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METHODOLOGY FOR EVALUATING LAYOUT CONFIGURATIONS – MATERIAL FLOW POINT OF VIEW

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ABSTRACT

Methodology for Evaluating Layout Configurations – Material Flow Point of View

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The key objective for this study is to create a methodology for evaluating facility layout configurations in the case company. Literature review of the study offers an understanding about different types of layout configurations, value creating and waste, and principles which help developing the value creation with layout design. In addition to the literature review, manufacturing operations of the case company is researched with semi-structured interviews and utilizing data from the information systems of the company.

Currently the case company does not have a methodology which utilizes data to support decision making for layout decisions. This study introduces how data created by digital twin about material flow of the case company's assembly processes can be used for supporting layout decisions. As an outcome of the study a software requirement specification is created for the digital twin. Another outcome of the study is a proposition how the data about the material flow should be used.

Outcomes of the study can be utilized when using the digital twin for layout evaluation and also applying the possibilities of the digital twin wider to the organization. What comes to the key principles of the method, outcomes of the study can be applied widely in the situations where developing material flow is a significant factor. However, this kind of digital twin and data created by it can be utilized only in the case company.

Keywords: facility layout, digital twin, material flow

TIIVISTELMÄ

Materiaalivirtaan perustuva layout-vaihtoehtojen arviointimenetelmä

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Oulun yliopisto, Tuotantotalouden tutkinto-ohjelma

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Työn keskeisimpänä tavoitteena on luoda kohdeyritykselle menetelmä tuotannon layoutvaihtoehtojen vertailemiseen. Menetelmän luomiseksi työssä muodostetaan kirjallisuuskatsauksen avulla käsitys erityyppisistä layout-vaihtoehdoista, arvon luomisesta ja hukasta sekä periaatteista, joita huomioimalla arvonluontia voidaan kehittää layoutin avulla. Kirjallisuuskatsauksen lisäksi työn kohteena olevan yrityksen tuotantoprosesseihin tutustutaan teemahaastattelujen sekä yrityksen järjestelmistä haetun datan avulla.

Tällä hetkellä kohdeyrityksellä ei ole käytössä menetelmää, jossa dataa pystyttäisiin käyttämään päätöksenteon tukena layoutia koskevissa päätöksissä. Tässä työssä esitellään, kuinka digitaalisen kaksosen tuottamaa dataa tehtaan kokoonpanoprosessien materiaalivirroista pystytään käyttämään päätöksenteon tukena. Työn tuloksena syntyy vaatimusmäärittely digitaaliselle kaksoselle sekä ehdotus, miten sitä tulisi tulevaisuudessa hyödyntää.

Työn tuloksia voidaan käyttää työn kanssa yhtäaikaisesti kehitetyn digitaalisen kaksosen hyödyntämiseen layoutsuunnittelussa, sekä digitaalisen kaksosen luomien mahdollisuuksien laajentamiseen myös muihin käyttötarkoituksiin. Työn tuloksia pystyy menetelmän perusperiaatteiden osalta soveltamaan laajasti tilanteisiin, joissa materiaalivirtojen kehittämisellä on vaikutusta. Kohdeyritykseen kehitettyä digitaalista kaksosta ja sen tuottamaa dataa ei pystytä suoraan hyödyntämään kohdeyrityksen ulkopuolella.

Asiasanat: tuotannon layout, digitaalinen kaksonen, materiaalivirta

FOREWORD

This study is the last part of my Industrial Engineering and Management studies before graduating. The study has made me learn a lot of new things as well as deepen my understanding about many of the theories I have learned earlier during my studies. I worked with the research project at ABB Wiring Accessories in Porvoo for four months during summer 2021 and came back to Oulu to do the rest of the reporting process of the study.

I would like to thank the people of ABB Wiring Accessories for welcoming me to do my study in your factory and giving me the warmest support while I was there with you. Big thank you also for Jetecon Oy for the collaboration during the digital twin project. The special mention and thank you goes for Ilpo Tanskanen from ABB and Jukka Majava from University of Oulu who were my supervisors and mentors during the study.

Oulu, 07.12.2021

Jaakko Ruth
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ABBREVIATIONS

BOM	Bill of materials
DTS	Digital twin shop floor
JIT	Just-In-Time
NNVA	Necessary non-value adding activity
NVA	Non-value adding activity
PS	Physical shop floor
SDTD	Shop floor digital twin data
SSS	Shop floor service system
TOC	Theory of Constraints
TPS	Toyota Production System
TQM	Total Quality Management
VA	Value adding activity
VS	Virtual shop floor
WIP	Work in progress

1 INTRODUCTION

1.1 Background

The layout of a manufacturing facility means the arrangement of workstations, machines, pathways, storages and other required elements to perform the manufacturing processes (Heizer & Render 2014). The layout affects to the amount of tied-up capital, work, and time to the production system and therefore the decisions related to it are relevant when improving the efficiency of operations. Key characteristics of a good layout are for example safety for people, effective space usage, support for good production quality, and effective material flow. (Heizer & Render 2014; Stevenson 1999) This study combines the problem of finding a good layout configuration from material flow point of view to the simulation tools to solve the problem. Material flows can be very complex but still there are usually unambiguous data available to analyze those. Simulation in turn requires good data in order to produce meaningful results (Jahangirian et al. 2010). Simulation is also a match for making layout decisions since changes in layout are usually difficult to execute and being able to test different configurations without having to make the changes in real life becomes beneficial (Stevenson 1999; Jahangirian et al. 2010)

The case company of this study is a manufacturing company which produces millions of products every year. The company has both fabrication and assembly processes located in the same factory which set challenges but also opens opportunities when developing production processes. Currently the company utilizes product focus strategy in its fabrication processes and repetitive focus strategy in its assembly processes. Also, references of different layout types are present in the facility. The company has increased the automation level of production significantly during past years and that progress will continue in the future. When the processes get continuously more efficient, and huge amount of capital is invested in automating the facility, also the methodologies used for operational development need to be developed. Currently there is not a clear methodology for using data in layout decision making in the company.

1.2 Objectives and research questions

Objective of this study is to create a methodology for utilizing data for decision support in layout design decisions. The following research questions are set in order to fulfil this objective:

RQ1: How does the layout affect value creation in manufacturing?

RQ2: What are the key factors of process simulation for layout decisions?

RQ3: How can the effectiveness of layout designs be measured in the case company?

Research questions one and two will be covered in the literature review and research question three in the empirical part of this study. The literature review will provide understanding about different types of layout configurations used in manufacturing. Value creation and waste are covered in the literature review in order to find the most important objectives when comparing different layout configurations with each other. The answer for research question three has two components: method and performance measures. Answer for the first part was given in quite early phase of the study since there was an interest for a digital twin in the case organization. This study therefore concentrates on finding the right performance measures metered in the digital twin and giving a proposition of how to use them in practice.

This study concentrates fully on evaluating material flows in the manufacturing and ignores the space requirement component of layout design. Therefore, a natural continuation from this study would be combining these the components of layout design together. As mentioned, the case company has both fabrication and assembly processes in the same facility. This study concentrates on simulating the material flows in the assembly operations of the facility because the material flow from and to assembly work centers are more complicated than in the fabrication work centers. Assembly department also connects flows from fabrication work centers and component warehouse so designing the assembly layout first has an impact to the optimal fabrication layout too.

1.3 Research process and thesis structure

The research is based on the case study method and includes collecting different types of data. Semi-structured interviews were conducted in order to understand the operations of the factory. Those operations were then communicated for the software developers along with the required data and requirements in order to come up with a digital twin of the assembly department of the factory. The data were gathered from the information systems of the company and part of that had to be transformed into a more convenient format of combined with data form a different source.

The thesis includes theoretical and empirical parts. The theoretical part of the study is the literature review, and it provides a foundation for managing to develop a digital twin for layout evaluation purposes and furthermore tools for developing material flows. Empirical part of the thesis includes documenting the process of creating the digital twin and also recommendations for using it in the future. Figure 1 illustrates the structure of the study and in which section each research question is answered.

