly lines are difficult to analyze because of the complexity brought by equipment options. Since equipment is often expensive, equipment selection decisions have long-term implications. The obstacles are referred to as FAL design problems, and they typically aim to lower total equipment cost. (Barutçuoğlu & Azizoğlu, 2011).

Kanban eliminates the need for complex information and hierarchical control systems on the shop floor, and it is a simple and effective option for implementing the JIT technique. The Kanban procedure is used for controlling processes so that each process produces a single product unit within a specified cycle time. This material flow control system's optimal state is its capability to achieve a one-piece flow method. Large-lot production and maintaining significant inventories between operations are wastes that should be minimized or eliminated. Workstations with no or low set-up times constitute an optimal Kanban-based JIT production system. Only in this scenario can one-piece flow production be considered, in which every type of container consumed by the downstream station is replaced with a full one produced by the upstream station, preserving the First-In-First-Out (FIFO) sequence. In this perfect scenario, the upstream production station is administered via the traditional 'mailbox,' which collects Kanban tags that are correctly organized depending on their arrival time (FIFO). Containers can be managed utilizing the 'full-empty' strategy thanks to the FIFO technique. In this case, the production pieces can simply be gathered in a Kanban box and consumed from the box using the FIFO method. Figure 10 displays the primary production Kanban management approaches based on the six different set-up time structures that characterize a generic workstation. (Braglia et al., 2019).

2.2.8 Production logistics

In order to respond to just-in-time (JIT) pull manufacturing, production environments require a reliable logistics infrastructure. The Just-in-Time (JIT) philosophy aims to provide the right parts at the right time, in the right place, and in the right amount. When the production of a part is allowed, it is pushed through the system in a pull system. The Kanban technique is frequently deployed in JIT manufacturing systems as a material flow control strategy. Kanban is the Japanese word for signboard or card. Kanban is a long-standing execution framework used by the Toyota Production System (TPS) in the assembly framework for data flow, allowing material streams to be moved from upstream to downstream. Many different types of Kanban systems have been explored, and their effectiveness in controlling production and inventory operations has been demonstrated. Several studies have been conducted to investigate the use and benefits of the traditional Kanban system. New research has focused on the viability of an electronic Kanban (e-Kanban) system over a traditional Kanban system. E-Kanban stands for electronic and is computer-controlled. (Elattar et al., 2022).

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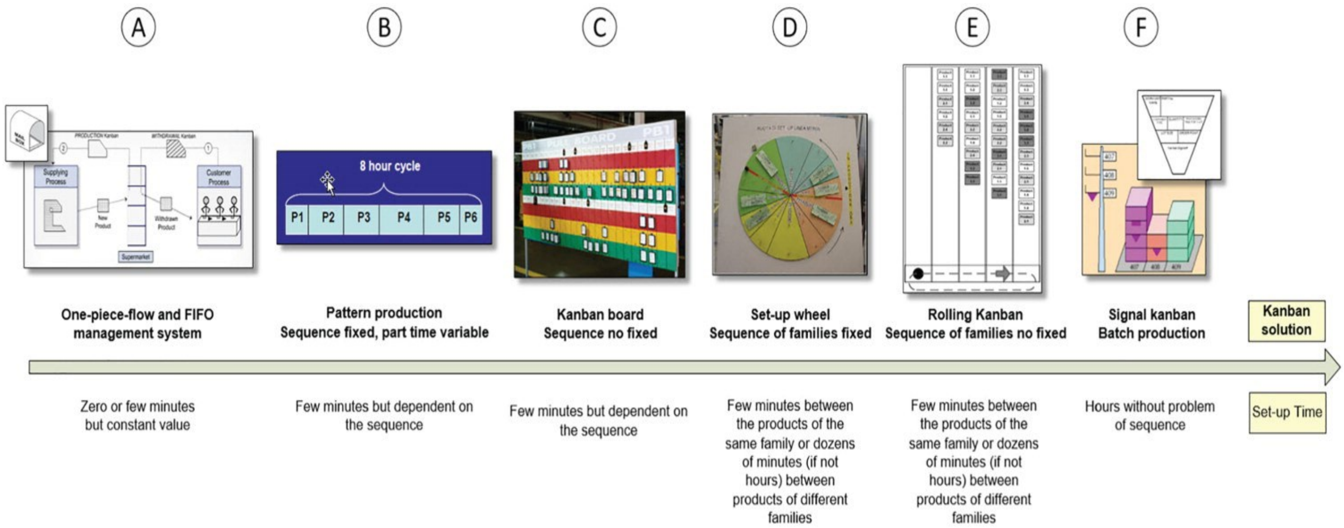

Figure 8. Controlling set-up times with Kanban system (Braglia et al., 2019).

2.3 Production layout designing

The layout design of a manufacturing system has a significant impact on its performance, so it is crucial to invest in the layout design process right from the beginning. The design of the production layout has many challenges, and the biggest of them is called the facility layout problem. The challenge of coordinating everything required for the production process is recognized as the facility layout problem. A facility is defined as any element that aids in the execution of an activity, such as a work center, a machine tool, a division, or a production unit. A more recent definition of the facility layout problem refers to it as an optimization problem that attempts to increase layout effectiveness by considering all interactions among facilities and systems for material management while planning layouts. During this optimization phase, there are various variables to consider, such as safety, noise, flexibility for future design modifications, and aesthetics, all of which are examples of basic subjective aspects of the facility layout planning process. (De Carlo et al., 2013). The layout redesign problem is defined as the design of a layout to increase the efficiency of a present running industry. The decision to redesign the current layout is very strategic and necessitates a significant financial expenditure. It is critical to effectively develop the layout for a system because it has a straight impact on the industry's performance. The facility layout design entails considerations about how to best arrange the available resources in order to minimize waste and maximize design objectives. Depending on the needs of the sector, these objectives may be qualitative or quantitative. (Sharma & Singhal, 2016).

There are numerous ways to deal with layout design issues. The majority of the literature on such problems is related to algorithmic approaches, procedural approaches, and software-based methodologies (Sharma & Singhal, 2016). Procedures for layout creation that deal with the techniques used to produce alternative layouts have three commonly used methods. Mathematical modeling, which refers to the application of mathematical optimization models. Knowledge of experts, which is a trial-and-error technique in which choices are generated based on the experience of a group of experts. Thirdly, software packages are a prevalent method used frequently today. Using specialized tools such as AutoCAD, alternatives are designed. Drawings of two-dimensional or three-dimensional facility layouts can be represented by computer-aided design software. (Pérez-Gosende et al., 2021).

Algorithmic techniques often simplify both design constraints and objectives in order to get at a simple function of objectives from which an outcome may be obtained. These strategies frequently rely solely on quantitative input data. Their design solutions can be easily evaluated by comparing their objective function values. The outputs of an algorithmic technique are commonly modified to meet particular design criteria such as department shapes, technological needs, material handling systems, utility supply, ergonomic limitations, work-in-process storage, space utilization, and so on. Procedural techniques can incorporate qualitative and quantitative objectives throughout the design process. The design process is divided into several phases for various techniques, which are then solved methodically. (Yang et al., 2000).

Industries spend a great deal of time and money designing layouts for improved performance. Because of the various inherent objective natures and the time-consuming data collection procedure, creating and evaluating the proposed layout is a demanding, long, and time-consuming operation. The assessment of a generated layout is an important step in the planning and design process. Simulation is one of the most effective techniques for evaluating layouts. A model of the real-world system is constructed and tested in various operating circumstances for evaluation purposes during the simulation. The evaluation of the numerous alternative layouts is the most vital aspect of the layout design approach. The nature of the layout project determines the approach chosen, but the ranking must be reliable, rational, systematic, and straightforward. The multiple attribute decision making (MADM) problems include selecting the best alternative from among those offered. MADM encompasses a wide range of methodologies and technologies, such as the analytic hierarchy process (AHP), weighted decision matrix (WDM), and simple additive weighting (SAW). (Sharma & Singhal, 2016).

2.3.1 Systematic layout planning - SLP

Systematic layout planning (SLP) is a sequential approach to layout design. It was designed by Muther in 1973, and it is still widely used in the layout design process or partially utilized and combined with other approaches. SLP is a relatively simple technique, and it is an established method for offering layout design guidelines in various industries, including manufacturing (Yang et al., 2000). SLP is divided into three distinct phases, including: 1. Data collection and analysis. 2. Searching through the obtainable layout options. 3. Evaluating alternatives and selecting the best possible layout (De Carlo et al., 2013).

As shown in figure 8, according to Yang et al. (2000), the SLP approach begins with a PQRST analysis of the total production activities (step 1). In order to ensure the validity of the input data during the design phase, the data collection fields P (product), Q (quantity), R (routing), S (supporting), and T (time) must be reviewed.

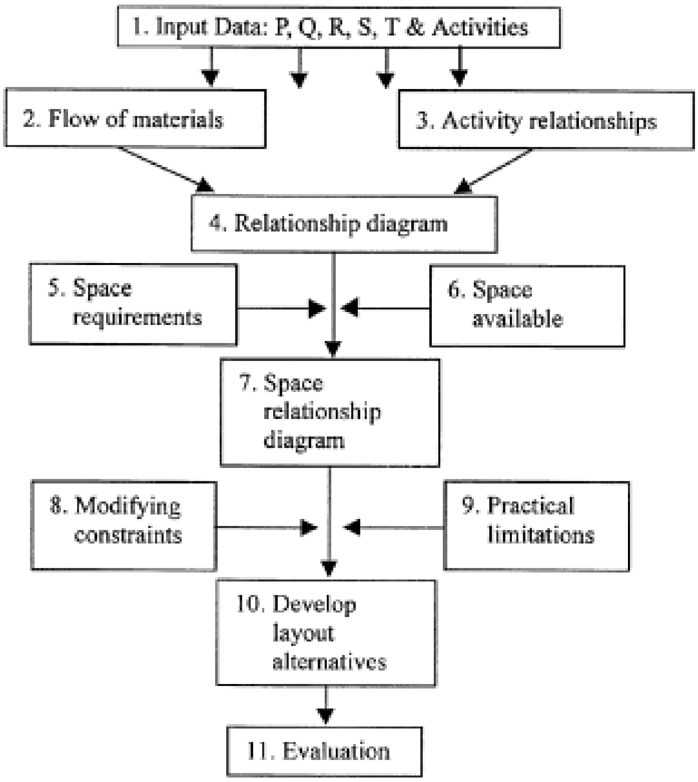

Figure 9. Systematic layout planning (SLP) procedure (Yang et al., 2000).

All material flows from the complete production line are gathered into a from-to chart in the flow of materials analysis (step 2), which illustrates the flow intensity among distinct tool sets or departments. Step 3, "Activity relationships," involves doing a qualitative investigation to identify the degree of proximity between distinct departments. The departments are spatially organized using the "Relationship diagram" (step 4). Relationships are placed near departments that have strong interactions and/or closeness. The stages "space requirements" (step 5) and "space available" (step 6) determine how much floor space each department will have. The "space relationship diagram" (step 7) extends the relationship diagram from step 4 by including departmental size data. Additional design criteria (step 8) and limits (step 9) are examined prior to the start of block layout development. Design candidates are then derived from alternative layouts in step 10. Step 11 chooses the best design among the candidates.

2.3.2 AutoCAD

AutoCAD is a program for generating two-dimensional technical drawings with precise measurements and dimensions, as these drawings are commonly used for building something. AutoCAD provides numerous commands for creating, modifying, and annotating 2D and 3D designs. AutoCAD provides precision and the ability to design lines, circles, and other objects with exact dimensions, which is way simpler than drawing with a pencil. Drawings are significantly easier to edit on a computer screen than on paper. CAD adjustments are also far cleaner. Using a CAD tool expedites the creation of numerous types of drawings, especially those involving repetition, such as layouts and multi-story floor plans. AutoCAD is the most popular CAD software because Autodesk offers solutions for numerous industries, including architectural, manufacturing, mechanical, electrical, etc. Figure 9 displays an illustration of AutoCAD design. (Hamad, 2020).

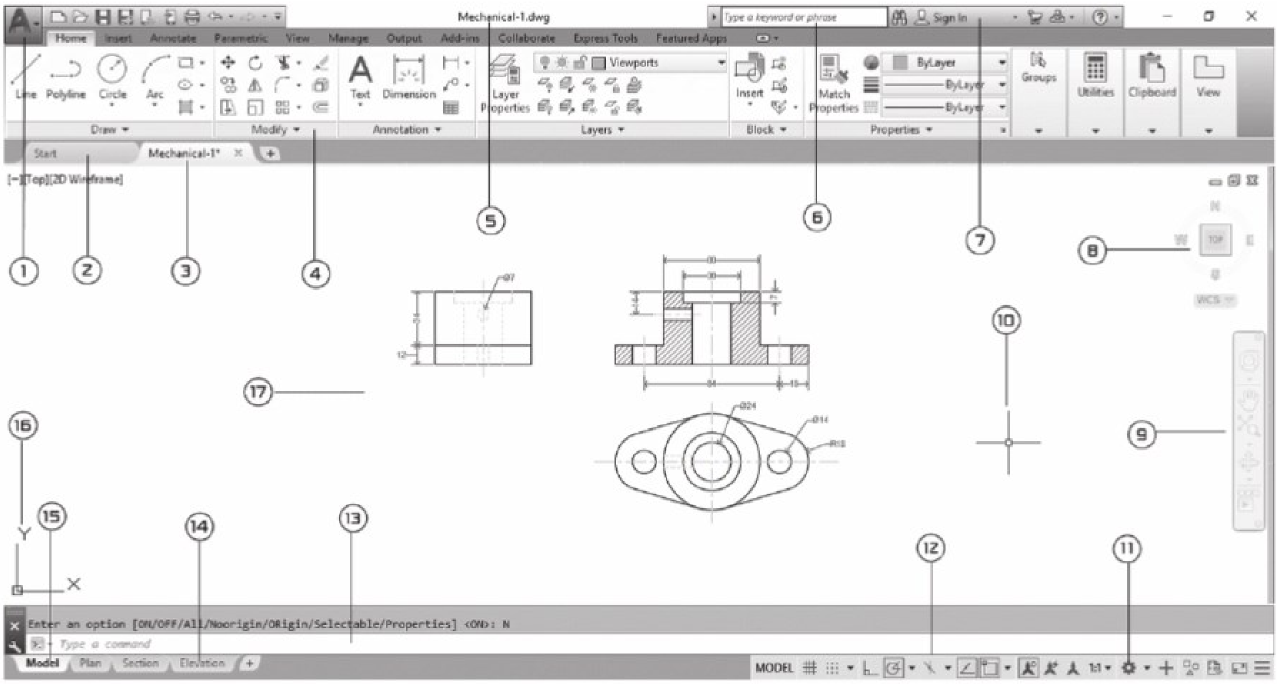

Figure 10. Illustration of the design using AutoCAD software (Hamad, 2020).

2.3.3 Weighted decision matrix

A Weighted Decision Matrix (WDM) is a quantitative technique for determining the relative ranking and preference of discrete alternatives that may be most advantageous for a process or methodology (Mustafa et al., 2015). The WDM principle states that the process, methodology, and entities' features, also known as design or decision criteria, are developed first. These are then weighted or prioritized according to their importance. The weighted features are then added together to give a relative rating (Wang et al., 2009). The WDM is composed of rows and columns that enable the examination of diverse preferences made available via the collaboration of criteria. It is one of the most commonly utilized quantitative approaches for dealing with multi-criteria decision analysis (MCDA) problems. It enables the selection or ranking of objects from a "collection" by rating them against numerous criteria of differing priority levels.

According to Sinha et al. (2022), the main constraints of this method are:

1. Selection of the features: The features are chosen based on the needs of the user. This demonstrates the user's bias. To solve this, when designing the features, additional input from experts or a review of available literature criteria should be used.
2. Scoring of features: The scoring of features may differ and vary according to researchers, so there is no single way to score the features.
3. Degree of importance of feature: The relevance of a feature cannot be considered to be the same for all of the selected traits, thus we cannot assign the same factor to all of them. As a result, an importance factor (IF) is typically assigned to account for this variation. Thus, the user determines the assignment of IF based on importance.

The formula for WDM is:
The final score *(T)* is defined as

$$T = WSx_1 + WSx_2 \dots . WSx_n \quad (1)$$

where WS is a weighted score defined as

$$WSx_{ij} = IFx_i * Sx_j \quad (2)$$

IF_{xi} is the importance factor and S_{xj} is the score obtained by the feature.

2.4 Synthesis of literature review

Manufacturing facility design, production development, and process development are three critical characteristics for increasing a company's productivity, profitability, and maximizing resource utilization. Lean production is a management philosophy that emphasizes waste elimination and value creation using methods such as just-in-time delivery (JIT), total quality management, and human resource management. This approach is supplemented by Six Sigma, which measures the capability of a process to reduce process variation and increase customer satisfaction, and Lean Six Sigma combines the strengths of both approaches. The DMAIC approach is a very useful data-driven process improvement methodology that provides a structured problem-solving procedure and is appropriate for large problem-solving tasks and projects.

The assembly line was created as a highly efficient and productive method of producing a particular product. Assembly lines are used in serial production, which necessitates agility, speed, and shorter cycle times. System layout is constrained by the assembly system and process flow principles, with different assembly line structures and layouts classified according to the volume and variety of products produced. Traditional large-batch manufacturing has higher held costs, longer lead times, and is more prone to product faults. One-piece flow focuses on waste elimination, which enables increased manufacturing flexibility, higher productivity, and lower scrap rates. Automation enables Industry 4.0 technologies to eliminate labor shortages, and Autonomous Mobile Robots and Automated Guided Vehicles are increasingly being used to replace human labor in a variety of industries, providing solutions, safety, flexibility, and authenticity to engineering challenges.