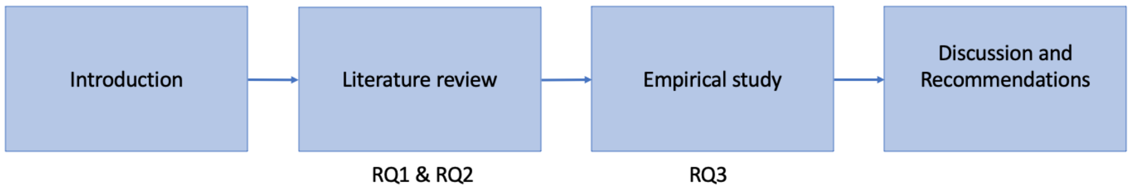

Figure 1. Structure of the study

2 LITERATURE REVIEW

2.1 Lean manufacturing

Lean is a management philosophy which key objective is to maximize the value creation for the customer while minimizing the resource usage. As a term lean production was introduced in 1991 in the book "The Machine That Changed the World" describing MIT study of the global automotive industry (Liker 2020). Foundation for Lean comes from the Toyota Production System (TPS) which is the internal production philosophy of Toyota Motor Company evolved during the history of the company. Especially Sakichi and Kiichiro Toyoda had huge impact in building the base principles of TPS. The main principles of TPS are focusing on the customer, continuous improvement, waste reduction and integration of processes (Majava & Ojanperä 2017). TPS received its name after Toyota had begun outperforming other car manufacturers in terms of productivity and quality in the 1970's with the lead of Taiichi Ohno's work with the production system. (Womack et al. 1991; Liker 2020) Lean has spread from production to other business functions like product development, supply chain management, finance, and marketing. In addition, many variations of the philosophy have been developed: Lean Six Sigma, Lean Startup, and agile development to mention a few. (Liker 2020) In this study lean means specifically lean production.

Womack et al. (1991) describe lean production as a combination of the advantages of mass and craft production. In practice this means that lean manufacturers are able to produce flexibly high variety of products in high quantities by making small batches without sacrificing productivity. Many tools to achieve that are associated to lean such as *value stream mapping, 5S, and Kanban*. However, just implementing the usage of tools and methods is not the goal or meaning of lean. (Womack et al. 1991) The main objectives of lean are achieving operational stability, creating *Just-In-Time* (JIT) system, having *In-Station-Quality*, and creating *culture* that supports the members of the organization to be flexible and capable. (Liker 2020) Figure 2 shows that the origin of the objectives in lean are in TPS. Operational stability means having standardized work in workstations and levelled workload between those stations. These principles extend to equipment and suppliers also. When the production system utilizes JIT, the right items in a right amount are in the right place at the right time. In-Station-Quality is a practice where defects are not passed forward from the place they have noticed. Rather than ignoring those the workers do not pass products with defects forward but track the root cause of the defect and eventually remove it so that same defect will not appear again. (Liker 2020; Shah & Ward 2007; Hines et al. 2004)

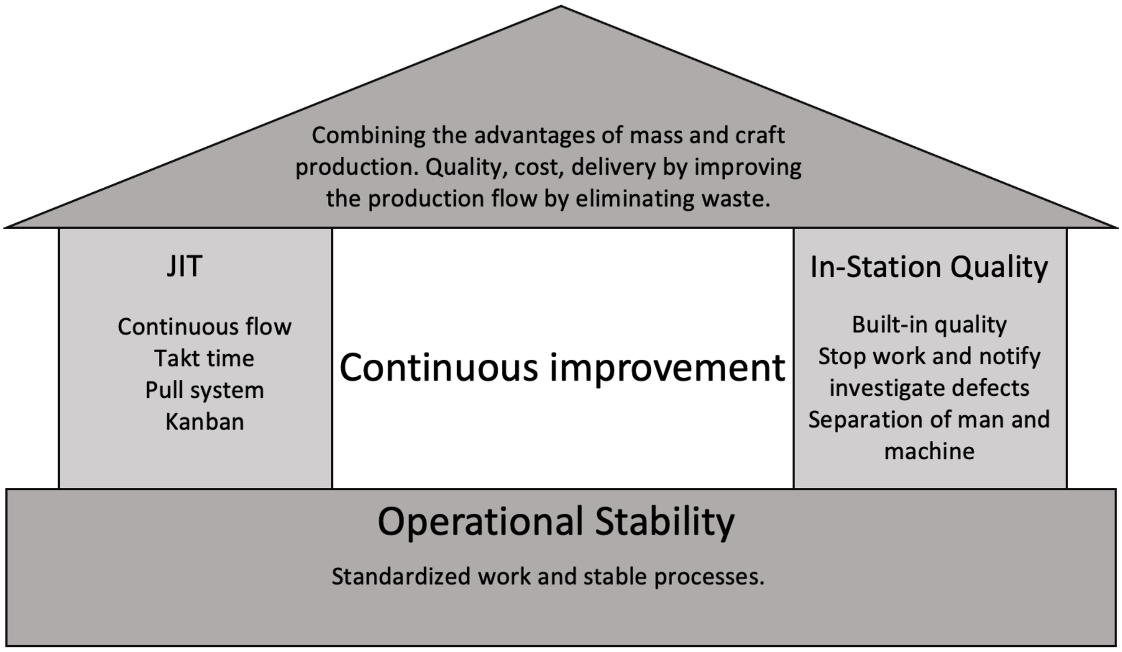

Figure 2. Toyota Production System (adapted from Liker 2020)

2.1.1 Value stream mapping and waste

Since the key objective of lean is to maximize the value, the processes have to be tracked in order to find out if the add value for the customer or not. Value stream mapping is one of the tools used in lean in order to recognize the value creation of activities. Value stream differs from value or supply chain as for the level of detail. Value chain covers the entirety of the activities from every company involved in the value creation. Value stream in turn is limited to the specific parts or operations of the companies that add value to the specific product or service considered. Therefore, the value stream is more detailed view to the value-adding process than the value chain. (Hines, Rich 1997)

There are seven categories of waste recognized in the Toyota production system (TPS) (Ohno 1988):

1. overproduction
2. waiting

3. transportation
4. unnecessary inventory
5. inappropriate processing
6. defects
7. unnecessary motion

Hines and Rich (1997) state that *overproduction* is regarded as the most serious waste because it is likely to affect the forming of other types of wastes. Overproduction easily causes lead and storage times to increase, and defects can be left undetected more probably when the overproduction happens. In TPS overproduction is reduced by using pull or *kanban* system. Waste of *waiting* means that time resource is not fully utilized. Waiting is present when the product is not being worked on, but also in the situations when worker is not doing activities to increase the value of a product. If the waiting cannot be totally eliminated for workers, it can be used for example for training or maintenance. *Transportation* means moving the products around. Taken fundamentally, any movement in the production facility can be understood as a waste, so the goal is usually to reduce transportation instead of totally removing it. The other incentive for reducing transportation is that excessive moving increases the risk of the goods to get damaged. *Unnecessary inventory* increases storage costs and this way lower the competitiveness of a value stream they exist in. They also can increase lead time and hide problems in the products and also in processes. *Inappropriate processing* means applying overly complex solution to simple procedures. Complex solutions can also lead to a bad layout which will then cause extra transportation. *Defects* are direct costs. Those cause also waste when they are corrected, and this can be even repetitive action in the worst case. TPS sees defects as opportunities to improve and continuous improvement can be sustained by actioning against encountered defects with kaizen activities. *Unnecessary motion* is related to the movements made by individual worker or machine while making the product. The ergonomics of the workstation should be corrected so that worker does not have to for example stretch for getting the component or tools for assembly. (Ohno 1988; Hines & Rich 1997; Liker 2020)

Removing or at least reducing the amount of waste in value stream is a way of improving productivity but not necessarily the quality. However, when improving the productivity by making the operations in the value stream leaner, identifying further waste and quality problems in the system becomes easier. Therefore, the systematic approach for reducing the waste is also a systematic approach for improving the quality in addition to productivity. It is also suggested that when making improvements in value chain, at least some understanding about what wastes is wanted to be reduced before making any value stream mapping activities. (Monden 1994; Hines & Rich 1997)

There are three types of operations in the internal manufacturing context which can be categorized in the following way (Hines & Rich 1997):

1. non-value adding (NVA)
2. necessary but non-value adding (NNVA)
3. value-adding (VA)

Actions that belong to NVA category are pure waste and they should be eliminated entirely. (Hines & Rich 1997) These can be for example moving materials from work center to another to for packaging it or inspecting a component before assembly.

NNVA operations include waste but are necessary due to the current operating procedures. NNVA activities are therefore needed for making the product or service but those do not as such add the value of the product or service. (Monden 1994; Hines & Rich 1997) For example, the worker may need to walk long distance to get parts needed in their work or they have to change the orientation of the product to be able to perform some assembly work. In these situations, the walking and changing the orientation are NNVA activities. For eliminating waste from NNVA activities there is typically required to make major changes to the operating system (Hines & Rich 1997). In previously mentioned cases the changes could be for example creating a new layout or changing the structure of a product.

Value-adding (VA) processes transform the final product or service in a way it becomes more valuable for the consumer than it would have been without the transformation. Examples of VA activities could be for example attaching components to form the final assembly or painting the product. (Hines & Rich 1997; Liker 2020)

2.1.2 Continuous improvement

Continuous improvement is one of the main principles in lean manufacturing. In quality management like total quality management (TQM) continuous improvement is understood via tools like process mapping, root cause analysis and PDCA cycle. (Samson & Terziovski 1999) There are many similarities between those and continuous improvement in lean, but this study concentrates on the lean perspective and high-level idea behind it.

In TPS continuous improvement is described by the Japanese word *kaizen* which means "improvement". When using kaizen as the lean suggests the organization makes little improvements which have a long-term effect to its processes whenever a possibility for those emerges. (Womack et al. 2007) This requires high level of participation in the organization since everyone is assumed to participate in improving the operations which they face in their everyday work. In order to have a long-term effect the improvements have to be targeted to the root cause of the problem. Lean offers for example *five whys* tool for finding the root cause of the problem. Idea behind five whys is that when facing a problem, the root cause can be found by asking "why" as many times as required to solve what is causing the problem. (Liker 2020) One example of the continuous improvement at Toyota is the possibility for every worker to stop the production line whenever they face a problem they cannot solve while the line is moving. At first this will cause the new production line to stop frequently compared to traditional mass production line. However, since every problem emerged on the line is tracked and their root cause is solved same problems will not repeat. In the long run this will make the production line with lean continuous improvement outperform the mass production line both in the productivity and quality. (Garvin 1993; Hirano et al. 2006)

2.2 Theory of constraints

Theory of constraints (TOC) is a management approach which suggests that performance of the system can be improved by concentrating on solving problems with a very limited number of constraints. (Ricketts 2020; Goldratt & Cox 2012; Lolla 2013) TOC was named by Eli Goldratt and it is also called as Constraint Management in some situations. The goal of this approach is to find the constraining element of a system and then design the system so that the constraining element is always used at its full potential (Ricketts 2020). TOC suggests that every system has a constraint which can also be called as the weakest link in the chain. This weakest link sets the capacity of the whole system. Constraints were not invented by manufacturing, but the idea originated from agriculture and the Liebig's Law of the Minimum. That suggests that the crop growth is controlled by the availability of the scarcest resource, not the total amount of resources. (Ricketts 2020; Pound et al. 2014).

Constraints can be categorized as internal and external constraints. Internal constraint limits the output that system can produce, and external constraint causes the market not to buy everything the system is able to produce. However, if the process associated with the system causes customers not to buy the products produced by the system, the constraint is internal. (Goldratt & Cox 2012) TOC states that there is only one constraint in the system at a time. This constraint can however change over time depending for example on the market demand for the product the system produces. If the constraint of the system is internal during the high demand it can change to an external one when the demand decreases. (Ricketts 2020)

When searching for the constraint it is often worth it to investigate convergence and integration points. For example, final assembly is an integration point because components from multiple sources come together there. There are many similarities with TOC and lean. Benefits of TOC are best achieved by combining with JIT. Where TOC strives to utilize the constraining element of the system on its full potential JIT suggests ensuring smooth flow of the production avoiding any unnecessary inventory to pile up. (Pound et al. 2014) It is often beneficial to position the constraint to support the strategy because a strategic constraint leads to achieving goals better than an arbitrary one. Positioning can be done for example by obtaining more capacity to the current constraint and therefore moving the constraint elsewhere. With positioning, the constraint can be moved to a place where its impact can be managed more easily. (Ricketts 2020)

Buffers are often used when managing constraints. Those disconnect elements of a system from each other so that distraction in one element does not inevitably affect another. (Lolla 2013) In the context of this study buffers are mainly *stock buffers* or *space buffers*. Stock buffer contains inventory material of certain kind and therefore disconnects warehousing from manufacturing or manufacturing from the market. The purpose of a stock buffer is to keep the required materials always available for the constraint to consume. Space buffer serves the constraint by offering room for the finished materials to locate after the constraint. This gives the opportunity that the constraint does not have to stop producing even if the consumption after the constraint is reduced. (Ricketts 2020; Lolla 2013) Work in progress buffers disconnect subsequent work centers from each other and finished goods inventory is the buffer between manufacturing and market for the products. Other types of buffers include for example time, cash, skill, and capacity buffers. (Ricketts 2020)

According to Ricketts (2020) up to 70% of manufacturers do not have an internal constraint. However, constraint management can improve the efficiency of the production also in these situations. Situation where no constraint management is applied in the production work is pushed through the factory. Work center utilization is high everywhere but work in progress piles up since the internal constraint cannot handle the push of other work centers. This leads to a situation where orders can be filled late because the internal constraint is busy on emptying pushed work in progress. Constraint management takes control of the stock buffer upstream from the internal constraint and chokes the push of work in progress into it. This leads to better productivity in terms of orders filled on time because demand now pulls the production and correct orders can be prioritized in the production. (Ricketts 2020; Lolla 2013)

2.3 Production flow

Flow is how the work progresses through the system. A good flow means that the work progresses in a steady and predictable way. (Kimura & Terada 1981) In this chapter the flow is explained from a lean point-of-view by introducing pull system and just-in-time (JIT) concept.

2.3.1 Pull system

Instead of "pushing" work for teams to perform, lean suggest establishing a *pull system*. In a pull system work is only performed when there is a demand for it coming from a customer or the later stages of a production process. Establishing pull to the production system can help increasing throughput and reduce cycle times by eliminating the multitasking of the teams. When teams are concentrating always on the task that has the highest priority also the capability for on time deliveries increase. Pull system is also a key for reducing work in progress and inventory between process steps. When work in progress is reduced also the possible defects are noticed earlier which reduces scrap and rework. (Kimura & Terada 1981; Hirano et al. 2006; Womack et al. 2007; Liker 2020)

Lean uses *kanban*, which is Japanese and means "sign", to control the flow in a pull system. It is a system for visually signalling teams when to start producing which item and when they cannot produce. (Kimura & Terada 1981) There are multiple possible types of kanban. Card kanban, container or bin kanban, and electronic kanban are examples of different kanban types. Each of them communicates workers which item to produce and in which quantity. Container kanban signals the demand by missing or empty containers and then worker performs the production and fills or replaces the required containers with full ones. Kanban also makes it possible to establish pull not only in the factory but in the whole supply chain by providing visibility for suppliers. Electronic kanban enables real-time signalling through the supply chain with linkages to the enterprise resource planning (ERP) systems. Electronic kanban also enables automating production and procurement processes. (Womack 2007; Liker 2020)

2.3.2 Just-in-time

Just-in-time (JIT) is an inventory system originating from TPS. JIT minimizes inventory and increases efficiency by establishing a supply chain which delivers the needed materials in the right quantity at the right time reliably. In other words, material deliveries are expected to arrive when those are needed in the production. (Ohno 1988; Hirano et al. 2006) For example, a car manufacturer utilizing JIT system can have even hourly deliveries from their suppliers and have effectively no inventory themselves. At the same time traditional mass producer can have inventories for weeks or even months of demand. Successfully utilizing JIT requires predictable production and reliable suppliers. Therefore, JIT is usually tightly connected with other lean principles like pull production and kanban. JIT manufacturers tend to have a close relationship with their suppliers and strive to improve their processes too. However, for the risk management purposes multisourcing is common for being able to respond in the situations where one supplier faces issues with deliveries. (Womack & Jones 1994; Hirano et al. 2006)

2.4 Layout in manufacturing

Layout decisions are one of the key elements determining the long-run efficiency of operations. Those are strategically important decisions since the layout determines which competitive priorities the company wants to emphasize: capacity, processes, flexibility or cost. In addition, the layout can have a significant impact on work life quality, customer contact and the image of the company. Taking these factors into account, the layout can be designed to support achieving the strategic goals and the desired competitive advantages: low cost, differentiation or response. (Heizer & Render 2014; Stevenson 1999)

The following factors should be considered when designing a layout (Heizer & Render 2014):

- utilization of space, equipment, and people
- flow of information, materials, and people
- employee morale and safe working conditions
- flexibility of the layout
- customer interaction

Heizer and Render (2014) emphasize the flexibility of the layout in the current world where life cycles of products and services are short, and the customer needs are changing rapidly. This is true in many places but as Stevenson (1999) states, there is also industries where physically large equipment yields the best productivity and the layout cannot be seen as a dynamic element. In the context of our case company the current equipment does not strictly limit flexibility of the layout.