Since the design of a production layout significantly impacts the performance of a manufacturing system, it is critical to invest in the layout design process from the very beginning. The facility layout problem, on the other hand, presents a significant challenge for designing the production layout. Facility layout planning entails considering a variety of qualitative factors such as safety, flow, flexibility, aesthetics, and future prospects. The literature suggests using software-based methodologies like AutoCAD and simulation to generate layouts. Ranking the various alternative layouts is an important step in the layout design process, and multiple attribute decision-making methods such as the Weighted decision matrix (WDM) include selecting the best alternative from among those available. SLP is a procedural layout design approach that consists of seven phases, including data collection and analysis, searching for layout options, and evaluating alternatives to determine the best layout. The Kanban technique is commonly used to control material flow in JIT manufacturing systems. The Kanban system can simplify material flow control and eliminate waste, and the ideal Kanban production system includes workstations with minimal set-up times and is best applied with a one-piece flow production method.

3 Methodology

This chapter provides a brief overview of the research methodology. It includes the research onion, data collection, data analysis, data used, process steps, methods, techniques, and tools used. In this chapter, the methodology and methods that were utilized to collect and analyze data in order to solve the research objectives and get answers to all three research questions will be presented. The research uses both nomothetical (how things are currently) and normative (how things should be in the future) research problems. The nomothetical problem analyzes the case company's current training center, concept, process, and bottlenecks, while the normative research problem designs and develops the training center and the process. The research onion designed by Saunders et al. (2009) was used to determine the methodology. Figure 11 depicts the six categories of the research onion: philosophy, approach, strategy, method selection, time horizon, and data collection and analysis.

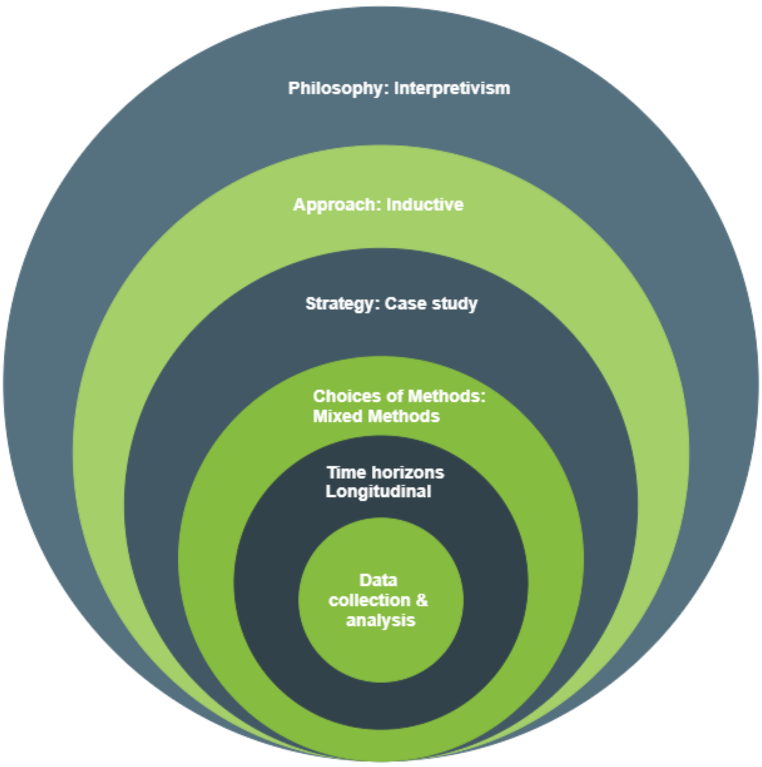

Figure 11. Research onion of the study.

Because of the nature of the research, interpretivism was chosen as the study's philosophy, inductive as the approach, and an action research case study as the strategy. The researcher was involved in the design process because he was simultaneously executing this entire project from start to finish for the company as a production development engineer, acting as a project manager and designer, and writing a Master's thesis on the subject. A significant amount of data was collected through continuous observations, and the process necessitated gaining a thorough understanding of the project and topic. Since the research required both quantitative and qualitative approaches, mixed methods were chosen as a technique. The study used a design science approach (re-design) to develop a training concept and process and build a new technical solution that provides immediate value to the case company.

3.1 Mixed method research

Due to the nature and topic of this research, mixed methodologies were used as a research method. Since the research was a case study, a mixed methodology was utilized to combine the strengths of both approaches and provide a comprehensive understanding of the research questions. In this study, a quantitative approach was used to collect and analyze numerical data, while qualitative data was used to understand the phenomena and processes. Data from both approaches were collected and analyzed simultaneously. The qualitative approach was used to make the quantitative approach's results more understandable, and the quantitative approach was used to support the qualitative approach's data. This research used observations, workshops, and focus groups as a qualitative approach. Surveys (weighted decision matrix), time studies, and CAD software are used as quantitative approaches.

3.2 Data collection

At first, the requirements, goals, and objectives of the new training center were established in collaboration with the production manager (customer) and the project team (the operations manager, project manager, process engineer, and production engineer). The goal was to develop and re-design a training center that supports the assemblers for One-piece flow method production for variable-speed drives. The aim was to design the best possible layout to guarantee safety, ergonomics, flexibility, clear flow, and maximum space utilization. The new training center was also not allowed to interfere with the main production lines while improving the efficiency of operations.

Observations were the primary method for collecting empirical data, and the research began with observations after defining the scope and goals of the project. The purpose of the observations was to gain knowledge of the researched phenomenon by observing it. The observations were carried out in a systematic manner on-site in order to become familiar with and understand the current training concept and process in order to design a new technical solution and develop the process. With observations, it was possible to identify waste, bottlenecks, and problems in the current design and process, as well as opportunities for improvement in the new design. To obtain all possible improvements during the observations, a few advanced assemblers whose job description included training were interviewed and openly discussed. There were also several continuous focus groups with the project team and the customer (production line and logistic partner) to achieve the best possible outcome of the design process with different perspectives and feedback. Work-time studies were conducted to determine the flow, outputs, cycle time lead time, bottlenecks, and waste time of the current process. Actual factory data collected from SAP systems also aided in determining the daily movement and quantity of material used in the assembly.

3.3 Data analysis

Observations, focus groups, and work-time studies enabled the layout planning process using Lean Six Sigma methodologies, DMAIC, and SLP practices. The collected data was analyzed in several workshops and visualized using various visual tools. The work-time studies: training process flow of work analysis, cycle time analysis, and AGV cycle time analysis were used in the development of the new design. The data and inputs from those work-time studies were also incorporated into the Weighted Decision Matrix (WDM). With the collected data and information, the AutoCAD software enabled the layout design process. Spaghetti relationship diagrams were used as a process analysis tool to illustrate and compare the process steps and movements of people and materials in the current design and after improvements in the new design. The process description of the new training center was also illustrated with a Flowchart because it conveniently demonstrates the process.

The new training center could be built in two locations. The first option was the location of the current training cells, and the second option was the location of the kit work-station. The new training center's design also included rethinking the current location of the kit workstation and studying and familiarizing the kitting process. Using AutoCAD, numerous potential 2-dimensional layout options, alternatives, and variations were created. SWOT analysis was used to identify and list the strengths, weaknesses, opportunities, and threats of the layout and location options. There were two large workshop voting sessions. In the first round of voting, the group voting method was used. Based on the features and characteristics that were established, the two best layout alternatives out of both location options were voted on. Voting was commissioned with the collaboration of the project team and the production line (customer) in order to take the customer's perspective into consideration and achieve the best possible general outcome for the final design.

Following that, the quantitative multiple attribute decision making (MADM) method was used to select the best layout alternative from those two location options. The weighted decision matrix (WDM) was chosen as a technique because it identifies the most advantageous discrete substitutes based on relative ranking and preference. The purpose of WDM was to serve as an evaluation method for choosing between layout options A and B for the final design solution. The voting was based on the scores of various criteria and features. Each criterion and feature were pre-defined, and the weight values were determined with the collaboration of the project team and the production manager. As a result, a final score was calculated using the statistical weights obtained for both options. There were two voting sessions: one among the project team and one among production (customer). From the project team, one process engineer and two production development engineers participated in the voting. Ten people from the customer's side took part, including: production technical supporters, production supervisor, experienced trainers and assemblers, kit workstation assemblers, logistics development specialist, logistic worker, and quality expert. There was a total of 13 voters, including the author of this research.

In order for the training center to be ordered, a scope of work for the new training center was created and delivered to the supplier. The center's technical features were clarified and instructed, and a process description (Flowchart) was created to demonstrate how the concept works and how to train assemblers to assemble different drives in the line. A detailed implementation plan and commissioning schedule were also established. Due to time constraints, the research excluded the actual commissioning and construction of the training center. It also excluded employee training, implying that training is handled by the factory's experienced assembly workers, whose job description includes employee training and integration.

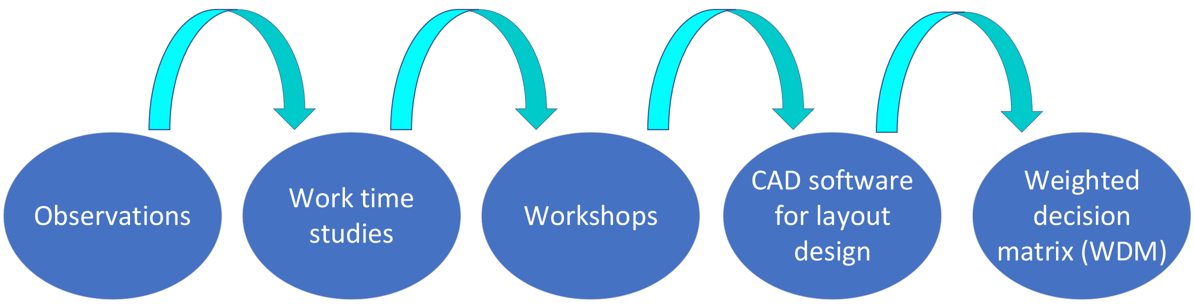

Figure 12. Data collection and analysis methods of this research.

4 Results & Findings

This is the main chapter of the research, and it will present the results and findings based on the methodology and data collection, examination, and analysis. The chapter begins with a description and analysis of the case company's current training concept and process, and it represents the project's scope of work and limitations. Following that, it describes the data collection and analysis processes. Then it continues by highlighting the identified improvement opportunities prior to initiating the design process of the new training center. Following that, the chapter presents the final result, the design and concept of a new training center. Finally, the chapter ends with the new training center's detailed implementation plan and estimated commissioning schedule.

4.1 Description of the current production system

To develop a production system and procedure, it is essential and critical to have a comprehensive understanding of the entire system and process. This section of the research focuses on the first step of the Systematic layout planning (SLP) procedure. The first step defines all of the project's input data and key drivers. It provides a description of the case company's current production method, products, and training concept, process, and layout to comprehend and determine the goals, objectives, and starting points for the concept that is being re-designed and developed.

4.1.1 Production method of the factory

ABB Drives factory in Pitäjänmäki manufactures frequency converters known as variable-speed drives for a variety of applications. The factory's variable-speed drive manufacturing is divided into three local manufacturing units: Drive Products (DP), Drives Service (DS), and System Drives (SD). This thesis focuses only on the Drive Products Small and Medium Drives department (S&M Drives). The S&M department uses the Make to Stock

(MTO) strategy to manufacture its products. S&M Drives operates with Lean manufacturing principles and has recently implemented new one-piece flow manufacturing lines for production. Variable-speed drives are also known as drives and will be referred to as 'drives' throughout this research.

Pitäjänmäki factory is an assembly plant where assemblers assemble manufactured parts into finished end products, and package them for shipping. On an assembly line, the main component assembly takes place, and then testers test the drives. When a drive passes a test, it is fed into the final assembly phase, where the remaining components are assembled. After that, the drives are packed for delivery with user manuals and accessories. Thus, some products are sent as plain base products to a sister factory or to one of the company's regional distribution centers. The logistics partner handles the delivery of assembled components to the factory as well as the distribution of finished products to customers.

4.1.2 The products

The primary function of a variable-speed drive is to regulate the flow of energy from the main supply to the process. Variable-speed drives (figure 13) are positioned between the power source and the motor. The power from the power supply is fed into a drive, which then regulates the power fed to the motor. There is a huge variation in different ABB production families that vary in size and features. General-purpose drives are used in a variety of light industries and infrastructure applications such as mixers, conveyors, fans, pumps, compressors, and centrifuges. Industrial drives are utilized in heavy industry and machine building.

Figure 13. ACS880-01, wall-mounted single drive. (ABB, 2023).

Even though the offerings are catalog products, there are also numerous types and variants for configuration. S&M drives are classified into 6 product families since their physical dimensions, size, functionality, protection level, and components differ. The products are available in premium (ACS880) and general purpose (ACx580) versions for each frame size R1–R6. Table 2 illustrates the primary product families and frame sizes that are currently produced.

Table 2. ABB S&M product families and frame sizes.

Product family	**Frame size**
ACS880-01, ACx580-01	R1
ACS880-01, ACx580-01	R2
ACS880-01, ACx580-01	R3
ACS880-01, ACx580-01	R4
ACS880-01, ACx580-01	R5
ACS880-01, ACx580-01	R6

Table 3 describes in further detail the dimensions of the drive frames included in this research. Thus, the study is focused mainly on the R4, R5, and R6 frame sizes. The maximum height, width, depth, and weight are shown in the table. As can be seen, the highest frame is 771 mm, the widest is 300 mm, the deepest is 448 cm, and the heaviest is 77kg, so these aspects had to be considered when designing the new training center.

Table 3. Maximum dimensions of the drive frames of the research.

Frame size	Height (mm)	Width (mm)	Depth (mm)	Net weight (kg)
R1	331	155	226	6
R2	432	155	249	8
R3	490	203	261	12
R4	636	203	274	19
R5	596	203	274	28
R6	548	252	357	45
R7	600	284	413	56
R8	681	300	436	77
CR6	771	252	448	75

4.1.3 Training of assemblers

Training and induction of assemblers take place in a separate area in the S&M department that is only used for employee training and integration. New employees who come to work as assemblers are thoroughly trained to learn the fundamentals of the company's operating methods, the importance of values, safety, and quality, and the assembly process. They are also taught how to use SAP, which is used in assembly production to process data, manage the manufacturing process, track components, and manage materials. They are also trained to use Andon, a data collection system used for monitoring and alerting operators to potential issues on the production lines. Because of the large number of different drive variants, the company's existing assemblers are also constantly trained. Continuous training allows employees to maintain a high degree of expertise and flexibility, as well as their enthusiasm for their job. A broad range of expertise allows for job rotation. Job rotation is a method of on-the-job learning that ensures the preservation and development of the working community's professional skills. Job rotation also maintains an employee's ability to grow on a continuous basis. While compiling a ‘workstation list’ for assemblers, job rotation enables more effective and flexible organization. When the assemblers have a high level of expertise in different frame sizes and production families, it is also possible to respond quickly to changes caused by sick leave. Because of these numerous reasons, it is critical to invest in and engage in the training concept and process comprehensively from the start. The company's experienced assemblers with many years of solid assembly work background have been selected as trainers. Trainers have a strong level of competence in all the different variants, as well as an educator mindset.

4.1.4 Current training concept

The main production lines operate as a One-piece flow method, where the assembly work of each product is divided into stages. Each assembler on the production line performs one phase at a time so that the products move along the line continuously and a smooth flow is maintained. There are four main production lines where assembly work for various drives and variants is completed. R4 drives are assembled as four-phase, R5 drives as five-phase, and R6 drives as six-phase. However, the current training process is based on a cell production model, which means that the drives are assembled from the beginning to the end by a single assembler. There are four different training cells, and at each cell, there is one assembler who is trained individually by his own trainer. The current training concept follows the process illustrated in figure 14.

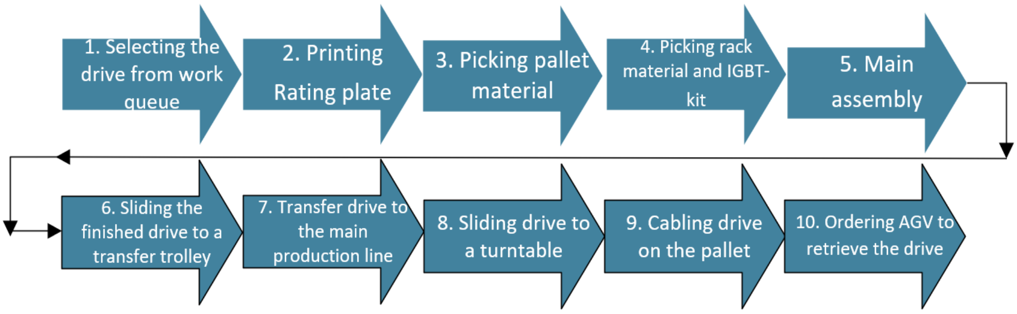

Figure 14. Work Breakdown Structure of the training process.

First, an appropriate product family and frame size are selected from the SAP work queue, which holds all the ordered drives awaiting assembly. After that, a rating plate is printed from the SAP system while the lead time starts, and the beginning of the drive is registered in the system. The heaviest and largest materials, such as skeleton, zinc, and chokes, are then retrieved with material trolleys from the EUR-pallets located on the main production line. During the same trip, the IGBT-kit is picked from the main production line's FIFO-rack, and it will also be attached to the drive during assembly. Following that, the main assembly process of the drive itself begins by following the work instructions with the guidance of the trainer. Smaller materials to be assembled on the drives are located in FIFO-racks behind the assembler in the assembly area. The racks are always filled according to the FIFO principle; when a Kanban box material is used, the assembler places an order, and the Kanban box with new material is on its way. While assembling, the trainer constantly guides the assembler, observes the assembly process, and performs intermediate checks. Constant checkups are performed to ensure that everything is in order and that nothing has been forgotten. It is essential to ensure that the components are assembled correctly, that the right screws have been used and that they are tightened to the proper torque, and that the critical screws that are tightened are marked with a marker. In terms of learning, safety, and quality, constant follow-up is critical so that no damage or assembly errors occur, and the drives won't fail the tests. The amount of follow-up depends on the personal level of the assembler being trained. The new assemblers are taught everything from the beginning, and existing assemblers' skills are expanded for different drive variants.

Once all of the components required for this main assembly stage have been assembled on the drive, the process proceeds to the testing system and final assembly. Thus, as there is no docking station in the training area, the finished drive is always slid onto a trolley and moved to the main production line for docking. The drive is transferred to the main production line by sliding it onto the turntable conveyors at the end of the line. A drive is moved from the turntable to the docking point, where the appropriate type of pallet for the drive has already been ordered. A drive is cabled and docked onto the pallet, and an AGV is ordered to retrieve it. The AGV picks up a finished drive on a pallet and feeds an empty pallet to the docking point in readiness for the next product. Finally, the AGV transports the drive to the manipulator system, where it is tested by the testers before going to the final assembly phase.

4.1.5 Layout and structure of the current training area

As previously stated, the layout of the current training concept is based on a cell production model. Figure 15 represents the layout and setup of the training area.

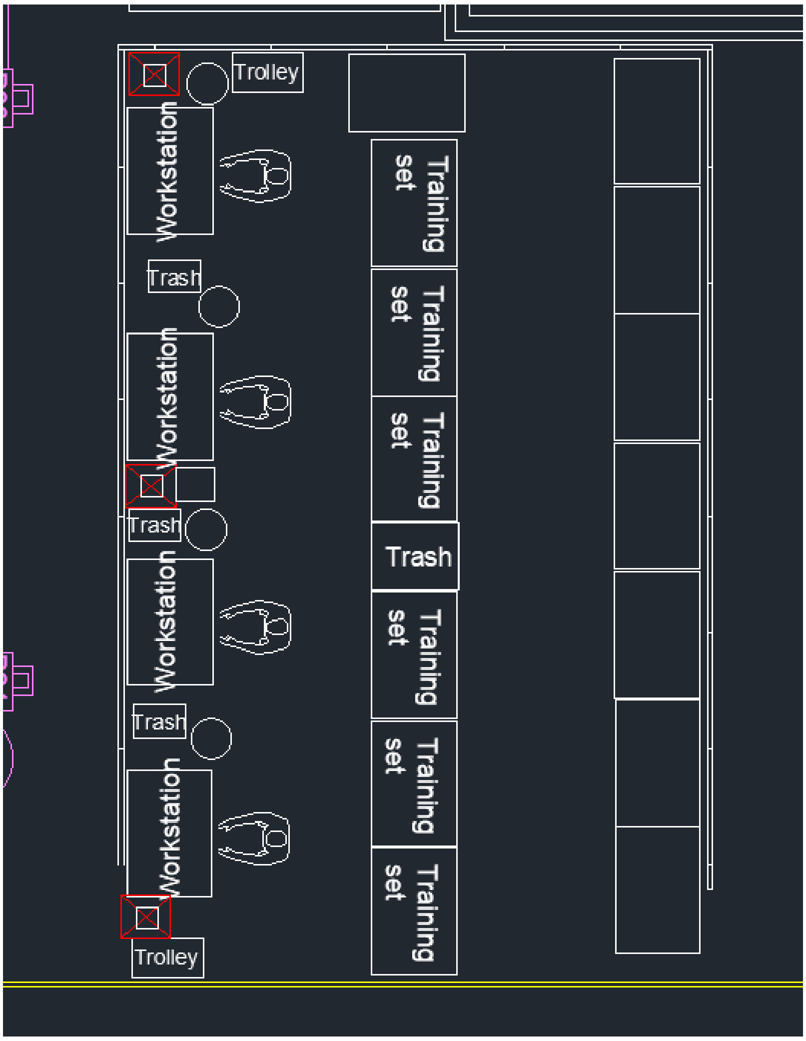

Figure 15. Layout and setup of the current S&M training area.

The training area consists of 4 individual workstations, 4 screw racks, 6 FIFO material racks, trash bins, 2 transfer trolleys, a printer, and occasionally one pallet containing pallet material, such as chokes and zinc. The empty pallets on the right are not involved in the training and are scrap in the area. The red squares are the poles to which the electrification and compressed air are inputted. A different assembler is trained at each workstation in accordance with the cell production concept, in which the assembler assembles the drive from start to finish while the trainer guides beside him. One workstation is dedicated to R6 frames, another to R5 frames, and two to R4 frames. The objects in the shape of a circle are screw racks, where less frequently used screws are stored since they do not fit on the workstations because of the large number of screws.

Smaller trash belonging to energy waste, such as bags and bubble wrap in which components are packed, are thrown into the small trash bins. There is a larger cardboard trash rack between the FIFO racks for cartons. There is also one printer in the area that prints a rating plate, which has to be attached to the device. The FIFO material racks are at an ergonomic distance behind the assemblers, as components are constantly taken from the racks and installed on the drive. FIFO material racks contain all of the rack materials that are assembled to drive but not the palette materials that must be brought from the main production line pallets. As mentioned before, since the training area lacks its own docking point and AGVs, finished drives are slid into the trolleys and transferred to the main production line for docking.

4.2 Scope of work and limitations of the new training center

The empirical research project began with the Define-phase of Lean Six Sigma's five-phase DMAIC-process method. The project was launched at the first workshop meeting, and key process outputs were identified, as well as what deliverables were expected as a result of the project. The requirements for a new training center were listed in the first workshop meeting, along with those of the project team and production manager (customer). Certain criteria, features, and goals had to be met by the new training center. The new training center and layout needed to be more effective, safer, ergonomic, and flexible, with a clear flow and maximum space utilization. The training center had to be 4-, 5-, or 6-phase (workstations), but there was a strong preference for the 6-phase one-piece flow production line, which means there should be 6 workstations where the manufacturing process is divided into 6 distinct stages. Thus, the design was required to maintain the previously mentioned established features and criteria. The concept also had to be a hybrid model, which meant that drives from different product families could be assembled on the line simultaneously in stages (one-piece flow) as well as in a cell model (alone from start to finish). If the assembling happens in a cell model, there must be some kind of system or technique to get drives out of the workstation so that other workstations are not disrupted whilst operating.

The new training center could be built in two different locations. The first option was the location of the current training cells, and the second option was the location of the kit workstation, so both options had to be examined and analyzed in order to indicate the best and most optimal location. The new training center should serve both the company's new employees who begin working as assemblers and the company's existing assemblers. Overall, it should provide a technical solution that improves the training concept, eliminates waste, bottlenecks, and problems of the current design, enhances quality, and makes operations more efficient.

The R1, R2, and R3 frame sizes must also be able to be assembled in the training center, which is simple to accomplish with the same design as the R4, R5, and R6 drive frames due to the straightforward and uncomplicated assembly procedure of these small frame sizes. However, after the analysis and design process were finished and the scope of work for the new training center was delivered to the supplier, additional changes to the scope of work were required because of the changes caused by the increased production volumes and limited factory area. Large Drives department larger R7, R8, and CR8 frame sizes were added to broaden the scope of work and design. As a result of these late scope of work changes, this research only includes the technical ability of the training center to serve these drive frames. This means that there will be no research and explanations of the current Large Drives training concept and process, no material planning and workstation equipment, and so on, because the research work has already been completed by other production development engineer experts and will still continue after this research.

4.3 Data collection and analysis

The case company’s operations, the S&M department's current training concept and process, and the scope of the work of the new training center were already described in the previous chapters. This chapter of the research is the analysis part of the topic. It proceeds with the DMAIC’s Measure and Analyze phase, where we need to understand the process as it is, collect data to evaluate process inputs, and assess current performance. We also need to analyze data with statistical tools and charts to prioritize key input variables in order to identify waste, bottlenecks, problems, and root causes. This chapter includes a description of the data collection and analysis of the current training cell concept and the whole process. It provides an explanation of the observations conducted, which helped to recognize the waste, bottlenecks, and issues in the current concept in order to identify the elements that could be improved. This section also continues with the SLP procedure. As part of the layout re-design process, work-time studies are performed to determine process cycle times, lead times, outputs, waste time, and capacity. It also enabled the determination of material flows and relationships between activities.

4.3.1 Observations on site

Observations on the facility's site were used as a qualitative approach, and they were the primary method for collecting empirical data. The purpose of the observations was to gain knowledge about the phenomenon being studied by observing it. There were several systematic on-site observation sessions to become more familiar with and understand the current training concept and process, as there was no top-level knowledge of it when the research began. To design a new technical solution and develop the process, the entire concept and process needed to be thoroughly understood. Constant notetaking, measurements, photography, and videography were all part of the process. It assisted in identifying the obstacles that the current training center, which utilizes a cell production model encounter.

Observations allowed the identification of issues, root causes, bottlenecks, and waste in the current process and revealed possible improvement opportunities for the new design. A few advanced assemblers whose job description includes training were openly interviewed and discussed to obtain all possible improvements during the observations. With the discussions and interviews, it was possible to obtain a point of view from people who work in that environment on a daily basis (customers), which aided in considering the customer's perspective and identifying all of the important aspects. Observations also aided in identifying the flow of the process, materials, and people, allowing for the data analysis phase: the continuation of work-time studies as well as the creation of spaghetti diagrams.

4.3.2 Bottlenecks and waste

In high-volume manufacturing processes, bottlenecks and waste are common occurrences. Bottlenecks in a business's operations are obstacles in a stage or process that limit a whole system's capacity to produce at its peak, resulting in clogged productivity. The case company, as previously stated, employs Lean manufacturing principles. As a result, it was critical to focus on waste elimination, which entails identifying all activities that do not add value to the products and processes. The goal was to create value by identifying and removing those bottlenecks and waste. The observations of the current training concept assisted in recognizing that the flow of the current process is not as clear, smooth, and maximal as it could be. There is a significant amount of unnecessary movement of people and materials, as well as inefficient processing. These bottlenecks and waste can be classified into five categories, as follows:

To begin with, the current training center operates on a cell model, which does not support the company's one-piece flow production principle. One-piece flow, as stated in the literature review, eliminates waste time, reduces product lead time, and creates flexibility. As a result, due to observations and the SAP database, the company's one-piece flow model has proven to be a more efficient and faster operating method than a cell production method. It is also easier to maintain quality and ergonomics with the one-piece flow when the stages are divided into smaller phases, so there won't be any possible assembly errors. It takes much longer to assemble the drive from start to finish than it does to produce the drives in a one-piece flow model, where the assembly process has been broken down into those smaller phases. Also, when new assemblers come in and get used to assembling the drives themselves from start to finish, challenges arise when they move to the main production line. In this case, the assembler must adjust to the way one-piece flow operates on the main production lines, particularly the pace, and tempo of the flow. The one-piece flow method also reduces the possibility of catastrophic errors and rework since the batches are smaller and the method includes more cross-checking.

Second, the current training center's design lacks its own docking station and AGVs, which means that when the product is finished, the assembler must always slide it onto the trolley and transport it to the main production line for cabling to the palette that is at the docking station. This procedure is inefficient and creates a lot of waste because it adds significant extra processing time to both the training process and the main production line. In terms of training, the procedure includes an additional step that disrupts the flow of the Lean. If a main production line assembler is present at the docking point at that time, the trainee will have to wait to get to the docking point. If, on the other hand, the trainee uses the docking point, the lines assembler must wait, which can take a long time if there is a new trainee, and the trainer must instruct. This causes a bottleneck and a blockage at the end of the main production lines, causing the flow of the line to suffer and the assembler of the last phase of the line to be in a hurry to assemble the next drive. Furthermore, the sliding process of the drive is not as ergonomic and safe with the current transfer trolleys that are used, and the design of the main production turntable conveyors is not appropriate since they were not designed for that sliding purpose.

Third, there are issues with the material concept, such as the location and picking of the material, as well as the unclear operating model. The current material concept wastes time when pallet material and IGBT-kits must be picked up far away from the main production lines pallets and FIFO-racks. There are 6 FIFO-racks in the training area, where not all of the rack materials have been able to fit, and some of the material needs to be retrieved from the main production line's FIFO-racks. The large amount of material in those FIFO-racks also slows the flow when searching for assembled components.

Fourth and fifth, flexibility and maximum space utilization of the current training area's layout and location. The current setup causes bottlenecks and waste because the facility is underutilized. The training area is not open and large, and it is restricted by three walls. These walls restrict the movement of people and materials, as well as the positioning of workstations, FIFO-racks, and other elements. The pallet materials do not fit in the area because there is not enough space for them, so they have to be picked up from the main production line's pallets. Logistics access to the area to refill the racks is not entirely optimal. The area is also quite far from the main production lines and AGV home base stations, which means that if a new training center and docking point are built in the area, the AGV route and people's accessibility may be affected. As a result, instead of the area in question and the AGV's route and performance, other area alternatives had to be studied for the new layout planning and design of the new training center.

4.3.3 Work-time studies

According to the SLP procedure, several work-time studies had to be conducted prior to the layout design process in order to determine what type of design would be suitable for the new training center, how to develop the current training process, and to identify the best possible layout location. In addition to the current location of the training center, one of the major focuses of the research was to examine other potential layout locations. As a result, the production area of the S&M factory had to be thoroughly investigated in order to find alternatives. Finally, another potential location was discovered, but this required additional research, such as more observations and work-time studies of another production process.

Work-time studies and clocking’s had to be taken that revealed the output and cycle times of the training cells to understand the capacity of the training process. Table 4 illustrates the variables, but the outputs of the training cells are confidential. The output was calculated by recording the time it takes to produce one product and the number of products completed per shift (each shift lasts 8 hours) in the training cells. The outputs of the training cells varied depending on the product family and variation being produced, as well as the trainee's personal level. Because frame size R6 takes longer to produce than frame size R5, and R5 takes longer to produce than frame size R4, the output of frame size R4 was the greatest and the output of frame size R6 was the smallest. The outputs also differed depending on whether the person was a completely new employee or an already experienced assembler whose skills were being expanded. The outputs also differed depending on how many assemblers were trained during the shift. The current training concept allows for the simultaneous training of 1 to 4 assemblers, but the new design may allow for the simultaneous training and induction of up to 6 assemblers. The average minimum outputs were counted when only one assembler was trained, and the average maximum outputs were counted when four assemblers were trained at the same time.

Table 4. Work time study: outputs of the training cells and kit workstation.

Work time study - OUTPUTS		
Output	Training cells	Kit workstation
Per hour (minimum)		
Per shift (minimum)		
Per hour (maximum)		
Per shift (maximum)		

As previously stated, we also had to investigate another location option prior to designing the layout. The S&M department's kit workstation was chosen as the second location option because of its area’s potential, features, and advantages. It is flexible due to the open area, and lack of walls, it has a large floor surface area, and the route is unobstructed and clear. At kit workstation, components are pre-assembled, meaning they are kitted and prepared for movement to the main production lines. Components that take time and are difficult to assemble have been moved to the kit workstation for pre-assembly kitting, allowing the main production lines to be more efficient, because those small and difficult kits no longer need to be fiddled with at the one-piece flow line and are then easier and quicker to assemble. For example, thermistors, and fans are kitted onto skeletons, and other smaller parts are kitted to each other so that the main production line gets ready kits such as busbars, capacitors, and panel holders. The logistics partner is in charge of delivering kit materials and components to the main production line, as well as other FIFO-rack materials and components. When the kit components run out of Kanban boxes and racks in the main production lines, the racks are filled as soon as possible using the Lean Manufacturing principles of JIT and push and pull control.

As a result of that other layout location option, we needed to understand the capacity of the kitting process. That meant we had to conduct work-time studies and clocking's that revealed the output of the kit workstation as well. Table 4 also illustrates the kit workstation variables, but the outputs are confidential as well. The output was calculated by recording how many times per hour and per shift, the logistic partner picked up and delivered finished kits from the kit workstation to the main production lines. Observations showed that since the output of the kit workstation is directly proportional to the flow of the main production lines, its output varied from day to day depending on the production volumes of the shift. The average minimum outputs were counted when there was a quiet shift, and the average maximum outputs were counted when all of the main production lines were operating. The output of the kit workstation was greater in comparison to the training cells, but they still cannot be directly compared because the processes and influence of the processes are significantly different.

4.3.4 Flow of work analysis

The flow of work analysis was also conducted, which meant investigating the differences in the general flow, movement of people, AGVs, and material between these two layout location options. There were three critical measurement variables to be measured when comparing both location options A and B. Option A is the location of the current training cells, and option B is the location of the kit workstation (new possible location). The variables and values can be seen in Table 5. The three variables were the following:

1. The AGV's total distance.

2. The total distance traveled to pick up the pallet materials prior to the assembly process.
3. The total distance traveled from the kit workstation to the main production line racks to deliver the finished kits.

Table 5. Flow of work analysis of AGV, current training cells and kit workstation.

Flow of work analysis AGV, current training cells and kit workstation				
Variable	**Location A**	**Location B**	**Gap of the distance (ratio)**	**Maximum gap of distance per shift (ratio)**
The AGV's total distance (ratio)	0,411	2,432	2,021	48,51
The total distance to pick up pallet material prior assembly process (ratio)	0,318	3,143	2,825	67,79
The total distance from kit workstations to the main production line (ratio)	1,6	0,625	0,975	27,30
Total distance:	2,33	6,200	3,871	

The measurements were taken by walking through the routes with a pedometer. The goal was to determine the maximum distance in meters covered by the AGV per shift if the AGV docking point is located at both locations, the total distance per shift of picking up pallet materials from the main production line at both locations and the total distance per shift of delivering finished kits at both locations. Finally, for both location options A and B, we were able to calculate total travel distances and gaps in meters, but they are referred to as ratios in this research because of confidentiality. The gap in the distance (ratio) is determined by how much difference there is between the location options. The lower the ratio (the closer it gets to zero), the better. With those distances, we were also able to calculate the maximum possible travel differences that could occur during a single shift by multiplying the distances with the maximum possible outputs of the training center and kit workstation.