Heizer and Render (2014) have recognized seven main types of layouts depending on the use context of it: office, retail, warehouse, fixed-position, process-oriented, work-cell, and product oriented. In this study we concentrate on the layout types that are relevant for optimizing the manufacturing processes inside a production plant. Those are *process oriented layout, product-oriented layout, work-cell layout* and in addition the combination of these layouts.

2.4.1 Product layout

Product-oriented layout strives to utilize personnel and equipment in the best way possible doing repetitive or continuous production of high-volume and low-variety products (Stevenson 1999; Heizer & Render 2014). Usually, the activities are placed in a form of a production line one after another in the sequence the product flows through them (Figure 3) The volume of the production has to be high enough for high equipment utilization and the demand stable enough for justifying the big investment in specialized equipment. The maturity of the product also has to be in a phase that allows making the investment decision in the equipment. Raw materials and components have to be applicable for the specialized equipment and high production volumes. This means in practice that the quality of and supply of those has to uniform. (Heizer & Render 2014)

Product-oriented layout lines can be divided into fabrication and assembly lines. Fabrication lines make components on a series of machines and assembly line combines the fabricated components together at a series of workstations. (Cooke 2012) The main objective in product-oriented layout is to balance the production line: in repetitive processes the time spent to perform work on a machine should be equal the time spent to perform work on the next machine. (Heizer & Render 2014) Required high volumes create both advantages and disadvantages of product-oriented layout. The volume lowers variable cost per unit, but it also requires large investment to establish the process. Advantages of product-oriented layout include also low material handling costs, reduced WIP inventories, easier training and supervision, and quick throughput. Other disadvantages are the interruption of whole process when failure emerges at any point of it and the challenge of flexibly transform the process for variety of products. (Stevenson 1999; Cooke 2012)

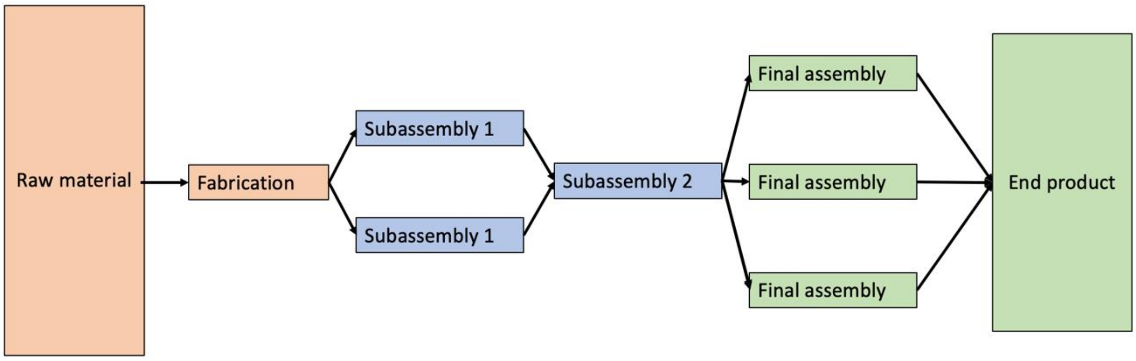

Figure 3. Example of a product-oriented layout (adapted form Heizer & render 2014)

2.4.2 Process layout

Process-oriented layout (Figure 4) is the choice for low-volume and high variety production where similar kinds of machines and equipment are located nearby each other (Stevenson 1999). Therefore, it is a traditional way to support a product differentiation strategy. In this layout each product or small group of products take a different route through the processes. The production is executed by moving the product through the processes in a required sequence for that particular product. The idea behind organizing the processes this way is to allow operations to be flexible in terms of equipment usage and changes in products and processes produced. (Heizer & Render 2014)

The advantage of process-oriented layout is mainly the flexibility. However, it can appear in many ways. For example, the ability to transfer jobs between machines or work center is an advantage if failures appear in some machine. Another way of practical advantage of flexibility is the ability of dealing effectively with small production batches and with wide variety of parts (Cooke 2012). Disadvantages of this layout type originate from the general-purpose use of the equipment. Since the process is not fixed, unique material handling and operations take place in addition to difficult scheduling and so orders take longer time to move through the system. The equipment also require highly skilled workforce and work-in-progress inventories are higher because the layout causes imbalances to the production process. (Heizer & Render 2014) The most common approach for designing a process-oriented layout is to minimize the costs of material handling. This can be achieved for example by arranging those work centers close to each other which have biggest flows of material or people between them. (Stevenson 1999)

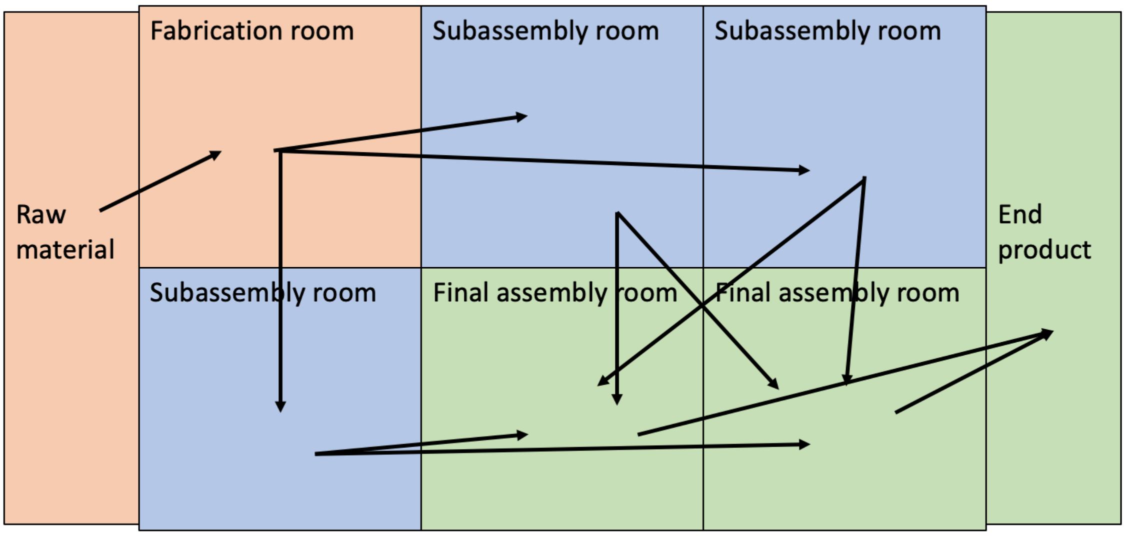

Figure 4. Example of a process-oriented layout (adapted from Heizer & Render 2014)

2.4.3 Cell layout

Cell layout (Figure 5) brings equipment, that ordinarily have been dispersed between different departments, into a group to produce single product or product group that are produced similarly enough compared to each other (Heizer & Render 2014). Cellular work can be utilized when the volume of a product is high enough for the special arrangement of equipment. (Stevenson 1999)

The first thing for establishing cellular production is to identify the groups of products that share similarities what comes to production. Cell production requires also well-trained employees that have flexibility in their skill set. Because the work cell groups together different tasks of the production process it requires fewer employees compared to assembly lines. Work cell also provides one-piece flow from machine to machine, which reduces the work-in-process (WIP) inventory. Reduced WIP inventory reduces the need for floor space between machines and raw material and finished goods inventories. Cell layout also allows improved communication between employees and improves scheduling effectiveness and material flow (Cooke 2012). All of these, help reducing direct labour cost. Improved scheduling and better material flow also increase the equipment utilization, and this can help reduce the investments in equipment. In addition, employees feel and accept more responsibility of the product quality since the product is more closely associated to them directly. The more versatile work can also boost employee morale compared to performing a single task over and over. This can lead to better productivity in addition to increased wellbeing of employees. (Stevenson 1999; Heizer & Render 2014)