The first measurements of the AGV revealed that the total distance in location option B is longer than in option A. The maximum gap of the distance (ratio) per shift covered by the AGV is 48,51 because the AGV docking point is further away. This causes additional movement for the AGV, so its capability also had to be measured and analyzed. AGV cycle time analysis is covered in Chapter 4.3.6. For this, additional research in the layout design was required, taking the variable into account while conducting the Weighted Decision Matrix (WDM) shown in Chapter 4.5.8. The second measurement revealed that the total distance traveled to pick up pallet material prior to the assembly process is also longer in location option B. The maximum gap of the distance (ratio) per shift is 67,79. This results in the previously mentioned extra movement of people and material, i.e., waste. This aspect had to be considered as well when creating the Weighted Decision Matrix (WDM). Finally, differing from the previous measurements, the third measurement revealed that the total distance from the kit workstation to the main production lines to deliver the finished kits in location option A is longer than in location option B. The maximum gap of the distance (ratio) per shift is 27.30. However, whether the new training center is in an old or new location, the actual process of the kit workstation does not change in this case, but it has a minor impact on the operations when the logistic partner's walking distance increases in option B. The WDM takes this variable into account as well.

With those clocking's, measurements, and comparisons, we were able to compare the capacities, output, movement, and flow of these two location options. It thus aided in generating spaghetti diagrams and subsequent layout planning with AutoCAD, enabling, SWOT analysis and a Weighted Decision Matrix (WDM) of both layout and location options.

4.3.5 Cycle time analysis

To gain more knowledge about the training process, we needed to conduct another important work-time study. A cycle time analysis was performed to determine how much time is spent in one cycle of the training process: when the drive is ready, transferred to the main production line, and a new drive is started. The purpose was also investigating the waste time of the current training process. In that cycle time analysis, we only considered the steps required in this research, meaning that the correct total cycle of the drive, including main assembly, testing, and final assembly was not considered since it is not included in the research. A total of ten different measurements were taken in the study. The features and variables can be found in Appendix 1, but the time values are confidential. The operation phases in the cycle time analysis clocking's were divided into four major main steps: 1. Transferring the finished drive to the trolley and transporting it manually to the docking point. 2. Time spent waiting to get to the docking point for cabling. 3. Sliding the drive to the docking point, attaching the cables, and ordering the AGV 4. Material collection and return to the training cell for the start of a new drive. We could calculate the total average time and total average waste time of the current process with using the cycle time analysis. Waste time was calculated by summing steps 1, 2, and 4 because they were considered extra steps in the current process that could be fixed. Step 3 is critical, which means it cannot be eliminated or reduced in the new possible concept or process either.

The cycle time study showed that the total time and waste time of the process varies a lot depending on many factors. As previously observed, if there is an old, experienced assembler at the training, the timeframe is shorter than if there is a completely new assembler. It also depends on the product family and frame size being produced, as the cabling process for the ACx580 product family took longer than the ACS880 product family due to the additional cables that needed to be installed. The ACS880 R6 variant's cabling process takes the longest. Step 2 also included an outside influencer of the process, the main production line. Because the training cells lack a docking point, the finished drives must be transferred to the main production line for cabling and docking. The total time was affected by whether the main production line assembler was present at the same time cabling the drive on the docking point. If there was an assembler, there occurred extra waiting time, which was the process's biggest bottleneck and waste time.

The measurements revealed that step 2 was the source of the most waste time. Step 4 generated the second most waste time, and step 1 generated the least waste time.

4.3.6 AGV Cycle time analysis

To determine the capacity of the two current Automated Guided Vehicles (AGV) that serve the four main production lines and a Timber (the frame sizes R1-R3) workstation, it was necessary to conduct third work-time study. The study was conducted to determine whether the current AGVs could also serve the new training center, which includes its own docking point. The Timber workstation demonstrates the layout location option where the kit workstation locates. Thus, according to a test, AGVs are not able to travel to the location of training cells because they lost the connection since there is no programming of logic in that area. The variables and features are shown in Appendix 2, but the time values are confidential. The study revealed whether the current two AGVs are sufficient or whether a new additional AGV purchase is required with the new training center. Several clocking's were taken, and the AGV's cycle time was compared in various situations. The measurements were taken in two scenarios:

Scenario 1: When the AGVs were 'free,' i.e., idle, and not retrieving drives from the main production lines.

Scenario 2: When the AGVs were 'operating/occupied'.

The measurements revealed that the capacity of the current AGVs' is insufficient to serve the new training center as well. This issue had to be considered in the new training center's technical and process design, as well in the project budget, since a new AGV purchase is required.

4.3.7 Spaghetti relationship diagram

The SLP procedure includes the analysis of a spaghetti relationship diagram, which shows the issues in the current training concept process steps, material flows, and people movements. The figure 16 displays a spaghetti relationship diagram of the production and material flow that illustrates the training process from beginning to end. The letter S in the diagram represents the starting point. The process steps in blue are divided into four stages in the diagram:

Step 1: Starting the assembly process by retrieving the palette materials and IGBT-kit with a material trolley from the main production line. Step 2: Continue with the main assembly process, picking the material from the FIFO-racks multiple times. Step 3: Sliding the finished drive to the trolley, transferring it to the main production line for cabling and docking, and ordering the AGV to pick up the drive. Step 4: Return to the training area before repeating the process again when starting the assembly of a new drive.

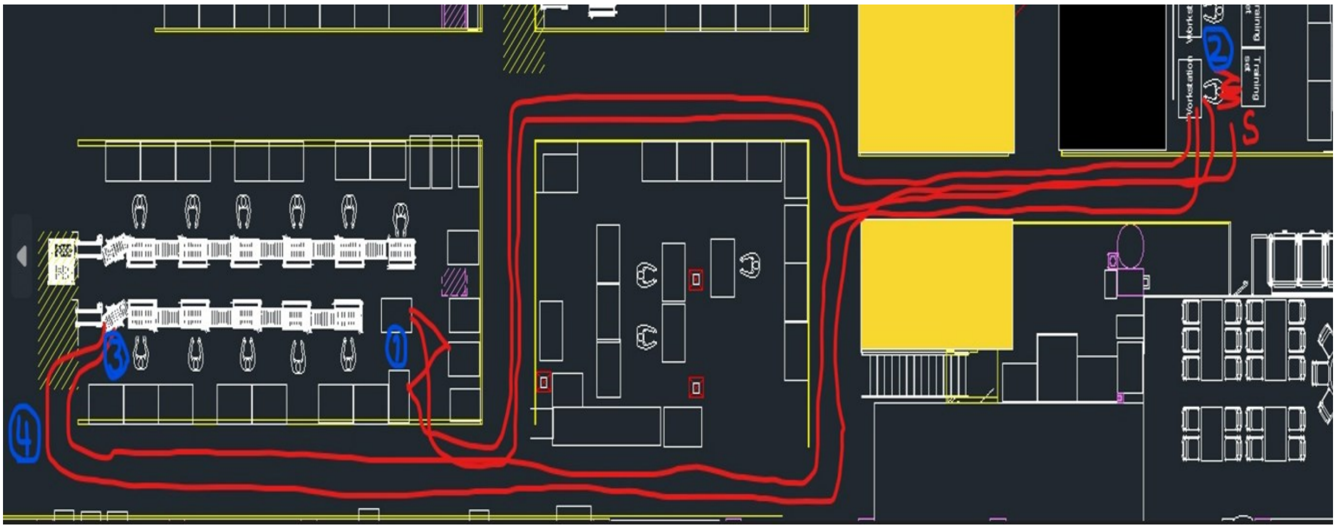

Figure 16. Spaghetti relationship diagram of production and material flow in the current training concept.

The current training area layout and training concept have numerous significant drawbacks. The flow of the process is not clear and effective, as shown in the diagram. It causes a lot of unnecessary and extra movement of people and materials, as well as disruptions, which can all be considered waste and bottlenecks in the process. Because the training area lacks necessary equipment, such as a docking station and an AGV that picks up finished drives from the training area, as well as necessary materials for assembly. Long transportation distances at the start and end of the process waste time.

Material picking trips and docking station trips are long and complicated, with paths crisscrossing with logistic partners and the main production line. As also mentioned earlier in the research, the third stage of the process, in which the main production line is used for docking the finished drives, causes a delay in the process and a disruption in the main production line's production. To conclude, having the right equipment and tools in the working area is essential. Also, having the right materials in the right place at the right time is crucial to achieving overall production effectiveness and the desired quality.

4.4 Improvement opportunities

The preceding chapters highlighted the current training concept and process problems, shortcomings, waste, bottlenecks, and root causes. This section contains a brief description of the technical, material, process, and layout improvement opportunities revealed by data collection and analysis. With observations, work-time studies, cycle time analyses, waste time analyses, and a spaghetti relationship diagram, it was possible to identify the problems with the current training concept and process. It was discovered that the current training concept and process effectiveness, flow, and safety are not at the desired level. Besides that, training cells are not flexible, and the current layout and location do not enable maximum space utilization. Furthermore, the training process also disrupts the main production lines' production. The improvement opportunities are divided into the following 5 categories:

1. **Technical improvement opportunities**: Replacing the cell workstations with a new one-piece flow line. If there is a technical design of a one-piece flow line that contains all of the necessary equipment and tools for the training process, the problems of unclear flow, inefficiency, waste, and bottlenecks would be eliminated. The process and flow will be more effective and clearer because there will be no unnecessary movement of people, extra transportation, or production blockages on the main production line.

2. **Material improvement opportunities:** Replacing the current FIFO-material racks with new, smaller material racks and possibly changing the pallet material concept. If the new design of the training center is a one-piece flow line, that means that there needs to be one rack for each frame size's phase. If all the rack materials are behind the workstations and all the pallet materials are close to the training area, that means that all the extra movement of people and material will be eliminated. It also makes the operation of logistics easier and more systematic.

3. **Process improvement opportunities**: Designing a "flexible hybrid one-piece flow line." Creating a design that allows the drives to be produced as a one-piece flow model and as a cell model. This will provide a lot of flexibility because more assemblers can be trained on the line at the same time for different frame sizes. It also makes it easier to train both new and experienced assemblers concurrently. It would also save resources and improve overall training quality.

4. **Layout improvement opportunities:** After resolving the three previously mentioned improvement issues, we are also able to determine the new training center's layout and design it accordingly. We are also able to answer the RQ2: Designing and creating the layout and solution that guarantees safety, ergonomics, flexibility, clear flow, and the maximum utilization of space. This will remove all the bottlenecks, waste, and problems of the current training concept and process.

5. **Pilot opportunities:** The new training center could also serve as a test line for new designs and features before they are implemented on the main production lines. For example, pilot testing the new SAP Digital Manufacturing Cloud (DMC) features and testing synchronized assembly line takt by using PLC-controlled stoppers that will be implemented on the main production lines in the future.

4.5 Designing of a new training center

This chapter of the research includes the design part of thesis topic. The designing part represents the propositions for the improvement opportunities. It is also a DMAIC approach's Improve phase, where solutions to problems identified in the first three phases of DMAIC are determined. Developing the training concept and process, eliminating root causes and waste, and implementing improvements are all part of this phase. Through creating solutions to the improvement opportunities, we were also able to answer the research questions (RQ1, RQ2, and RQ3) of the thesis. The chapter begins with the development of the workstations and equipment, the logistics and material concept, and the training process. Following that, it presents the layout design process, and workshops during the design process, and concludes with the Weighted decision matrix (WDM), which was used to vote on the location of the new training center.

4.5.1 Development of the workstations and equipment

This section describes the technical requirements and features in order to provide solutions to the identified technical improvement opportunities before the layout design. As the research and analysis revealed, the current cell workstations must be replaced with a one-piece flow production line that enables more effective flow and production. The new one-piece flow line would have 4-6 workstations, turntable conveyors between each workstation, 1-2 docking points, a ball table, transfer trolleys, and a new AGV. Due to ergonomics, all workstations should be electrically height adjustable and contain all of the necessary assembly equipment. However, the line must be hybrid, which means that each workstation must be equipped to enable the production of all product families from start to finish. As a result, workstations should have enough space for screw container profiles because each workstation requires a large number of screws. Workstations should also have enough space for PCs that use SAP, smart screwdrivers, pneumatic screwdrivers, selectors, bottle holders, RFID readers, and other assembly tools such as carpet knives, post-it notes, magnetizers, and so on.

Due to the flexible hybrid feature, the drives must be able to be removed and slid back onto the turntable conveyors between the line. The turntable conveyors allow drives to be taken into and onto the line if the line operates as a cell model rather than a one-piece flow method, which means that each workstation produces a different product family or drive frame simultaneously. The drives are slid onto the transfer trolley and moved to the docking point to avoid interfering with the production of another workstation. The design also requires electrically height-adjustable transfer trolleys that are specifically designed for this purpose. For reasons of safety and ergonomics, the turntables and transfer trolleys should have a docking system that is compatible with one another. Turntables and transfer trolleys should also have brakes that activate during the procedure to keep the trolley balanced and edges that prevent the drives from falling during sliding the drives or moving the trolley. All different types of drives must fit in the trolley, so trolley dimensions must be compatible with the sizes of all drive frames.

The ball table should be designed for the purpose of moving the drives on the line if the one-piece flow production line is L or U shaped, instead of a straight line, because turning and moving the drives is easier and lighter on balls than on conveyor platforms. For safety purposes, the ball table must have edges on all sides, excluding the sides where the drives slide onto the table. Depending on the final design and shape of the line, the training center should also include 1-2 docking stations. With those docking stations, we can send drives from the training center without having to travel to the docking stations on the main production line. The process and flow will be more effective and clearer because there will be no unnecessary movement of people, extra transportation, or production blockages on the main production line. Finally, as the work-time studies revealed, we require a new AGV purchase and AGV fleet integration due to the insufficient capacity of the current AGVs. The logic of the new AGV should be capable of ordering and delivering empty pallets to the docking stations of the training center, as well as sending finished drives and pallets to the testing system. The new AGV, as well as the existing AGVs, should be programmed to serve all the main production lines as well as the new training center.

4.5.2 Development of the logistics and material concept

Because of the proposed new technical design, we must also modify the current material concept and design a new one, as the new training center uses a one-piece flow production method. This necessitates the replacement of the current set FIFO material racks with FIFO-racks that contain only the material required in the exact phase. Since we want to maximize space and create flexibility, the solution was a smaller FIFO rack that contains all of the necessary rack materials and components required in the assembly process, rather than the standard-sized FIFO-racks that are currently used in production. As a result, each frame size would have its own material rack containing all of the materials required for the stage in accordance with the one-piece flow method from both the ACS880 and ACx580 product families. Thus, the R4 frame size has four racks, the R5 frame size has five racks, and the R6 frame size has six racks. In addition, there would be one rack in the training area containing all of the IGBT-kits required for assembly as well as all of the frame variation materials that are rarely used during the training process. If the line is operated using the one-piece flow model, the racks are always changed and placed behind the correct workstation on the line in advance, depending on the frame size being assembled.

When all product families and frame sizes are considered, there are 17 pallets of pallet material, which is enormous. Because of the limited floor space, all of the pallet material could not fit into the training area, as measured, and observed on the site. Depending on the design, shape, and phases of the training line, 2-4 EUR palettes can be placed on the area, as analyzed. The pallet material concept could work in accordance with the Milky-way concept, meaning the appropriate pallet materials are ordered in advance when they are needed at the right time. In the alternative scenario, if there is no space in the area, they will still be picked up from the pallets of the main production lines, because work-time studies revealed that this step produces the least amount of waste time and no specific bottleneck, and it can thus be accepted in the new process if no other solution can be developed.

4.5.3 Development of the process

Due to the ability of finding solutions and re-design the technical features and material concept of the current training design, we are also able to enhance and develop the entire training procedure. The new technical design should allow us to create a flexible One-piece flow line that can produce products as a One-piece flow production model as well as a cell production model. This gives us a lot of flexibility because we can train different frame sizes and product families in the line at the same time, according to demand and need. However, the new training center should ideally always operate with a One-piece flow model whenever possible, just like the main production lines. Since more assemblers can be trained on the line at the same time for different frame sizes, the new design will provide a lot of flexibility to the process. It makes it simpler to train both new and experienced assemblers at the same time. Depending on the number of workstations and how many assemblers are trained simultaneously, the production of drives could be divided into 1, 2, 3, 4, 5, or 6 stages, depending on the frame sizes. The production flow can also process, run, and operate in both directions if the line is U-shaped. The new process increases the output, improves the efficiency, and flow of the drives, and most importantly, reduces cycle time and waste time, allowing for more time to be allocated to the actual training of the assemblers. Due to these factors, it also saves resources and significantly improves overall training quality.

4.5.4 Layout designing

After defining the technical, material, and process requirements and features provided by data collection and analysis, it was time to begin designing the layout of the new training center. Since the development of the current training concept constitutes a layout re-design, it was crucial to make use of all the data from observations, work-time studies, waste time studies, and cycle time analysis in order to design a layout that is more efficient. As previously stated, the purpose and goal were to design and create a layout and solution that ensures safety, flexibility, ergonomics, clear flow, and maximum space utilization. According to Lean principles, the solution should eliminate all bottlenecks, waste, and problems associated with the current training concept and process. This section of the research covers the final two stages of the SLP procedure: searching through obtainable layout options, evaluating alternatives, and finally selecting the best possible layout. Creating and evaluating the proposed layout was a difficult and time-consuming process due to the inherent diversity of objective characteristics and the long data collection procedure.

4.5.5 AutoCAD layout design

The latest AutoCAD 2022 software was chosen as the layout design technique and application. As we needed to design a new layout that fits within the given area, it was effective to generate two-dimensional technical drawings with precise measurements and dimensions using AutoCAD. As previously stated, we had two facility layout location options, and those are shown in figures 17 and 18:

1. Option A: The location of the kit workstation.
2. Option B: The location of the current training cells.

In these figures, all workstations, equipment, materials, etc., are erased to show how the facility's empty layout plants looked prior to starting the layout design process. The space and area of layout option A are slightly larger.