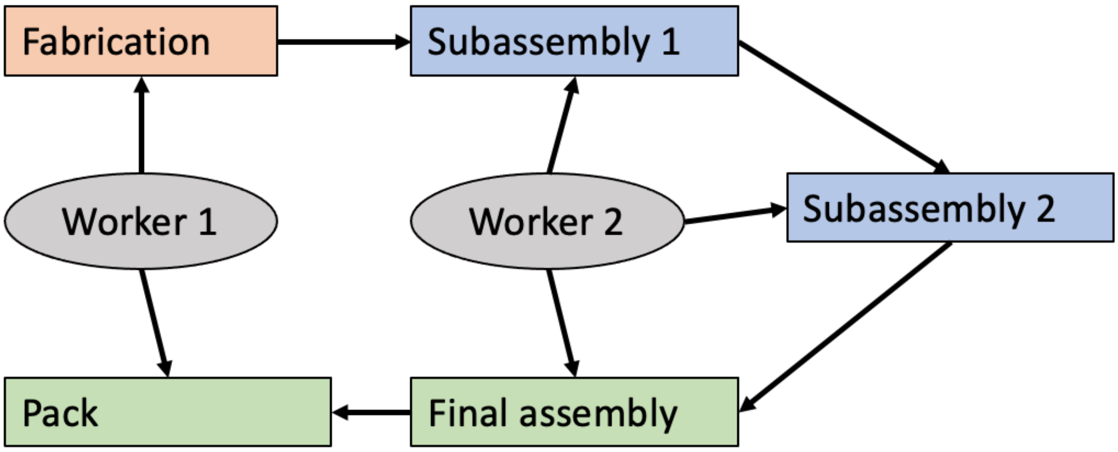

Figure 5. Example of a cell layout (adapted from Heizer & Render 2014)

2.5 Process management

Process management activities strive to align the processes of and organization with its strategic goals. It includes methods and tools for analyzing, defining, optimizing, monitoring and controlling processes. (Harmon 2014) In this chapter the relevant methods of process management for this study are covered.

2.5.1 Process design

Desired process design depends on what competitive advantage a company wants to utilize with it: *low cost, differentiation or response*. (Heizer & Render 2014) Harmon (2014) have recognized the same possibilities and refers to them as strategies for competing. *Low cost* as a competitive advantage or *cost leadership* as a strategy for competing means that the company can offer the product at the cheapest price. Usually this is achieved by utilizing the economies of scale which allows better control to suppliers and channels, and also resources to make own operations more efficient. *Differentiation* is an alternative for cost leadership. There company offers higher quality or otherwise more desirable products than the competition so that customers are willing to pay more from those than the lower cost alternatives. This can be achieved for example by using more expensive materials or creating a distinct design. (Harmon 2014; Heizer & Render 2014) Harmon (2014) uses term *niche specialization* having the same content than the *response* with Heizer and Render (2014). Response or niche specialization is an ability to focus on specific customer groups or market segments needs by usually offering just a subset of the offering typically sold in the industry. This requires the production to be able to adapt according to the needs of the target market (Harmon 2014; Heizer & Render 2014) When the desired competitive advantage to utilize with the process design is known the next step is to evaluate how the process adds value and does it eliminate the steps that do not do that. (Heizer & Render 2014)

Heizer & Render (2014) categorize process strategies in four different groups: process focus, product focus, repetitive focus and mass customization focus. Process focused strategies are used in production situations where high degree of flexibility is needed. Product focused processes are high-volume and low-variety processes which are utilized in producing products with low quantity of inputs. Repetitive focused processes are usually assembly lines which use *modules*. Modules are components for the final assembly and those are connected in a repetitive process. Repetitive focused processes offer less flexibility than process focused since the structure of the process is designed to be more fixed. However, the possibility to choose which components to put together combines to some extent the economic advantages of product focused strategy and the flexibility of process focused strategy. Mass customization focus is the most difficult of these strategies to utilize. This kind of process produces goods and services for vast variety of customer demands, quickly and with low cost. This strategy therefore strives to make "precisely *what* the customer wants *when* the customer wants it economically." (Heizer & Render 2014)

The type of the production line has an effect on the process design. There are three different types of common production lines: single model line, batch model line and mixed model line. Each machine or team in the production line operates at a certain cycle time, which is the time required to perform one entire task the machine is supposed to do. This includes both the active time spent with processing and the passive time the item is waiting during the process. One way of evaluating the efficiency of the production line is measuring utilization of production resources in a particular cycle time. (Marsudi & Shafeek 2013) Productivity is a measure for the efficiency of this process of change. It indicates the ratio of goods or services created to the resources used. In general level the goods and services are referred as outputs, and resources, which can be for example labour or material, as inputs of the production process. (Heizer & Render 2014)

Heizer and Render (2014) suggest that tools for analyzing the process design and detecting waste can be categorized in five groups: flowcharts, process mapping, value-stream mapping, process charts, and service blueprints. Hines and Rich (1997) have recognized seven value stream mapping tools for reducing the seven wastes: process activity mapping, supply chain response matrix, production variety funnel, quality filter mapping, demand amplification mapping, decision point analysis, and physical structure mapping. This study concentrates on process activity mapping because it is best for recognizing the wastes that are most relevant in the layout point-of-view.

Process activity mapping

Process activity mapping or process analysis is used mainly to reduce waiting, transportation, inappropriate processing, and unnecessary movement. I can be helpful for also reducing unnecessary inventory, but it has low correlation with reducing defects and overproduction. The general approach of this tool is constructed from the five following stages (Hines, Rich 1997):

1. the investigation of the flow of processes
2. the identification of waste

3. a consideration of whether the process can be rearranged in a more efficient sequence
4. a consideration of a better flow pattern involving different flow layout or transport routing
5. a consideration of whether everything that is being done at each stage is really necessary and what would happen if excessive tasks were removed

The end product of process activity mapping can be for example a table where process is described in the relevant point of view. Forming the table and more importantly the understanding of the process, preliminary analysis of the process is required. This is then followed by detailed recording of all the items required in the process. After the items are known, more information from the process can be listed (Figure 6). These can be for example the activity type, machine or area of the activity taking place, distance moved, time taken, and number of people involved. The table can be used for analyzing the process further and recognizing the room for improvement. It can for example help eliminating unnecessary or NVA activities and simplify those that are unnecessarily complicated or NNVA. After the improvements are planned the table can also be a basic tool for comparing the alternatives for the process. (Hines, Rich 1997)

#	Step	Flow	Machine	Dist (m)	Time (min)	People	OPERATION	TRANSPORT	INSPECT	STORE	DELAY	Comments
1	Components	S	Warehouse				O	T	I	S	D	
2	Delivering to intermediate landing in production	T		70	4	1	O	T	I	S	D	
3	Waiting for the production batch to begin	D	Assembly cell		5		O	T	I	S	D	
4	Feeding the components to assembly machine	O	Assembly cell	10	2	1	O	T	I	S	D	
5	Connecting the components	O	Assembly machine		2		O	T	I	S	D	
6	Putting the finished products to a box	T	Assembly cell	1	0,5		O	T	I	S	D	
7	Waiting the box to fill up	D	Assembly cell		5		O	T	I	S	D	
8	Delivering the box of products to quality inspection	T		20	2	1	O	T	I	S	D	
9	Inspecting the quality	I	Inspection cell		0,5	1	O	T	I	S	D	
10	Delivering the box to packaging	T		10	1	1	O	T	I	S	D	
11	Packaging the products	O	Packaging machine		2	2	O	T	I	S	D	
12	Delivering the package to loading dock	T		25	2	1	O	T	I	S	D	
13	Waiting for the shipment	D	Loading dock		25		O	T	I	S	D	
	TOTAL		13 Steps	136	51	8						
	OPERATORS				6	3						
	%-Value adding				12 %	38 %						

Figure 6. Process activity mapping table (adapted from Hines and Rich 1997)

2.5.2 Simulation

In the context of process management and manufacturing, simulation means using software to make models of manufacturing systems. Benedettini and Tjahjono (2009) argue that computer-based simulation is one of the most valuable tools for designing manufacturing systems. However, usage of simulation remains limited since manufacturing systems tend to be very complex. This sets challenge for simulation models to correspond to the complexity of the system to be simulated and at the same time remain user-friendly enough to be helpful for system designing purposes. (Benedettini & Tjahjono 2009) According to Jahangirian et al. (2010) the three most studied applications for simulation are scheduling, process engineering in manufacturing, and supply chain management. Process engineering in manufacturing consists for example process design and improvement, design of new facility and performance measurement. (Jahangirian et al. 2010)