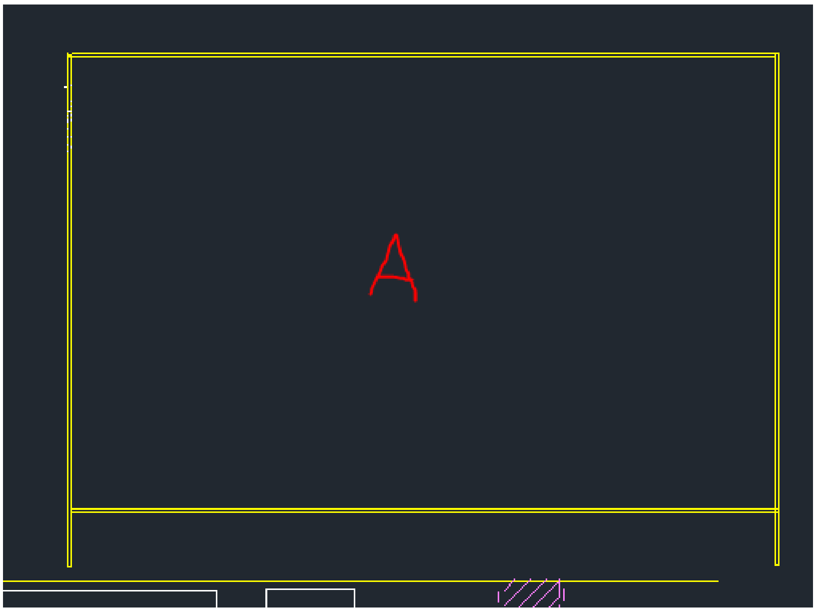

Figure 17. Empty area of layout location option A. The location of the kit workstation.

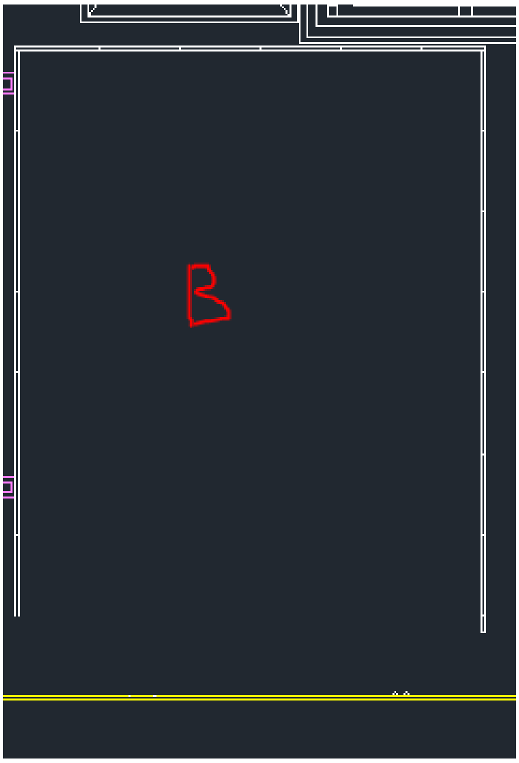

Figure 18. Empty area of layout location option B. The location of the current training cells.

According to the defined requirements and features, we needed to place all of the necessary workstations, equipment, materials, components, etc. that form the flexible hybrid one-piece flow line in those two layout plant options of the facility. We needed to create and design a variety of layout alternatives that differed in terms of stages, shapes, features, equipment, and overall setup and placement.

4.5.6 Mapping different layout options

This section presents a list of various possible and potential layout options created with AutoCAD. Based on the data collection and analysis, criteria, scope, and requirements, three alternatives from location A and three alternatives from location B were generated, which makes a total of six options. The options were either a 4-phase or 6-phase one-piece flow line. The possibility of a 5-phase line was eliminated during the early layout designing phase because it was determined not to be a viable alternative because of the criteria. All layout options have a total of 16 FIFO racks, as shown in Table 6 below, because that is the optimal number of racks for the training concept and process based on observations, calculations, and tests. In that case, with this number of racks, we can ensure that each frame size has the appropriate number of racks for its stages. Each rack, in accordance with the one-piece flow, contains the materials and components from both product families that are required at that particular stage. Meaning, the R4 frame has 4 racks, the R5 frame has 5 racks, and the R6 frame has 6 racks. The sixteenth rack is intended for the IGBT-kits, and variation components that are rarely used so that assemblers do not have to retrieve them anymore from the main production lines' racks.

Table 6. The production families and number of FIFO-racks per frame size.

Product family	Frame size	Phases	FIFO-racks
ACS880 / ACx580	**R4**	4	4
ACS880 / ACx580	**R5**	5	5
ACS880 / ACx580	**R6**	6	6
+ ACS880 / ACx580 variation and IGBT-kit rack	**R4, R5, R6**		1

There are three shape setup options: a straight line, an L-shaped line, and a U-shaped line. They all differ in terms of features, equipment, and the placement of materials and equipment. All six layout variations are mentioned and explained further below. Each alternative's positive and negative aspects, such as strengths and weaknesses, opportunities, and threats, are discussed.

The first possibility: The layout alternative 1.1 of location option A (figure 19). This is a straight 4 one-piece flow line. The setup includes 1 printer, 4 workstations, 4 buffer turntable conveyors (one between each workstation and one before the docking station at the end of the workstations), three transfer trolleys, 1 docking station, two trash containers, and 1 AGV that retrieves finished drives from the docking station and delivers empty pallets. Drives can be slid off and on from each turntable conveyor if the line is operated as a cell model.

The most significant advantage is that the area is open (no walls anywhere) with plenty of room to operate and move around. In terms of logistics, filling the FIFO-racks is simple and straightforward, and changing the racks is barrier-free, quick, and easy. In addition, the area can facilitate at least three pallets of pallet material. This 4-phase line alternative, on the other hand, is not flexible at all because it has four phases, so the process flow of frame sizes R5 and R6 is not as optimal and clear as the frame size R4 process flow. That means the phases must be divided in the training process differently than in the main production lines. Aside from that, the placement of the FIFO racks is inefficient and not optimal for frame sizes R5 and R6; when producing these drives, they must be slid to the opposite side of the line when FIFO racks are in the way. There is a traffic corridor on this side, so the idea is not the best and most optimal choice. The capacity of this alternative is restricted to simultaneously training 1 to 4 assemblers.

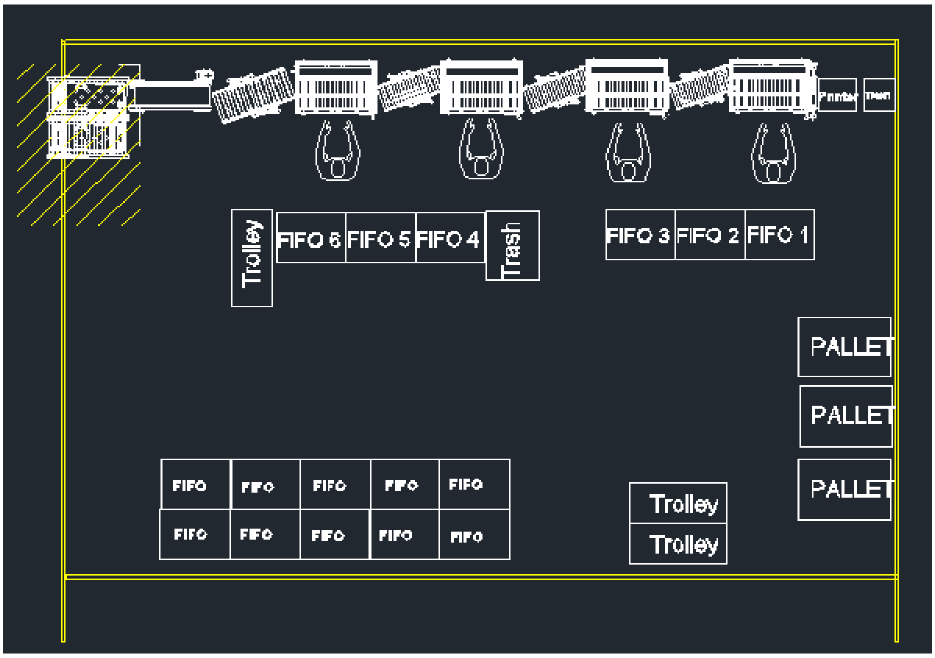

Figure 19. Layout alternative 1.1 of location option A. Straight 4-phase one-piece flow line.

The second possibility: The layout alternative 1.2 of location option A (figure 20). This is a so-called L-model 6-phase one-piece flow line. The setup includes 1 printer, 6 workstations, 6 buffer turntable conveyors (one between each workstation and one before the docking station at the end of the workstations), 1 buffer table, 1 ball table, 4 transfer trolleys, 1 docking station, two trash containers, and 1 AGV that retrieves finished drives from the docking station and delivers empty pallets. As in the first alternative, drives can be slid off and on from each turntable conveyor if the line is operated as a cell model.

The most significant advantage is that the alternative is more flexible, as it has 6 workstations that enable a clear and optimal One-piece production process flow also for the drive frame R5, which operates as a five-phase, and for the drive frame R6, which operates as a six-phase. In this alternative, changing and filling the racks are also quick and easy. However, the area is not completely clear, and the placement of the FIFO-racks is inefficient because they cannot be placed directly behind the assembler at every point of the line due to the line's space and shape. Furthermore, the area cannot facilitate any pallets of pallet material, so they needed to be picked up from the main production lines. The capacity of this alternative is restricted to simultaneously training 1 to 6 assemblers.

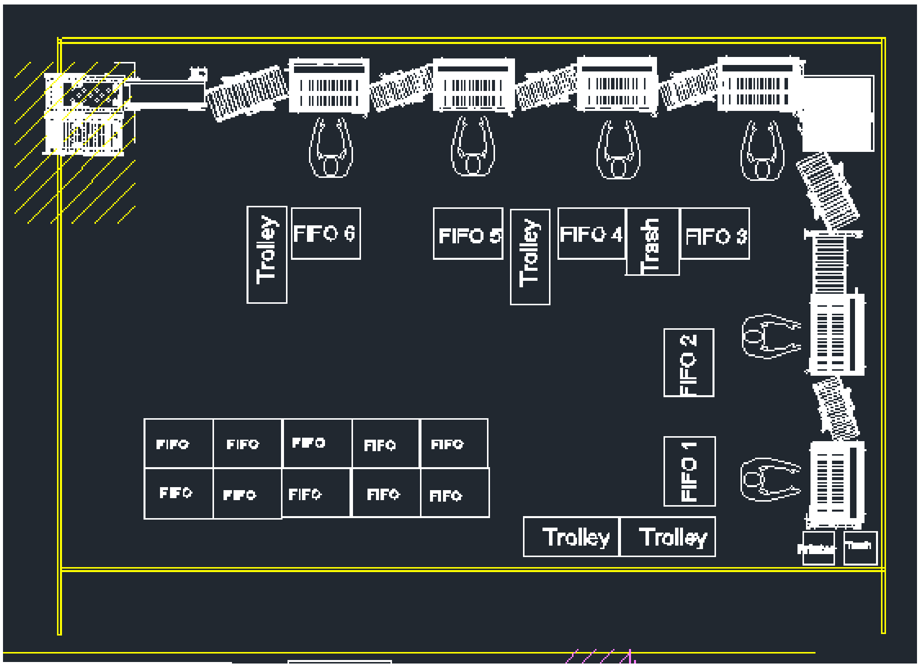

Figure 20. Layout alternative 1.2 of location option A. L model 6-phase one-piece flow line.

The third possibility: The layout alternative 1.3 of location option A (figure 21). This is a so-called U-model 6-phase one-piece flow line. The setup includes 2 printers, 6 workstations, 6 buffer turntable conveyors (one between each workstation and one before the docking station at the end of the workstations), 1 ball table, 4 transfer trolleys, 2 docking stations, 4 trash containers, and 1 AGV that retrieves finished drives from the docking stations and delivers empty pallets. As in the other alternatives, drives can be slid off and on from each turntable conveyor if the line is operated as a cell model.

The most significant advantage is that the alternative is very flexible since it includes 6 workstations that allow for a clear and optimal one-piece production process flow for all frame sizes. The unique, agile, and effective feature of this alternative is its U-shape, which allows the line and process to be run and operated in both directions because the docking stations are located on both sides of the line. The placement of FIFO-racks is effective in this alternative because the racks are directly behind the assemblers, making use and filling of the racks quick and straightforward. The placement, use, and operation of transfer trolleys are straightforward and efficient. The positioning of trash cans is also effective. Two pallets of pallet material can be facilitated in this area. The only disadvantage is that the placement of FIFO-racks that are not currently in use is rather tight and restricted, so moving and changing racks must take place outside of the area where there are corridors. This option's capacity is limited to simultaneously training 1 to 6 assemblers.

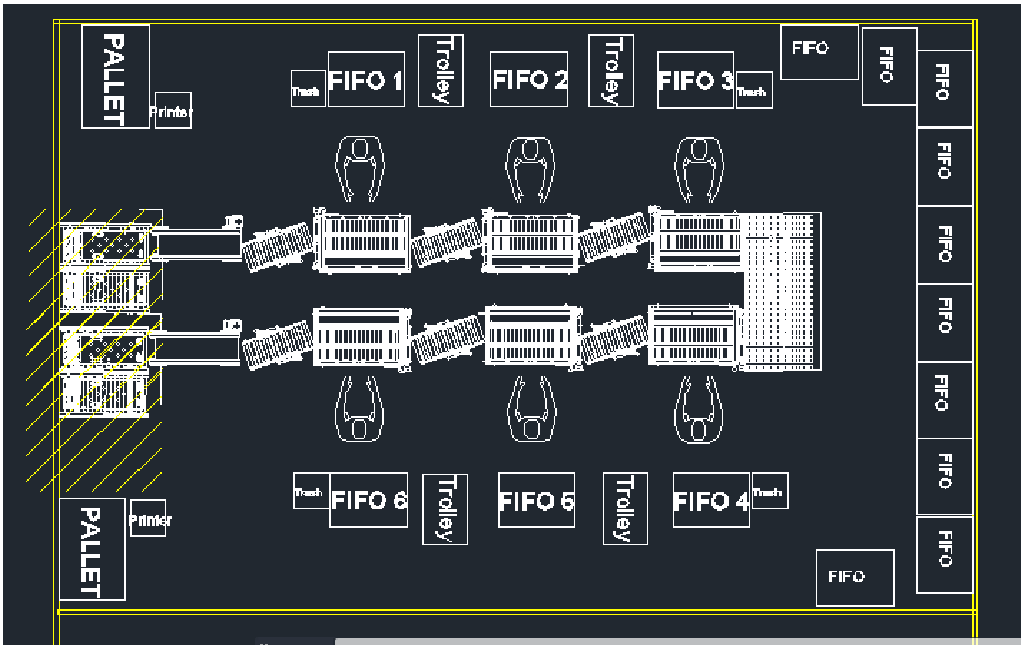

Figure 21. Layout alternative 1.3 of location option A. U model 6-phase one-piece flow line.

The fourth possibility: The layout alternative 2.1 of location option B (figure 22). This is likewise a straight 4-phase one-piece flow line, similar to layout alternative 1.1 of location option A, and the setup is similar, but the material and equipment placement is different due to the shape of the area. This option looks remarkably identical to the current training cells but with a one-piece flow line and a new FIFO-rack mechanism. The major advantage of this location option is that we do not need to change and relocate the kit workstation. Also, the area of location option B is more tranquil than area A because it is further away from the main production lines. Filling and changing the FIFO-racks is easy, and the area can facilitate at least three pallets of pallet material. The main disadvantage of this location is the three walls (white lines) that drastically restrict the area, meaning that the flow and movement of people and materials are ineffective. This alternative, like layout alternative 1.1 of location option A, is not flexible at all due to the four workstations, i.e., four phases. Also, because of these three walls, using the transfer trolleys is significantly more difficult in this location area, thus while using the trolleys, we must move the FIFO-racks out of the way, which is not an optimal procedure. This option's capacity is limited to simultaneously training 1 to 4 assemblers.

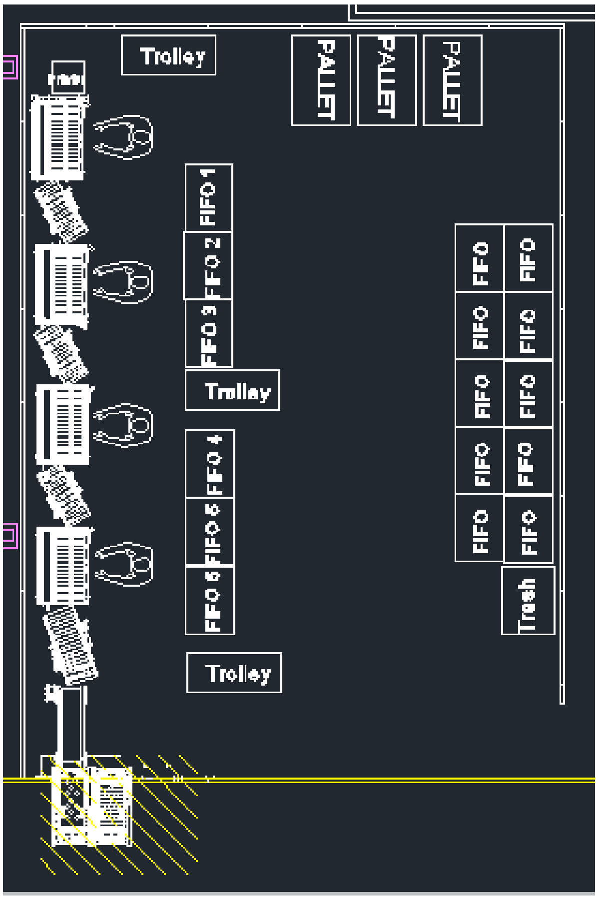

Figure 22. Layout alternative 2.1 of location option B. Straight 4-phase one-piece flow line.

The fifth possibility: Layout alternative 2.2 of the location option B (figure 23). This is an L-model 6-phase one-piece flow line, equal to layout alternative 1.2 of location option A, and the setup is similar, but there is one additional buffer table, and equipment placement and material placement differ due to the form of the area. The major advantage of this location option is that we do not need to change and relocate the kit workstation, and the area is more tranquil than area A because it is further away from the main production lines. This option is flexible since it has 6 workstations that allow for a clear and optimal one-piece production process flow for all drive frames. The major disadvantages of this alternative are the same as those of alternative 2.1. However, because of the line's shape, the area is even more restricted, and the placement of the FIFO-racks is inefficient because they cannot be placed directly behind the assembler at every point. Furthermore, because the location cannot facilitate any pallets of pallet material, they had to be picked up from the main production lines. The capability of this option is limited to simultaneously training 1 to 6 assemblers.