2.5.3 Digital twin

Glaessegen and Stargel (2012) defined digital twin as an integrated multi-physics, multi scale probabilistic simulation of a complex product. According to this definition the parts of a digital twin are the physical product, virtual product, and connected data which ties the physical and virtual products together. This enables directly comparing and analyzing the theoretical values of big data and the real values of the product lifecycle activities (Tao et al. 2018). Therefore, the product lifecycle can be simulated, monitored, optimized and verified with digital twin. This yields an opportunity to iteratively optimize various activities by verifying the changes with digital twin. (Tao et al. 2018)

Tao et al. (2018) summarizes the three main characteristics of digital twin:

1. Real-time reflection
2. Interaction and convergence
3. Self-evolution

Real-time reflection means that the virtual space of a digital twin can keep synchronization and fidelity with the physical space. Interaction and convergence characteristics require the data generated in various places in the physical and virtual space can connect with each other. In addition, there has to be interaction and convergence between historical and real-time data. Digital twin cannot either rely only on expert knowledge, but it has to collect real-time data from all the deployed systems. Self-evolution characteristic is enabled by updating the data in real time and continuously improving the digital twin by comparing the virtual space and physical space in parallel. (Tao et al. 2018)

Digital twin in product manufacturing

When referring to the product manufacturing as a process of transforming the raw material inputs to the finished product outputs, three main aspects should be included in the digital twin: resource management, production plan, and process control. (Uhlemann et al. 2017) Resources for the digital twin mean for example materials, operators, machines etc. required to manufacture the selected products in the simulation. Resource management include also allocating the resources for the processes. Then the production plan should be introduced in order to define the operations needed for manufacturing such as molding, assembling, logistics etc. The process control includes data about production schedule, material storage, and material quality etc. (Tao et al. 2018; Uhlemann et al. 2017)

Digital twin shop floor (DTS) is a new paradigm for developing product manufacturing. It consists physical shop floor (PS), virtual shop floor (VS), shop floor service system (SSS), and shop floor digital twin data (SDTD). PS is the real manufacturing plant which receives production tasks and executes orders strictly to output final products. VS is an ultra-high fidelity and full digitalized mapping of PS. It can simulate and forecast production plans and processes and even give optimization strategies for SSS. SSS is a set of service systems supporting the manufacturing operations. SDTD refers to all of the data in PS, VS, and SSS and drives the DTS. (Tao et al. 2018)

2.6 Synthesis of the literature review

The goal of the literature review is to answer the research questions one and two.

RQ1: *How does facility layout affect value creation in manufacturing?*

Literature review defines the value creation from the lean manufacturing point of view. The key takeaway from this is to divide operations to separate activities and categorize the activities into VA, NNVA or NVA by determining if the activity adds value for the customer. The value creation of the manufacturing can be examined by for example using value stream mapping. Process activity mapping is a value stream mapping tool introduced in the literature review since it is the most relevant tool for finding the wastes relevant for layout design purposes. After defining the value creation and tools for examining it, the literature review introduces the main categories of layout types and process designs. Correct facility layout type seems to be a significant factor for the value generation and waste reduction of the production. Volume and variety of the production are the main variables determining the right layout type for the production processes. By choosing the wrong layout type for the production a lot of waste can be generated because of the unnecessary or inconvenient activities occurred due to the layout decision.

RQ2: *What are the key factors of process simulation for layout decisions?*

The key factors for the process simulation are the outputs and inputs of the simulation. The output of the simulation should help making decisions about which type of layout suits best for the company. This can be done by comparing the waste generation of different layout configurations. The most significant waste to which can be affected by the layout design is transportation, so simulation should produce outputs that represent the amount of that type of waste. In order to create this kind of simulation required resource management, production plan, and process control activities should be as inputs for the simulation.

In addition, literature review introduces paradigms used in process development such as TOC and JIT. Those are in an important role when pre-evaluating layout designs for comparison in the simulation. Definition, requirements and possibilities of digital twins are introduced since it was chosen as a simulation method for the production processes.

3 EMPIRICAL STUDY

The case company of this study is a manufacturing company that produces accessories for electric installations. Some of the products are fabricated by injection molding and some of the products require assembling fabricated parts together with the electric components. The structure of the products is relatively simple but numerous variants and thousands of components make the manufacturing as a whole very complex. The company is a market leader in the Nordic markets and millions of end products are finished in the factory annually.

The empirical of this thesis can be divided into three stages:

- Setting up the data and tools
- Analyzing the material flows
- Assessment of the results

Setting up the data and tools include semi-structured interviews, and data gathering from the systems of the case company. In addition to that a simulation is created as a tool for mapping and later analyzing the material flows in the case company's facility. Analyzing the material flows of the factory includes utilizing two different methods. The first method is to visualize material flows by connecting the gathered data in Microsoft Power BI software and then visualizing the flow with suitable visualizations. The second method is to use a digital twin of the factory to compare current facility layout with a different configuration. Creating the digital twin with Visual Components software has been closely related to this study. Therefore, the software requirements specification has set to serve the layout optimization purposes. Also, data gathering for this study and creating the digital twin has been parallel. Assessment of the results contains analyzing the results got from applying research methods, and also the recommendations based to the analyzed results.

3.1 Setting up the data and tools

3.1.1 Collecting data and knowledge

Firstly, the processes to be simulated were limited to ones which happen inside the factory. To understand the production processes and material flow in the factory, several semi-structured interviews were organized. All of the interviewed persons were part of the organization of the factory. Their main responsibilities were engineering specialist, production line manager, production team leader, procurement specialist, and manufacturing technical manager. The goal of the interviews was to understand the overall operations of the factory to be able to narrow down the scope of the study. After this the interviews concentrated on building an understanding of the selected operations of the factory and being able to find the relevant data from the systems. Interviews regarding the practical manufacturing operations were held in the factory at the departments where the operations took place. This way the operations were observed at the same time and clarifications were easier to illustrate. Interviews regarding management systems and processes were held face to face or via video conferencing tools. The information gathered from interviews were recorded to notes. The interviews were analyzed by deciding which kind of data would be needed in order to create a representative simulation from the operations.

The factory can be divided into two different departments in terms of the production operations. These are injection molding department and assembly department. These departments are organized as entities but of course the synergies are tried to be utilized. Injection molding department fabricates plastic components which are later used in the assembly in order to produce the end products. Injection molding department contains several machines which are used to fabricate large number of different components. The department is run in three shifts for five days a week, but not all the machines are run simultaneously. In the early phase of the study and the interviews a decision was made to concentrate only to the assembly department of the factory. Main reason for this was upcoming development projects in the department which would benefit from a systematical methodology to evaluate layout configurations. In addition, incoming material flows are more complicated in the assembly department which will give better and more varying situations to analyze.

The assembly department is divided into four teams: electrical products, power sockets, switches, and packaging. These are furthermore supported by inner logistics team. This study concentrates on the material flows on the work centers producing power sockets and switches since those produce the products with the highest demand, and therefore material flow is the most intensive there.

Work centers

Work centers in the assembly plant can be categorized into three different types: assembly machines, hand assembly and combination of machine and hand assembly. Assembly machines operate independently. Human workforce is needed for feeding input components for the machine and taking the assembled products or components away when finished. In the assembly plant of the case company this kind of automatic machines produce for example power socket and switch bodies. Pure hand assembly is mainly applied for the final assembly of the end products. In the combination work centers, robot or machine performs specific stages of the assembly to reduce the need for human work.

Material flow options

All of the materials are packaged in boxes which are stacked on pallets. The number of components can be hundreds of thousands on a pallet and tens of thousands in a package in the case of the smallest components. End products fit in packages that contain from a few to a few hundred products. Pallets can then contain from a few hundred to a few thousand products.

Components are stored in a warehouse which is in the same building as the production plants or in shelves located close to assembly work centers. Internal logistics transports the components to correct warehouse locations using forklifts. In the case of a purchased component, those are collected from the loading dock and in the case of internally fabricated component those are collected from the injection molding work centers.

When an assembly worker prepares to start producing an upcoming production batch, they order inner logistics to bring them the required components from warehouse locations. If the assembled product contains components or semifinished products that are stored at the work centers, they collect those themselves using pump trucks or by hand. When the worker finishes the production batch or the space buffer after the work center fills up, they move the finished products to a dropping point dedicated for this purpose. In the case of semifinished products, they move those to the storage location which is near the work center where particular material is consumed. Internal logistics move finished products from drop point to loading bridge using forklifts.

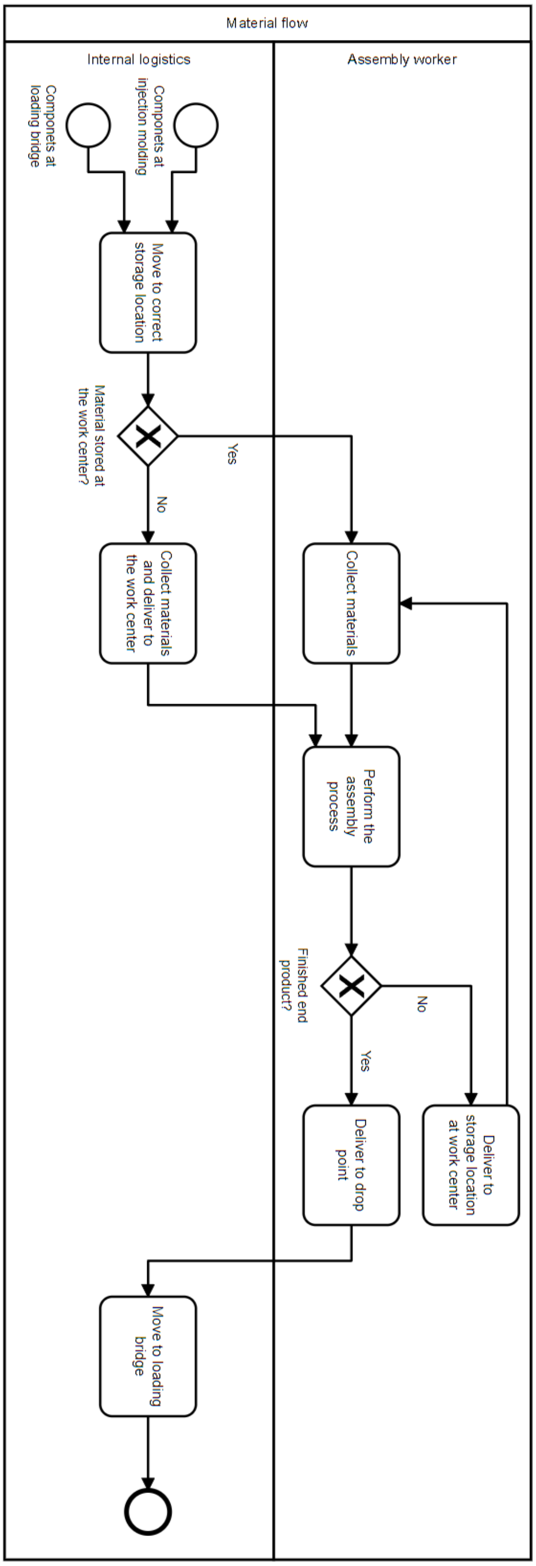

Figure 7. Process diagram of the material flow in the assembly plant.

Data used in this study and in the simulation was gathered from the ERP and warehouse management systems of the case company. In order to analyze material flow, the following input data was required to be gathered.

Table 1. Input data for material flow analysis.

Materials	Work centers	Operations
BOMs - Components - Quantities - Levels Packaging Consumption	Routing by material - Base quantities - Coefficients for machine and human work usage - Setup times	Storage locations Reorder points Batch sizes Working shifts

The first requirement for analyzing material flows is to know all of the materials that are under examination. Therefore, every component that are part of some product selected to this study has to be listed. Also, the amount of the component for each product has to be known. In addition, the information about the level of the component was gathered for each product in order to determine in which order the components are assembled into an end product. When the data for determining the sequence of the flow is collected, the movable units have to be determined for investigating the true movements. For this purpose, data from the pallet and package sizes was collected in this study.

Routing data for the work centers is necessary in order to get the information where certain products or components are assembled. Routing data also enables investigating and comparing throughputs between work centers and is therefore needed when planning stock and space buffers. Also, some additional variables from the production have to be collected in addition to routing data in order to understand the logic of material flows. In this study those variables show where each material is stored, how much of each product is assembled at one time, and when does the work take place in the factory. Materials that had to be taken into examination in order to simulate the assembly process can be divided into eight categories depending on the materials management procedures. These categories show whether the material is finished end product or a component. Those indicate also that if the component is purchased from a supplier, assembled in the assembly plant, or fabricated in the injection molding plant. In addition, the category shows if the material is stored or not. Figure 8 show the categories set to the simulation and how those are treated. Because the simulation will cover only the assembly processes, components fabricated in injection molding department are created without simulating the production process.

Simulate production	Create to work center or storage	Create to loading bridge
FINISHED TO ORDER	MAKE TO ORDER MEB	BUY TO STOCK
FINISHED TO STOCK	MAKE TO STOCK MEB	BUY TO ORDER
MAKE TO ORDER		
MAKE TO STOCK		

Figure 8. Material management categories for the digital twin.

3.1.2 Developing digital twin

A digital twin from the case company's assembly processes was created during this study. Software requirement specification was part of this study, but software development was conducted by an external company using Visual Components software. This digital twin is later used in this study as a tool for analyzing material flows.

Input data

The digital twin simulates the operations of assembly plant as an entirety but does not simulate the precise actions conducted in individual work centers. Digital twin uses the data described above as inputs for simulating the production activities. The simulation is created in a parametric way so that the input data can be changed for simulating different use cases. Overview about the input data and the adjustability can be seen in Figure 9. The digital twin contains layout of the facility which determines the locations of work centers, storages, and the routes which can be used for moving between those. The layout is adjustable, just like the input data, in order to simulate different layout configurations. Production schedule for the simulation is also adjustable but in this study all of the simulation runs are conducted with the same production schedule determined by the actual consumption of the products.

	Resources	BOM	Routing	Storage and Batch data	Packaging	Production schedule	Shifts
Adjustable by user	Partly	Yes	Yes	Yes	Yes	Yes	Yes
Content	Workcenters, storages and the locations of those.	Bill of materials. Contains all of the products and components belonging to those.	Indicates the work center where material is produced. Contains also coefficients for machine and human labour, and the setup time.	Storage locations, batch sizes and reorder points for materials.	Pallet and packaging sizes for materials.	Batch size, batch count and order in which the end product are wanted to be produced.	Shifts on duty and the number of workers in each shift.
Description	User can't add any resources but can move those freely in the model.	User can add and modify BOMs freely.	User can freely adjust for materials and resources existing in the model.	User can freely adjust for materials and resources existing in the model.	User can freely adjust for materials and resources existing in the model.	User can freely adjust in order to simulate different production scenarios.	User can freely adjust in order to simulate different utilizations.

Figure 9. Input data and the adjustability of the digital twin.

Output data

The simulation logs data from material consumption in each work center, throughput of each material in each work center, transport distances and times between locations in the layout, resource utilization levels, and also has readiness to log the energy consumption of the work centers. (Figure 10) The most important data from the material flow point of view is the transportation data. There each transportation route is determined by the arrival and destination locations. Then the number of transports between those locations is calculated and total transport distance and time measured. Then the total distance and time is divided by the number of transports in order to get the mean value of those for a metric to analyze material flows.

	Materials	Transports	Energy	Throughput	Workers	Utilizations
Content	Shows total amount of each inputted and outputted item by each work center.	Shows statistics about transports between each arrival and departure location.	Shows energy consumption on each work center. Currently lacks input data.	Throughput time of each production batch.	Shows worker utilization for intralogistics.	Work center utilizations by states.
Variables and metrics	Metrics include for example pcs/h and pcs/shift.	Number of transports, transport distance and transport time. Distance and time per transport.	Energy consumption by production batch or even individual component. Energy used in the assembly for each end product.	Basic statistic about the distribution of throughput times between production batches.	Moved distance and ratios of time used in different states. (Transporting, moving, idle, blocked, break.)	Ratios of time used in different states. (Busy, idle, blocked, setup.)

Figure 10. Output data of the digital twin.