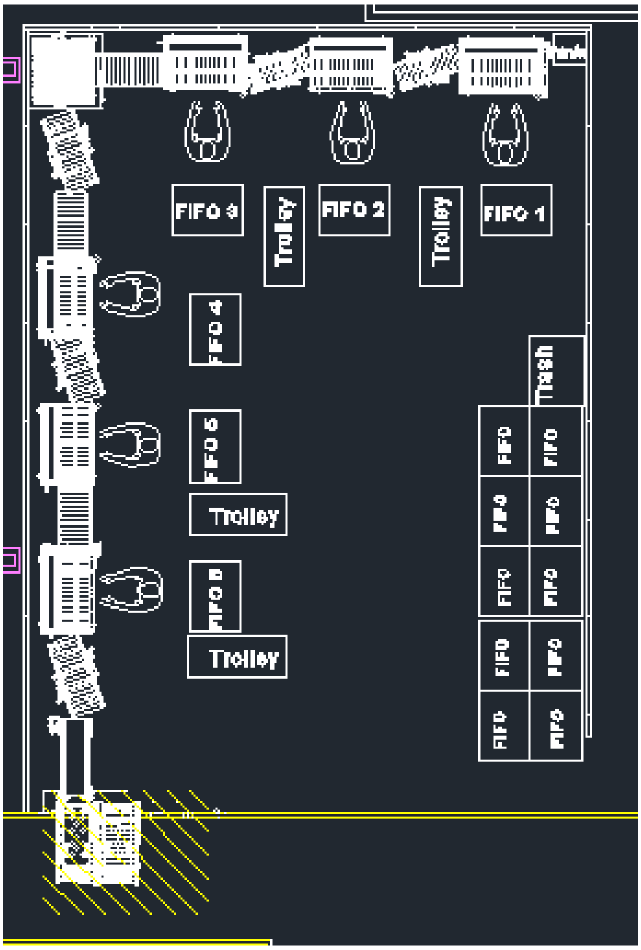

Figure 23. Layout alternative 2.2 of location option B. L-model 6-phase one-piece flow line.

The sixth possibility: Layout alternative 2.3 of location option B (figure 24). This is a U-shaped 6-phase one-piece flow line, equal to layout alternative 1.3 of location option A, and the setup is similar, but the material and equipment placement differs due to the shape of the area. The main advantages of this option are the same as those of layout alternative 1.3, as well as the fact that we do not need to change and relocate the kit workstation, and the area is more tranquil than area A because it is further away from the main production lines. On the other hand, the major disadvantage of this solution is that the placement and filling of FIFO-racks are ineffective since the area behind the racks is quite narrow, and logistic workers cannot easily fill the racks, thus they may have to fill the racks on the same side where assemblers use the racks. The FIFO concept is not fully supported by this approach and design. The capability of this option is limited to simultaneously training 1 to 6 assemblers.

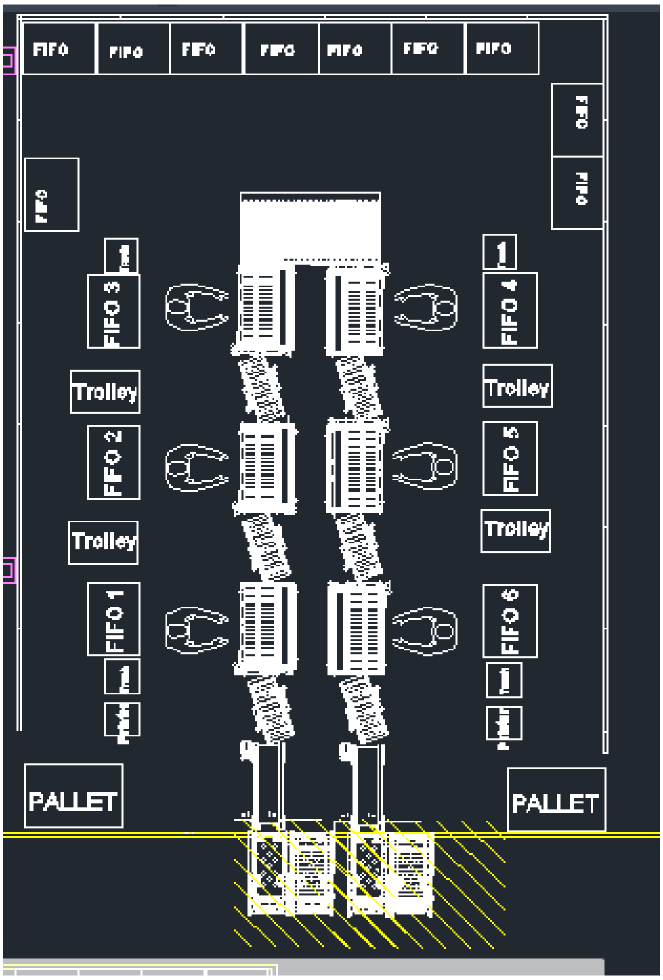

Figure 24. Layout alternative 2.3 of location option B. U-model 6-phase one-piece flow line.

4.5.7 Workshops

Since changes in layouts, production, and processes affect multiple stakeholders, several workshops were organized to exchange information. To stay up-to-date and avoid overlapping prerequisites in the plans, production changes in the shared areas must be considered carefully when making decisions. During the project, several workshops were held with the project team (operations manager, project manager, production engineer, and process engineer) throughout the design phase to review and monitor the project's status and situation. The goal of the workshops was to present results, brainstorm, exchange opinions and perspectives, analyze them together, and spar in order to create the best possible end result as a team. A few workshops were also held with other stakeholders, including the customer (production line: production manager, production supervisors, production support team) and logistic partner. Several workshops were also organized with the new training center's supplier before and after the order was placed in order to receive the training center in accordance with the correct specifications and scope of work and to ensure that the supplier fully understood the specifications and requirements.

Two large workshops were also held as part of the project, with the objective of reaching a general agreement among all internal stakeholders (project team, production line, and logistic partner) regarding the optimal location, design, and features for the training center. Workshop 1: This was established in order to vote on the best two layout alternatives from both location options A and B. At this workshop, all of the different layout options were presented in detail, and the positive and negative features of each layout option, i.e., strengths, weaknesses, opportunities, and threats, were highlighted. The U-shaped 6-phase one-piece production lines, i.e., alternatives 1.3 and 2.3, were the dominant and clear winners in this workshop, as these options had the highest potential according to each criterion and attribute. Following the voting process in the same workshop, the criteria, weightings, and scores for the Weighted decision matrix (WDM) for the subsequent workshop were also determined. Workshop 2 continued with these two layouts, with the goal of voting and selecting a winner between these two location options A and

B. The workshop 2, WDM, and voting session are covered in greater detail in the following Weighted Decision Matrix chapter.

4.5.8 Weighted Decision Matrix

According to the SLP procedure, the widely used Weighted decision matrix (WDM) was chosen as a quantitative technique for resolving this multi-criteria decision analysis (MCDA) issue. The WDM played a very important part in the research since it enabled the selection and ranking of these two items (layouts) by scoring them against various features of varying priority levels. The WDM was created specifically for this project, based on the formula and instructions provided in the literature. The goal was to select a winner between these two layout options, A and B. The WDM was based on the following principle: 1. Establishing the features and criteria. 2. Weighting and prioritizing criteria based on importance. 3. Finally, the weighted criteria were scored to form a relative ranking. As previously stated, the weight values were determined in collaboration with the project team and the production manager. The criteria were established collaboratively by giving weighting values that were essential and correct at each point, in accordance with the company's operating principles and the principles of Lean and Systematic layout planning. Voting was based on assigning a score to each criterion. The total score was then multiplied by predetermined weights.

The weighting scale was 1 to 5, where 1 means little importance and 5 is very important. The most important criteria are labeled 5, and the least important are labeled 1. However, only weighting values of threes, fours, and fives were assigned because it was decided that all of these criteria were extremely important. The scoring scale was 1 to 5, with 5 being the highest score and 1 being a very poor score. The WDM was created using the formula that was expanded and given in the WDM literature review: An average score (the average scoring points of 13 voters) was calculated from each criteria column, and this average score was multiplied by the weighting value to get the total score of each criterion. As a result, the final score was calculated by summing up the total scores of each column together. Thus, the WDM weighting values were hidden from the table for the duration of the voting session to avoid biased answers and to ensure the reliability of the results in order for them to be as realistic as possible. The WDM followed the formula shown below:

The total final score *(T)* is defined as

$$T = WSx_1 + WSx_2 \dots . WSx_n \quad (1)$$

where WS is a weighted score defined as

$$WSx_{ij} = IFx_i * Sx_j \quad (2)$$

IF_{xi} is the importance factor and S_{xj} is the score obtained by the feature.

Participants in the voting session were carefully considered, and the perspectives of various parties were included because the new training center and the changes it brings will affect many people's daily activities. Everyone who voted had extensive knowledge of the principles of the S&M department, main production line operations, the training process, and the operation of the kit workstation. There were two different voting sessions: one among the project team and one among production, i.e., the customer. From the project team, one process engineer and two production development engineers participated in the voting. From the customer's, i.e., production side, ten people participated, including: production technical supporters, production supervisor, experienced trainers and assemblers, kit workstation assemblers, logistics development specialist, logistic worker, and quality expert. The voting involved a total of 13 people, including the author of this research.

As previously stated, the research involved investigating these 2 different location possibilities (A and B), observing the processes, taking measurements, performing work-time studies, analyzing them, mapping different alternatives, and selecting the top two potential alternatives from both options. So based on those attributes, the following characteristics and criteria were the most important in the WDM's (table 7) execution: safety and ergonomics, clear and effective flow, AGV functionality, flexibility, and maximum space utilization. Other factors were total costs, time, operational maintenance, and the tranquility of the training area. Therefore, prior to the final design of the new training center, its impact on three major variables had to be considered: the operation and flow of the kit workstation, the unobstructed and safe corridor passageway, and the operation, flow, and safety of the AGV and its route. Consequently, these variables were also chosen as criteria. These criteria features were reviewed from three different production viewpoints: the main production lines, the kit workstation, and the new training center. During the voting session, all parties were given clear instructions on how to fill out the WDM and what each criterion included. During the voting, the layout drawings of both options A and B, as well as the outputs of the current training center and kit workstation, were visible. The flow of work analysis table of the AGV, current training cells, and kit workstation were also available. There was also a comment form attached, where participants could add to their thoughts if they had new observations or perspectives. The criteria of the WDM table are expanded below the table 7 to provide a more precise understanding of what each criterion consists of and what characteristics it involves for layout options A and B. Both the positive and negative sides are explored.

Table 7. Weighted Decision Matrix (WDM) for resolving MCDA issue and ranking the layouts of the new training center.

Weighted Decision Matrix					
		OPTIONS			
Criteria	Weighting	Layout A		Layout B	
		Score	Total	Score	Total
1. Safety and ergonomics of training center	5	4,3	21,5	3,5	17,3
2. Clear and efficient flow					
2.1. Clear and efficient flow of main production lines	4	4,3	17,2	3,5	14,2
2.2. Clear and efficient flow of kitworkstation	4	3,2	12,9	3,8	15,4
2.3. Clear and efficient flow of the new training center	4	4,6	18,5	2,8	11,1
3. Functionality of AGV's					
3.1. No Impact/change on the AGV route	4	4,0	16,0	1,3	5,2
3.2. Safety of the AGV route	5	3,8	19,2	1,6	8,1
3.3. No impact on main production lines	5	3,4	16,9	2,6	13,1
4. Flexibility of the layout	4	4,5	17,8	2,5	9,8
5. Maximum space utilization	5	4,3	21,5	2,0	10,0
6. The total cost and time of the comission	3	3,3	9,9	2,5	7,6
7. Operative maintenance during the modification work					
7.1. Operative maintenance of the old training system	3	3,1	9,2	2,8	8,5
7.2. Operative maintenance of the kit workstation	5	3,0	15,0	4,2	21,2
8. Tranquility of the training area	3	2,8	8,3	4,2	12,7
	TOTAL:		**204,2**		**154,2**

Criteria 1.1. Safety and ergonomics of the training center. Meaning overall safety and ergonomics of the workstations (electrical height adjustable, FIFO-racks close, behind the assembler, enough space to operate, etc.) and an area that allows materials to be handled without excessive bending. Both options A and B meet the standards and requirements for high safety and ergonomics. However, option A has better ergonomics because there is more space behind the racks. **Criteria 2. Clear and efficient flow:** The flow of work, people, and material. These criteria have been broken further into subcategories 2.1, 2.2, and 2.3. Starting with **Criteria 2.1. Clear and efficient flow of main production lines.** The implementation and operation of the new training center must not disrupt the general flow of the main production lines. The overall flow of the main production lines remains the same in both options A and B. **Criteria 2.2 Clear and efficient**

flow of the kit workstation. As previously stated, selecting option A requires the relocation of the kit workstation to location B. The finished kits would then be relocated further away from their current location. This means more movement for the logistics partner. In option B, the kit workstation would remain in its current location. In Chapter 4.3.3, the outputs and impacts of the kit workstation and current training center were stated. **Criteria 2.3. Clear and efficient flow of the new training center.** Both line options A and B have the same physical structure. Thus, in Option A, the flow of production and material is clearer and more efficient due to the open space. Due to the distance, picking up pallet material from the main production lines is easier and faster. However, this necessitates increasing the capacity of the main production lines' pallet material and shortening material delivery times. The area of option B, on the other hand, is limited by three walls, so filling the material into the FIFO racks may only be possible from the front side, which does not fully support the general FIFO principle.

Criteria 3. The functionality of AGV (AGV home station - training center's docking point – manipulator test system). These criteria have also been broken further into subcategories 3.1, 3.2, and 3.3. Starting with **Criteria 3.1. No impact or change on the AGV route**. Option B requires the programming and development of a completely new AGV route. It implies that the AGV will pass through the main corridor and the logistics area, causing distractions. Option A requires only minor changes to the route (similar to the route of the docking point of drive frames R1-R3). As mentioned in Chapter 4.3.3, when the AGV is operational, the total length of the route (AGV home station-training center's docking point-manipulator test system) is shorter in option A and longer in option B. NOTE: In this section, a grade of 5 indicates that the impact and change are very small, while a grade of 1 indicates that the impact and change are very significant. **Criteria 3.2. Safety of the AGVs route.** Option B requires redesigning the logistics area's layout and restricting the route to ensure an unobstructed and safe route for AGV. The current toilet corridor must be decommissioned or limited in its usage. Option A uses the same route as drive frames R1–R3, which is already perceived as a safe and barrier-free route. **Criteria 3.3. No impact on main production lines**. The operation of the AGVs must not have a negative impact on the main production lines with the implementation of the new training center. Because of the new training center's faster takt and cycle times, AGV must pick up the finished drives for testing more frequently than before (output and repetitions are dependent on the training center's assemblers, flow, and cycle time). According to the tests, the total operation time/cycle time of the AGV (departure from the home base to pick up an empty pallet from the test system manipulator -> delivery of an empty pallet to the training center's docking point -> retrieval of the finished drive from the docking point -> delivery of the finished drive to the manipulator for testing) is longer in option B because of the distance of the location.

Criteria 4. The flexibility of the layout. Option A is more flexible due to its open area. This means that the line and FIFO-rack placement are more effective and flexible, and the racks are easier to move, transfer, and change in the area. It is easier to fill the racks in terms of logistics. Delivering and positioning potential pallet material is also easier. Option B is restricted by three walls, which significantly limits its flexibility. Racks cannot be placed or changed as quickly, and the logistics operation is also more restricted. **Criteria 5. Maximum space utilization.** Option A has a slightly larger total area, and it is also possible to slightly expand the area in the worst-case scenario from one side if absolutely necessary. The area in Option B is smaller, and it is still bounded by three walls and a heavy shelf in front of one of them. **Criteria 6. The total cost and time of the commission.** Costs incurred during the modification process. NOTE: In this section, a score of 5 represents the lowest possible cost, and a score of 1 represents the highest possible cost. The total costs will be higher in Option B. **Criteria 7. Operative maintenance during the modification work.** These criteria have also been broken further into subcategories 7.1 and 7.2. Starting with **7.1. Operative maintenance of the old training system.** Keeping the current training system operational during changes. In both options A and B, we must be prepared before the change that training will be interrupted or organized on a free main production line if possible. **Criteria 7.2. Operative maintenance of the kit workstation.** Maintenance of the kit workstation. Both options A and B will maintain the kit workstation operating. Option A, on the other hand, necessitates a plan for relocating the kit workstation to a new location B, as well as a production-free schedule to move it to ensure that the operation of the kit workstation won’t be disrupted. Finally, the WDM ends with **Criteria 8. The tranquility of the training area.** There is slightly more general production noise and movement in Option A, which comes from the main production lines, testers, and logistics operations. The noise, however, is not critical. Option B is more tranquil because the area is less affected by that noise and has less general traffic.

As shown in the WDM table, option A is the winner in ten criteria, while option B is the winner in three criteria. Consequently, the final results demonstrate that option A was the clear and quite overwhelming winner with 204.2 points. Option B received 50 fewer points, resulting in a score of 154.2. The WDM results and final result can be considered reliable because the weighting values were hidden, and the participants voted neutrally. However, it should be noted that one person may interpret a feature differently than another, which affects the score given by the person. Finally, if the WDM process had failed or proved untrustworthy, the voting session would have been repeated, ensuring the reliability of both the data and the participants. On the other hand, the production manager would have played a significant role in deciding on the location since the production manager is primarily responsible for the department's production and area. In conclusion, utilizing Weighted Decision Matrix as an MCDA issue methodology, the ranking and selection of the layouts for the new training center were determined. Therefore, option A will be implemented. This means that the new training center will be located and implemented in the area where the current kit workstation is, and the kit workstation will be relocated to the area where the current training cells are.

4.6 Flexible 6-phase OPF training center

This is the final section of the design phase, where the final solution of the research is presented in greater detail and specifically but concisely. The final outcome is a Flexible 6-phase U-shaped One-piece flow training center. The technical solution, workstations and equipment, concept and process flow, logistics and material concept, and process description are all covered in this chapter. It also concludes with a spaghetti relationship diagram demonstrating how the new design solved and improved the issues in the current training concept's process steps, material flows, and movement of people.

4.6.1 Technical solution / Workstations and equipment

The final result of the design process is a new U-shaped 6-phase one-piece flow line that is "hybrid", which means it is flexible and versatile as it is capable of producing all product families as a one-piece flow model in phases as well as a cell production model from start to finish. This feature guarantees excellent training quality and effectiveness. The final technical solution of the new training center, as illustrated in figure 25, includes the following setup: 6 workstations, 6 turntable conveyors, 2 docking stations, 4 transfer trolleys, 1 ball table, 2 printers, an AGV that retrieves finished drives from docking stations and delivers empty pallets, and a PLC-controlled stopper system. All workstations and equipment are compatible with each other.

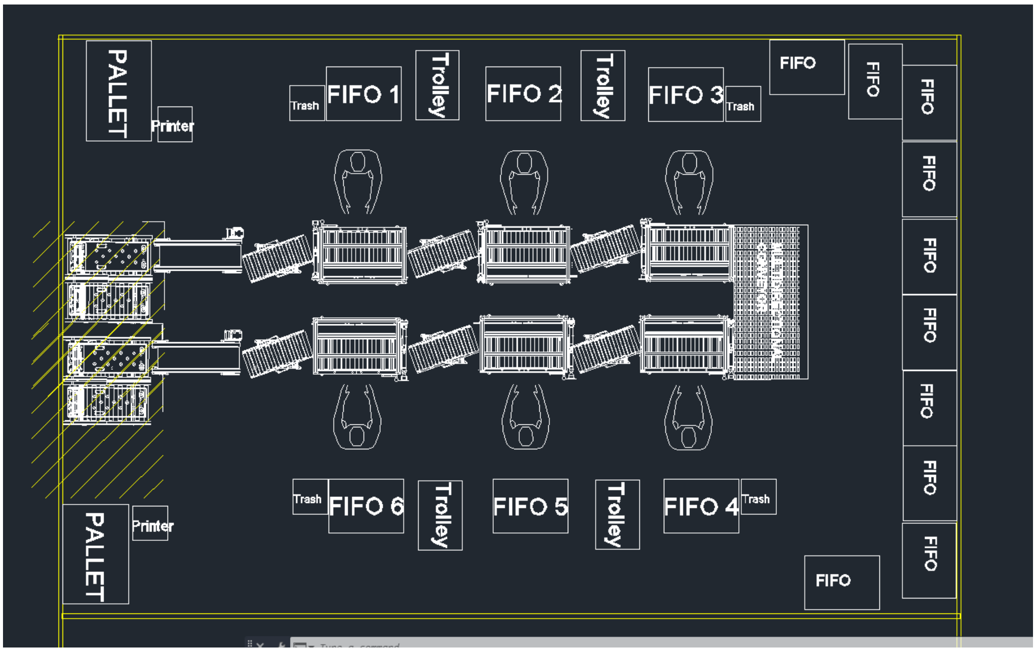

Figure 25. The final result of the design process. U-shaped, flexible hybrid one-piece flow training center with six phases.

Safety, ergonomics, clear flow, and effectiveness were all top priorities during the design process. Each workstation, turntable conveyor, and ball table have edges and fall protections. Hence, it is ensured that all workstations are safe and ergonomic, featuring electrically height-adjustable features and predetermined homebases, as well as three predetermined heights for turntables. Each workstation is outfitted in a manner to ensure that all six workstations can produce every product family and drive frame as a one-piece flow model and as a cell production model from start to finish. In addition, every workstation is equipped with a pneumatic stopper on both sides of the workstation and controlled with a PLC system to ensure safety. Because each workstation requires a large number of screws, every workstation has 5 screw container profiles. Every single workstation also includes a PC that uses SAP, one smart screwdriver, three pneumatic screwdrivers, a selector, a bottle holder, an RFID reader, and other assembly tools such as a marker pen, a carpet knife, post-it notes, a magnetizer, and so on. Standard-height turntable conveyors are compatible with workstations.

The drives can be removed and slid back onto the turntable conveyors between the lines due to the flexible hybrid feature. The docking systems on the turntables and transfer trolleys are compatible with one another. Pneumatic stoppers on turntables and transfer trolleys activate when the drive is docked to the turntable or moved to the trolley. Trolleys also have brakes as a feature that activate during the procedure to keep the trolley balanced, as well as edges that keep the drives from falling while sliding or moving the trolley. The ball table also has edges, and it is used for sliding the drives on the line because turning and moving the drives on balls is easier and lighter than on conveyor platforms. The ball table is crucial and plays an important role in the outfitting because it creates the U-shape for the line. Docking stations are standard in height and include pneumatic screwdrivers for cabling the drives. These docking stations are equipped with programmable logic controllers (PLCs) that enable the utilization of AGVs and the ability to send drives from the training center without having to travel to docking stations on the main production line anymore. The process and flow will be far more effective and clearer because there will be no bottlenecks or waste from unnecessary movement of people, extra transportation, or production blockages on the main production line.

4.6.2 Concept and process flow

The new training center introduces a completely new concept and process flow because it is capable of producing all product families as a one-piece flow model in phases as well as a cell production model from start to finish. The specifications of the turntable conveyors allow drives to be taken into and onto the line by docking the transfer trolley and sliding the drives to the trolley. If the line operates as a cell model rather than a one-piece flow method, the drives are always slid to the transfer trolleys and moved to the docking stations at the end of the line. This procedure occurs when each workstation simultaneously produces a different product family or drive frame. This allows us to avoid interfering with the production of another workstation and the main production lines. Primarily, the training center was developed for the one-piece flow model operation since it is the case company’s new operating principle, and it is more effective method. The advantage of the one-piece flow method is that the process has a shorter cycle time, allowing for faster, more flexible, and easier production. When assemblers have already learned the production pace during the training process, this allows them to effectively transition and integrate into the main production line, where one-piece flow is used. It is possible to learn the steps and phases more easily, allowing for better future assembly quality. Furthermore, when the steps are shorter and easier, the risk of errors and rework is minimized. The cell production model, on the other hand, has the advantage of lower material costs, and the pace of other people's work does not affect your own work. However, the cell model, on the other hand, has a longer cycle time, is significantly less efficient and assembly process is heavier, so it has higher overall costs. Furthermore, the risk of assembly errors and rework is much higher.

The training center is capable of serving frame sizes R4, R5, and R6 in divided phases with balanced stages, meaning that there is the same workload in each phase. This means that the R4 frame is four-phase, the R5 frame is five-phase, and the R6 frame is six-phase. In addition, the training center's flexibility allows it to produce drives in 2 and 3-phases. However, in this case, the Assembly line balancing problem (ALBP) will be included in the patterns, so the balancing of the phases should be divided equally. It requires observations and possible work-time studies after the implementation in order to get the phases divided equally.

The U-shaped line enables production flow in both directions, allowing drives to be produced to the left and right simultaneously. However, assemblers must remember to order the correct pallet type for the drive frame via the PLC when using docking stations, with pallet types A, B, and C available. Overall, the new concept and process flow improve the quality, flexibility, flow, and effectiveness of the training and integration of both new and experienced assemblers. With the help of this concept, we are able to train assemblers significantly more efficiently and flexibly, thereby increasing productivity and output and reducing cycle time and lead time enormously. From the perspective of both assemblers and trainers, as well as customers, this is a successful and important development.

4.6.3 Material concept and logistics

As a material and logistics concept, we were able to replace the set FIFO-racks with new, smaller FIFO-racks that are half the size of the company's standard FIFO-racks. This is possible because the volume of the training line is small in comparison to the main production lines, resulting in less material logistics and consumption. The new rack concept enables one-piece flow as FIFO-racks contain all the rack materials and components required in the assembly process of each frame size and phase. Consequently, each frame size has its own material rack containing all the ACS880 and ACx580 product families' materials required for its stage according to the one-piece flow method. As a result, the R4 frames have four racks, the R5 frames have five racks, and the R6 frames have six racks. In addition, all of the IGBT-kits required for assembly, as well as all of the frame variation materials that are rarely used during the training process, are stored in an additional rack in the training area. So, in the final concept, there will be a total of 16 FIFO-racks. When using the one-piece flow model, the racks are always changed and placed behind the correct workstation on the line in advance, depending on the frame size being assembled. This saves space because the racks are organized systematically, and moving and changing the small racks is also drastically simpler and lighter.

The pallet material concept, on the other hand, remains unchanged as a result. This is due to the fact that location layout option A was selected, which means that all the main production lines and pallet materials are right next to the training area. As already mentioned, in the main production lines, the drives require a total of 17 pallets of pallet material when all product families and frame sizes are considered. All of the pallet materials could not anyhow fit into the training area due to the limited floor space. According to the cycle time study, picking up pallet materials from main production lines causes no significant waste time and no specific bottleneck, so it can be accepted in the new process. However, the area could accommodate two pallets of pallet material, suggesting that the pallet material concept could also work in accordance with the Milky-way concept, meaning that the appropriate pallet materials are ordered in advance when they are required at the appropriate time. This concept works only when the training line produces 1 to 2 different drive frames simultaneously. If the line produces many drives simultaneously, the concept won't work because of the limited floor space. Thus, this requires forethought and can only be implemented once the training center is fully operational. The Milky-way method, however, does not add significant value to this process, according to the earlier research provided by the company. To conclude, if all the rack materials are behind the workstations, the racks are optimal size and easy to move, and all the pallet materials are close to the training area, all extra movement of people and material is eliminated. It also makes logistics operations easier and more systematic.

4.6.4 Process description

The process of the new training center can proceed in either of the following production methods: one-piece flow model or cell production model. Thus, the one-piece flow production method is prioritized and should be used as an operating model whenever assemblers are trained, since the training center was designed for that method. If it is not possible to use one-piece flow, then the cell production model should be used. These two options are illustrated and described visually in the Flowchart (figure 26) below, which represents the process description of drive frame R4.

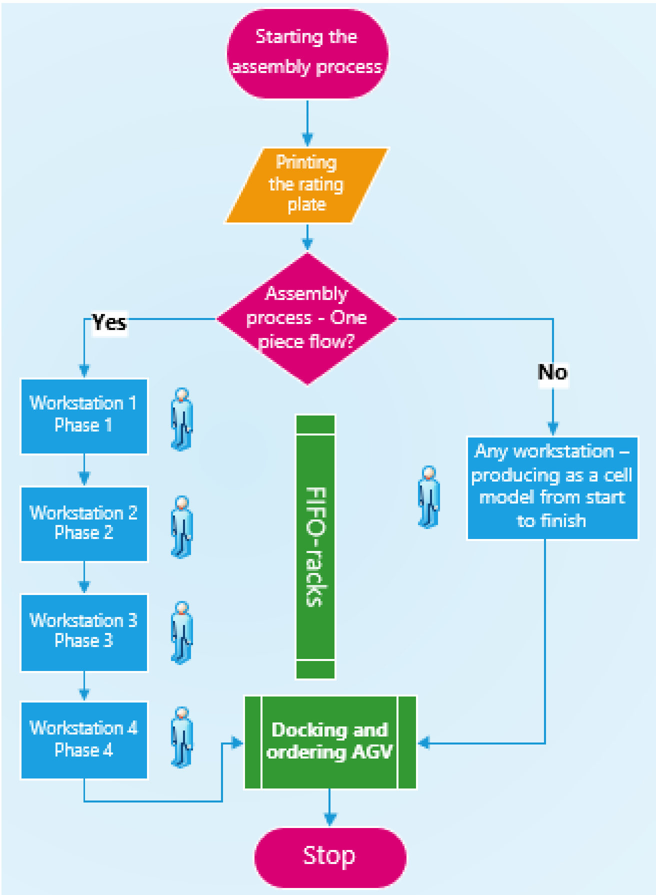

Figure 26. Flowchart of the new training center process. The diagram depicts the R4 drive frame process.

The following Flowchart demonstrates the sequence of steps and two decisions required to complete the training procedure. Each step in the sequence is represented by a block shape. Connecting lines and directional arrows connect steps. This allows both assemblers and outsiders to view the flowchart and follow the process logically from start to finish. The one-piece flow process description for drive frames R5 and R6 is the same, but instead of four phases and workstations, there are five and six workstations and phases.

4.6.5 New spaghetti relationship diagram

The process and flow of the new training center are much more straightforward and efficient than the process and flow of the old training cells, as shown in the new spaghetti relationship diagram (figure 27). With the new technical design (workstations, docking stations, AGV, transfer trolleys, and ball table), the new material concept (smaller one-piece flow FIFO-racks), and the new process flow (one-piece flow), the issues, waste, and bottlenecks have been eliminated and value has been created. There is no additional movement of people or material, no issues with process steps or material flows, and no disruptions to main production lines. Figure 27 illustrates a spaghetti relationship diagram of the R6 drive frame's manufacturing process as a one-piece flow model.

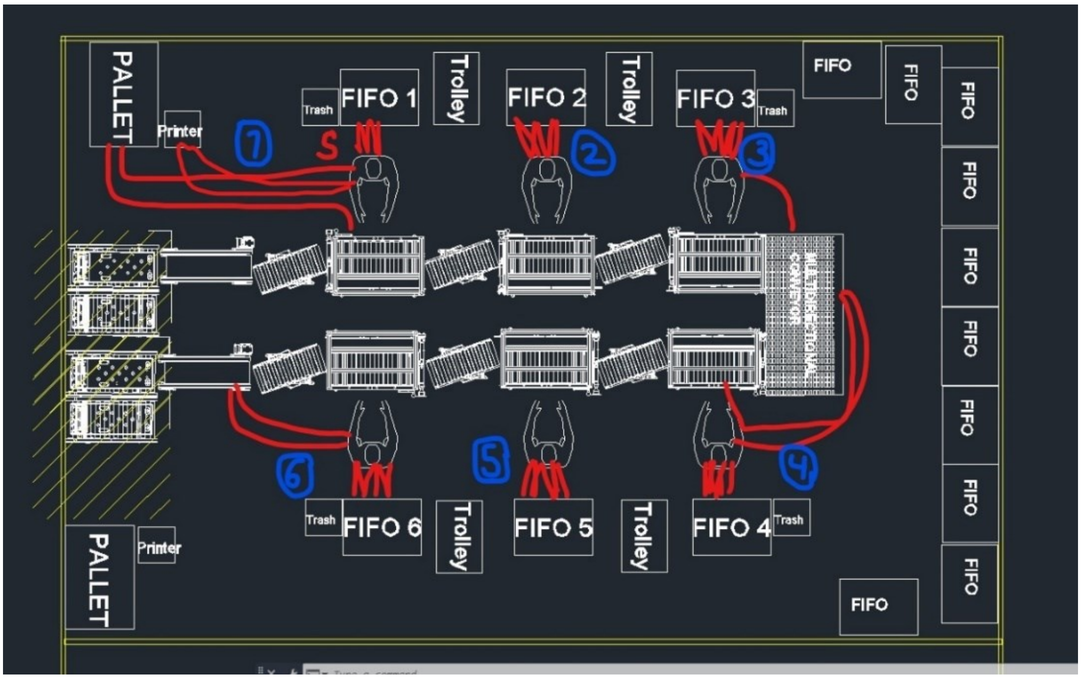

Figure 27. Spaghetti relationship diagram of production and material flow in the new training concept (the R6 drive frame).

In the figure, the red-letter S represents the starting point. The process steps in blue are divided into six stages: Step 1: Starting the assembly process by printing the rating plate. Then collecting the pallet materials and picking the material from the FIFO-racks multiple times while assembling. Step 2 to Step 5: Moving forward with the main assembly process, picking the material from the FIFO-racks multiple times while assembling. Step 6: Proceeding with the main assembly process, picking material from the FIFO-racks multiple times while assembling. After finishing the drive, moving the drive to the docking station for cabling and ordering the AGV to pick it up. Then repeating the process.

Overall, the spaghetti diagram clearly demonstrates that the new layout, design, and concept of the training center were successful. The new training center meets all of the requirements, goals, features, and criteria that were established for it at the start of the design phase.

4.7 Implementation plan

The implementation of the new training center is briefly addressed in this chapter of the research. The implementation phase consists of putting the new design and project plan into action. Thus, due to the lengthy confirmation time of the investment proposal, modifications that were added to the scope of work, and the long delivery time of the supplier, implementation in this thesis refers to the scope of work that was created for the supplier, validation, implementation plan, and detailed schedule instead of the commissioning of the training center. Hence, this section covers the scope of work prepared for the supplier and the plan for various stages of training center implementation with an estimated schedule. The stages are pre-commissioning (Pre-FAT and FAT) and ramp-up execution (SAT).

4.7.1 Creating a scope of work for supplier

For several reasons, the same supplier who designed and delivered the S&M department's main production lines was chosen as the supplier. The main reasons were compatibility with the main production lines, the supplier's existing know-how, the features of the training center, commercial criteria, and prices. Many workshops were held with the supplier during the designing and ordering phases of the new training center. The supplier was contacted early in the design process and briefed on the future needs of the company and about the new training center. After the design of the new training center and its features were determined, a scope of work was created for the supplier. Thus, the scope of work was modified numerous times to ensure that both parties (ABB and the supplier) had a common understanding of the desired solution and to achieve the best possible outcome. The scope of work was also additionally modified at the last minute because the drive frames R7, R8, and CR6 from the LD department's larger product family were included in the scope and project. For the purchase permit of the training center, an investment proposal was drafted and submitted for approval to the case company's upper management, because the acquisition was immense.

The content of the scope of work included requirements, safety, reliability, availability, system maintenance, and spare part maintenance features and conditions. It also included training and the schedule of the project, in addition to Factory acceptance test (FAT) and Site acceptance test (SAT) conditions. The technical content of the scope of work was basically the same as the content of Chapter 4.6 Flexible 6-phase OPF training center, but the details were simply clarified and formed. It included the training center's technical requirements, workstations and equipment, concept, and process flow, excluding the material and logistics concept.

In a nutshell, the scope of work indicated that the concept must be capable of handling various types of products, including ACX580/880 R1-R8 and CR6, which differ in size, weight, and other physical attributes. The concept must be capable of handling the products in a safe, high-quality, and efficient manner in order to support the required production volumes. AGV purchase, programming (ordering empty pallets and sending finished drives and pallets to the testing system) and PLC-controlled stopper programming were also included in the scope. Many negotiations were held regarding the specifications, objectives, offer, and prices, after which a new training center was ordered as a consensus. As a result, the work scope is intended to be a turn-key solution. The supplier is responsible for delivering the entire production line, including workstations, turntable conveyors, docking stations, transfer trolleys, AGVs, and logic programming. ABB's logistics partner is responsible for purchasing the FIFO-material racks. The assembly tools, smart and pneumatic screwdrivers, and other assembly equipment were ordered from the standard supplier.

4.7.2 Commissioning steps and timeline

The implementation of the new training center adheres to the ABB gate model procedure, which is utilized to control new acquisitions and projects. The initiative or project is divided into distinct stages in the gate model to provide guidance for managing transformations and supporting ABB principles, strategies, and value creation objectives. There is a validation phase before implementation to make sure that the business case and implementation plan are realistic and that the pilot test has validated the solution. This requires creating an implementation plan that includes the various steps of implementation, piloting, reviewing the project budget and schedule, and assessing risks prior to implementation. The implementation plan and schedule for the training center are depicted in figure 28 below. It includes a release roadmap and an estimated implementation timeline with scope and activities.

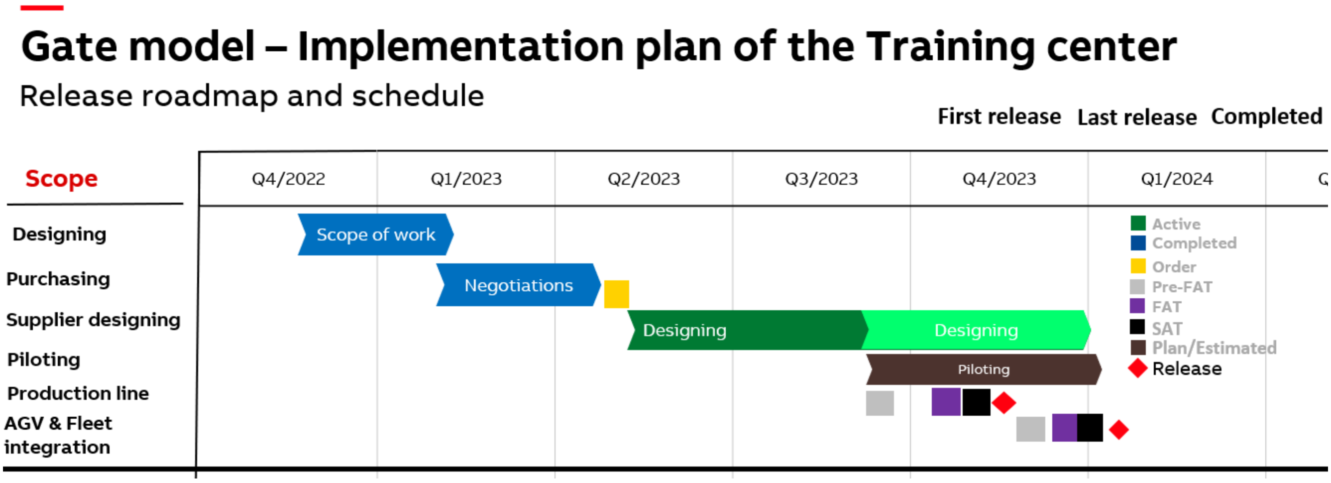

Figure 28. The new training center's implementation roadmap and estimated timeline.

The road map timeline is illustrated quarterly, which means there are four quarters in a year. As depicted in the figure, the scope includes six distinct objectives. The training center's first objective is the designing phase, which included the creation of the scope of work that launched at the start of the project in the middle of Q4/2022 and ended in the middle of Q1/2023. Following the preparation, modification, and finalization of the scope of work, there was the Purchasing phase, which required workshops, negotiation meetings, and sparring. At this point, the investment proposal was also awaiting approval. This phase began in the middle of Q1/2023 and ended when the training center was ordered from the supplier in the middle of Q2/2023. The schedule and plan for the steps after the middle of Q2/2023 are estimated because those actions will happen in the future, after this research. The supplier's designing phase began in the middle of Q2/2023 when the training center's scope of work was put into action to obtain the final solution. This phase ends in its entirety at the beginning of Q1/2024. Due to delivery times, the training center's design and delivery are divided into two parts: 1. Production line (workstations, turntable conveyors, ball table, docking stations, and transfer trolleys) and 2. AGV design and fleet integration. As the production line's delivery time is approximately two to three months less than that of the AGV, the production line will be implemented first. However, the Designing phase includes the Piloting phase, which includes the pre-commissioning phases Pre-FAT and FAT, and line and process ramp-up phase SAT.

The estimated pre-commissioning, which consists of a pre-factory acceptance test (Pre-FAT) of the production line, is to be held at the end of Q3/2023 at the supplier's site. The goal of Pre-FAT is to ensure that the scope of work, technical requirements, and design objectives are met so that the system is capable of entering FAT. Following that, a factory acceptance test (FAT) is scheduled for the beginning of Q4/2023. FAT is also a supplier-side test that is performed on the equipment and components before the training center is delivered to ABB's site for SAT. The goal is to ensure that the system meets the requirements, functions, and objectives that were set in actual action, in production. Before the FAT-day, a detailed FAT plan should be available, and a system checklist should be used. The most significant aspects must be observed during the FAT. It assists in identifying and correcting potential errors prior to SAT and final delivery. FAT is carried out in collaboration with the supplier, project team, and technical support team. The duration of FAT is going to be 8 to 10 hours.

The site acceptance test (SAT) is performed during the commissioning phase, when the supplier assembles the production system on the client's (ABB) premises. The SAT is scheduled to take place right after the FAT in the middle of Q4/2024, and it will also be an 8- to 10-hour continuous test run. The SAT is the final confirmation that the performance observed during the FAT is replicated after the training center has been installed on-site, ensuring that nothing has changed or been damaged throughout delivery and installation. The SAT provides final confirmation to all parties that the systems meet the performance standards. This procedure includes fully functional testing of the equipment and components after they have been installed and integrated with support systems. The training center should operate in a safe and efficient manner while maintaining a high level of quality. Thus, when the AGV and fleet integration are delivered, the entire system can be tested. First Pass Yield (FPY) on SAT should be 99%, and the implementation period should be as short as possible, so that it does not disrupt the main production lines. The commissioning checklist and overall requirements will be the same as they were in FAT. The SAT consists of the supplier, project team, production (customer), and a safety expert. After the customer (ABB) has delivered written approval stating that the SAT has been accepted, the SAT is considered approved. The warranty period begins with the written approval of a passing SAT. The training center can then be released for the production use.

The pre-FAT, FAT, and SAT of the AGV and Fleet integration follow the same procedure and targets as the production line implementation. Its pre-FAT is expected to be organized in the middle of Q4/2023. FAT is set to take place at the very end of Q4/2023, followed by SAT at the start of Q1/2024. If everything goes as planned, the last release will take place immediately after this, at the beginning of Q4/2024. That means the training center has been completely delivered. After the last release, the new training center should be fully operational, and the new training concept should be entirely implemented. The procedure is also documented so that future improvements can be easily replicated. At that point, the DMAIC's final stage Control begins, in which the control system must be established and validated for long-term capability. Thus, the goal is to verify, monitor, and control the implementation after that and always continuously develop the concept and identify possible improvement opportunities. If there are no hiccups or showstoppers, the training center will be fully operational, and the project will come to an end. However, it would be wise to keep the Lessons Learned workshop, where feedback on successes and potential failures, future improvement opportunities, and respective actions defined for future projects are identified and listed.

5 Conclusions

This is the final chapter of the research, and it includes the conclusions of the results and findings chapter. The section includes discussion, achievements, lessons learned, reliability, and possible risks, and concludes with future research and actions.

5.1 Discussion

The aim of this research was to design a new training center for the case company's variable-speed drive assembly production. The objective was to analyze the current training concept, design a new technical solution, and create a detailed implementation plan with an estimated schedule. The designing process was carried out using the systematic layout planning procedure (SLP), Lean practices, and operating principles of the case company. The research began with familiarizing and analyzing the current training concept through process observation and work-time studies. This allowed for the identification of bottlenecks, waste, and hiccups in the current design and process, which aided in the determination of potential improvement opportunities. The layout design process began after the improvement opportunities had been determined and listed. Because there were two potential location possibilities for the new training center, both options were examined. Using AutoCAD software, a variety of layout solutions and alternatives were designed for both location alternatives.

Throughout the project, numerous workshops were held in order to achieve the best possible final solution among all stakeholders. These layout alternatives were mapped with the help of the project team, production team, and logistic partner in order to select the two best layout solutions from both location options. The Weighted Decision Matrix (WDM) was then used to resolve the multi-criteria decision analysis (MCDA) issue and choose a winner between these two layout options A and B. The WDM performed an important part of the research because it allowed for the selection of the winner based on ranking. Flexible 6-phase one-piece flow training center was the final design solution.

The scope of work of the design was delivered to the supplier, and the new training center was ordered. The research also included developing an implementation plan with detailed schedule for the training center's future commissioning.

Overall, this research is a successful and comprehensive package. The research and results are analyzed, explained, and illustrated in an understandable, logical manner so that case company employees, university, and outsiders can understand and internalize the research.

5.2 Achievements

The objective of the research was to analyze the current training concept and process, design a new effective technical solution and concept, and create a detailed implementation plan with an estimated schedule. Due to the objective, the research questions RQ1, RQ2, and RQ3 that were established at the start of the research and project had to be answered. These three research questions were following: **RQ1:** ʹʹHow to develop and re-design a training center that supports the assembler for One-piece flow method production of variable-speed drives?ʹʹ **RQ2:** ʹʹHow to design and create the best possible layout and solution to guarantee safety, flexibility, ergonomics, clear flow, and the best utilization of space?ʹʹ **RQ3:** ʻHow to implement a training center that does not disrupt the main production lines and makes that way operations more efficient?ʹʹ The thesis can be considered highly successful because the project was completed in time, the new training center was ordered, and every research question was extensively answered. The waste, issues, bottlenecks, and problems could be eliminated with Lean Six Sigma and Systematic layout planning practices. All three research problems were clarified, and a solution was found for each of them. The answers and solutions are briefly reviewed below:

RQ1: The new design and process of the training center will now support variable-speed drive one-piece flow production. As previously stated, the new design is a U-model

Flexible 6-phase one-piece flow line. The new design is a hybrid model, which means it can also produce drives using the old method, i.e., the cell production model. It can be stated that the new design and process improve the quality of training and integration significantly because training is easier and more efficient for perspective of trainers, trainees, and supervisors. In the future, assemblers will directly learn the company's one-piece flow production method and integrate better, avoiding previous problems that occurred when assemblers were transferred to main production lines after only being taught the cell production model.

RQ2: All five parameters that were set were considered in the layout design and final solution of the new training center with the help of SLP procedures and Lean practices. WDM additionally assisted in selecting the best option by taking into consideration all set features. Overall safety of the new training center's components and features (workstations, AGV, transfer trolleys, tools, stoppers, etc.) is high. The training line is flexible, enabling the production of all S&M department product families and drive frames as a one-piece flow as well as a cell model for both directions. In addition, due to late modifications, the center is also able to produce LD department drive frames R7, R8, and CR6. The training center's ergonomics are excellent due to the workstations' height adjustment feature and the assemblers' limited movement. Since bottlenecks and waste time were removed and the process was simplified, the flow of the training center and process is significantly more straightforward and clearer. There will be no extra movement of people or material. Furthermore, the one-piece flow model is far more efficient than the cell production model. Maximum space utilization was also achieved by selecting layout location option A, which is open to the area and has space for possible future changes.

RQ3: The current AGVs were unable to retrieve finished drives from the training area because the old cell production workstations lacked their own docking stations. The drives had to be transported a long distance to the main production lines for docking, resulting in waste, bottlenecks, and disruptions to both the main production lines and the training process. The new training center design incorporates two docking stations from which the AGVs retrieve finished drives for the test system and feed empty palettes into the station for the new drives. The implementation, commissioning, and schedule have all been carefully planned to ensure that there are no interruptions and disruptions to the main production lines. The training center is also located away from the lines, ensuring that the AGVs' operations are not disrupted. As a result of the new training center's arrival, the training process no longer interferes with the main production lines at all. Since waste time can now be used for training, the training process is much more efficient than before, quality improves, and output increases. As a consequence, without the previously encountered distractions, the operation of the main production lines is significantly more efficient. Production volumes are expected to rise as waste is eliminated, lead times are reduced, and outputs increase.

5.3 Lessons learned

People always learn something new from every project, and these things usually become apparent in the middle of the project or after it is completed. Many factors and reasons beyond your control can cause changes. Changes to the scope of work in the middle of a project are common in re-design projects due to increased production capacity, new plans, and overlapping projects. In this research, late modifications to the project's scope of work occurred at the end of the project, after the official designing part was completed, so the scope of work of the thesis had to be expanded and redefined. The most significant changes were synchronized assembly line takt using PLC-controlled stoppers and the addition of Large Drive department drive frames to the scope of work. Other production changes have been planned for the LD area, so there was no floor space left for the own training center that was originally planned for the LD drive frames. Fortunately, we were still able to respond to these late-stage changes on a relatively short timeline by modifying the scope of work. Furthermore, the investment proposal, which was made at a slightly late stage by the project team, and extended for approval by upper management, caused additional delays. Because of these factors, the training center's delivery date was delayed, deviating from the original plan. Besides, even more delays were caused by the lengthy negotiations, waiting for the last offer, and the supplier's long delivery times. Thus, once the new training center is fully operational, an internal company Lessons learned workshop for this project must be held. However, as a corrective action at this stage, it could be simply stated that better foresight in the scope of work and its delineation is required in the future. It is critical to reserve a longer timeline to allow for schedule flexibility for large procurements like this.

5.4 Reliability and possible risks

Overall, the final design solution can be assumed to be functional and reliable in terms of design, scope of work and specifications. The data collection, analysis and designing process was systematic and WDM was used wisely by hiding the values at the voting session and choosing the participants carefully. The final design solution was reviewed and cross-checked numerous times in workshops with the collaboration of all stakeholders, including the project team, operations manager, production line, and supplier, all of whom are experts in their respective fields. The customer's perspective was considered at every stage of the project, as they will be working in the environment where the final solution will be implemented every day. Actual final design, on the other hand, is heavily reliant on the final solution developed and provided by the supplier. However, the supplier has prior experience in the design and delivery of the S&M main production lines, so the risk of defective design is low, and the supplier can be trusted. Nevertheless, after implementation, the training center and process necessitate monitoring, control, and stabilization from all project stakeholders. Given the risks, it's possible that in production use, it may also necessitate corrective modifications or in the worst case, re-planning, which can be sometimes typical for this type of procurement. However, Pre-FAT, FAT, and SAT are created specifically for this purpose, so that all features that require modification can be fixed prior to final commissioning and release. This particular new training center and concept is designed exclusively for variable-speed drive production for ABB Drive

Products. However, the concept should work in other variable-speed drive factories where the processes and operating principles are similar.

5.5 Actions and Future research

Even after this thesis is returned, the new training center project will still continue in practice. In order to achieve the best functional end result, the supplier's design phase of the final solution necessitates communication and constant interaction between the stakeholders. The implementation plan must also be put into action at the commissioning state, i.e., Pre-FAT, FAT, and SAT. Before the actual commissioning of the training center, the relocation of the kit workstation to a new location must also occur. It is important to consider the assembly line balancing problem (ALBP), where the balancing of the phases should be divided equally if the training center is operating as 2 or 3 phases. As stated, that requires observations and balancing after the implementation to be able to divide the phases equally. Furthermore, because LD drive frames were included in the training center's scope, the training center requires additional research and planning regarding the logistics and material concept, and the equipping of the workstations. These factors must be considered in order to achieve a perfect and functional end result.

If the compiled plan, anticipated steps, control, and collaboration are followed, there should be no problems in achieving a functional and effective final solution. Additionally, the training center could be used for piloting new products and variants, as well as balancing work phases. It could also be used for actual volume production, but other factors such as the testing system's capacity should be considered so that it does not cause additional bottlenecks in the production process when the test system is blocked by excessive output. To conclude, the training center should be used primarily for one-piece flow training purposes since it was designed for that.

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Appendices

Appendix 1. Cycle time analysis

Cycle time analysis - CPL TRAINING CELL										
Cycle	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Description of the operation phase	**Time (min)**	**Time (min)**	**Time (min)**	**Time (min)**	**Time (min)**	**Time (min)**	**Time (min)**	**Time (min)**	**Time (min)**	**Time (min)**
Transferring the finished drive to the trolley and transporting it manually to the docking point										
Time spent waiting to get to the docking point for cabling										
Sliding the drive to the docking point and attaching the cables and ordering AGV										
Material collection and return to the training cell for the start of a new drive										
Total time										
Waste time										
Total time Average										
Waste time Average										

Appendix 2. AGV capacity analysis

Work time study - AGVs	
AGVs being 'free,' i.e., idle, and not retrieving drives from the main production lines.	**Time**
Retrieving the finished drive that has been docked and supply the new palette to the OPF4 line	
Retrieving the finished drive to the manipulator for testing	
Total Time	
AGVs being 'free,' i.e., idle, and not retrieving drives from the main production lines.	**Time**
Retrieving the finished that has been docked and supply the new palette to the Timber line	
Retrieving the finished that has been docked and supply the new palette to the Timber line	
Total Time	
AGVs 'operating/occupied'.	**Time**
Retrieving the finished that has been docked and supply the new palette to the Timber line	
Retrieving the finished that has been docked and supply the new palette to the Timber line	
Total Time	