Challenges with the digital twin

Accuracy of a simulation highly depends on the input data. In this case the simulation strictly follows the routing data gathered from the case company's ERP system and no measurements of the real-life performance is utilized. Processes of the case company are well defined but still a couple of issues were faced when making the digital twin. Processes simulated include quite much human labor and that opens up many opportunities where the process can differ from the base case. For example, intralogistics worker can combine some small transportations and deliver those with one trip. This is extremely hard to simulate because there is not unambiguous situation when this happens. Therefore, the digital twin likely simulates little more transportations than is required in the real-life.

Another example of the challenges relates to production planning. There were situations where producing a batch of a product or semifinished product needed higher amount of a certain material than what was its reorder point. In real-life this should not be a problem since production planner notices this situation if the stock of the component is not enough for producing a product it belongs to. Then they just trigger a production order for that component. The simulation in turn gets stuck if there are not enough components to produce the full batch of a product and at the same time the stock level of the component does not go under the reorder point. Workaround for this is to grow the reorder points of materials which face this issue. This should not be a problem since inventory levels were not in the focus of this study or simulation.

3.2 Analyzing the material flows

3.2.1 Visualizations with Power BI

In order to investigate and visualize material flows in the assembly department the previously mentioned data had to be connected. Connection process contained three main steps: finding the structure of end products with BOMs, connecting routing data to BOM data, and lastly connecting material consumption statistics to the BOM and routing data. This was done using the Power Query tool of Microsoft Power BI with using the material code as a reference when connecting different datasets. Variable for transportations in these visualizations is the number of packages transported. This is a good indicator for material flows since the proportions of packages of different materials are close to each other. Therefore, the number of packages moved represents better the effort needed for transportation than for example number of components moved.

Sankey flowchart in the Figure 11 helps to identify the connections between work centers. The number of transported materials decreases through the assembly process, but the physical size of the transported material increases. Therefore, it is logical that the number of transportations is at the same magnitude in both ends of the process.

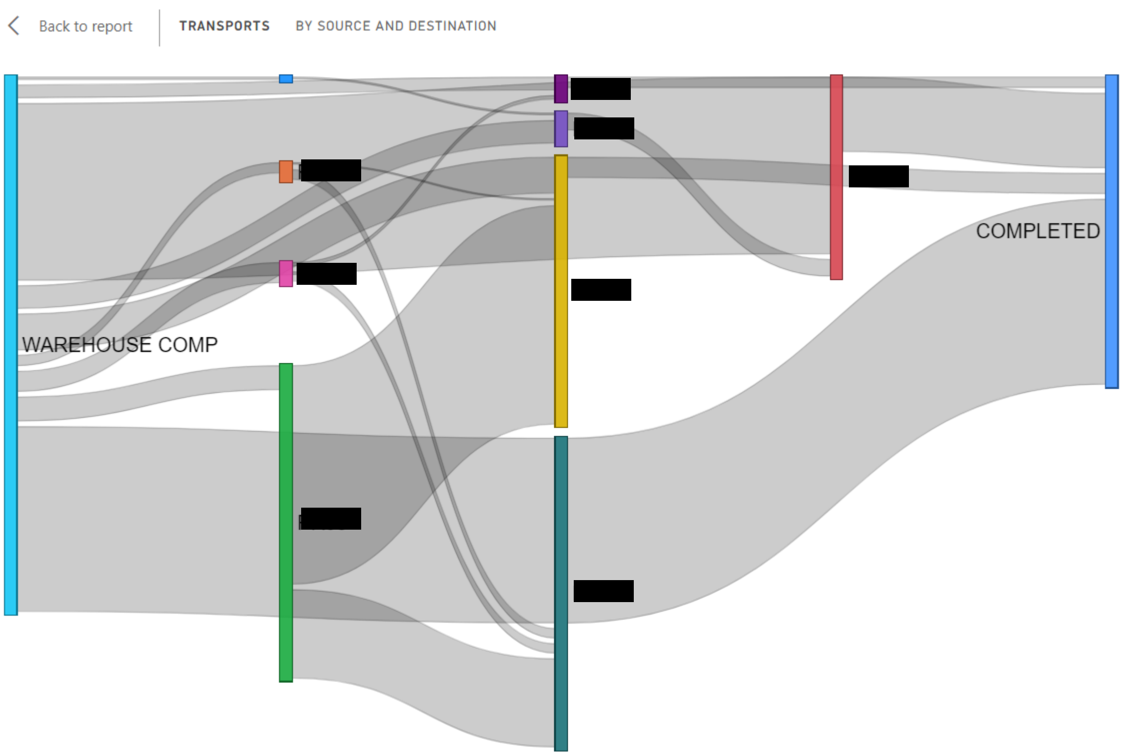

Figure 11. Sankey Flowchart of transportations between resources.

Flow matrix of transportations in the Figure 12 illustrates the same thing as the Sankey flowchart. It does not provide as pleasant illustration but includes the absolute values. Both of these visualizations should be useful when investigating which connections are the most important when designing an optimal layout from the material flow point of view.

Source	[redacted]										Total
[redacted]				2 400,00							**2 400,00**
		105,00									**105,00**
	11 280,00										**11 280,00**
								33 406,00	13 402,00		**46 808,00**
									1 275,00	365,00	**1 640,00**
								51,00	1 303,00		**1 354,00**
	2 950,00										**2 950,00**
	28 272,00										**28 272,00**
WAREHOUSE COMP		3 297,00	203,00	27 017,00	3 518,00	2 918,00	1 401,00	5 347,00	28 232,00	1 793,00	**73 726,00**
[redacted]	1 460,00										**1 460,00**
Total	**43 962,00**	**3 402,00**	**203,00**	**29 417,00**	**3 518,00**	**2 918,00**	**1 401,00**	**38 804,00**	**44 212,00**	**2 158,00**	**169 995,00**

Figure 12. Flow matrix of transportations.

3.2.2 Simulation with the digital twin

The simulation was executed in the same way than it would be useful to do when searching for more optimal layout configuration. Firstly, the production schedule was defined in a way what is reasonable. In this case that meant creating a production schedule for little over a month using last year's consumption data as a basis. Then this simulation was run with the current and modified layouts and results from both runs were saved for comparison.

Modified layout was created by moving two highly utilized work centers closer to work centers where their semifinished products continue. Two different work centers were moved to the previous locations of the earlier mentioned work centers to make space for them. When moving the work centers of storage locations, it is important to move those on a XY-plane so that those do not rise above the simulation. To move a resource the inbound and outbound buffers have to be moved to a desired location and the offset adjusted so that it is on a path.

Even if the product travelled less distance and time out from the highly utilized work centers, the modified layout ended up being little worse overall compared to the current one. Travelled distance increased by 1,6% and time travelling increased by 0,7%. This is because these work centers require a lot of components and the distance between storage places of those and these work centers grew due to the move.

3.3 Assessment of the results

The Power BI visualizations illustrate the number of transportations between resources. Digital twin adds the distance and time consumed to this equation to provide more in-depth information about the material flows. Both analyses yielded similar results about the transportations and therefore supported each other. Power BI is a faster way to build an understanding about the relationships between different resources and can give initial ideas about in which direction the layout should be developed. Trivially, it should be a good way to develop layout configuration options by placing the resources with most transports near each other and do not pay so much attention to the resources with less traffic. Then those layout configurations can be easily tested with the digital twin, which can prove if the assumptions have been right by bringing the distance and time variables into the equation. Currently there are no possibility to automatically optimize the layout with the digital twin by setting constraints.

The digital twin created do not meet the strictest definition about real-time reflection, interaction and convergence, and self-evolution from Tao et al. (2018). Digital twin of this study mostly resembles a virtual shop floor (VS) from that definition but has also capabilities of other elements of a full digital twin. In order to make digital twin utilizing real-time data, there has to be sensors and a system which could provide the data for a simulation continuously. In the injection molding department this is already possible with some machines so more advanced digital twin could be possible in the future.

The material flow is highly important when making layout decisions at a manufacturing plant. However, space requirements and constraints are also crucial factors in this decision making. Previously mentioned methods do not solve issues about space requirements in layout design so those should be taken into account otherwise. Visual Components offers tools also for that and the case organization has already utilized those features of the software. This kind of functionality can be added to the same model as the digital twin or keep in a separate model. At this point the digital twin is visually very simple since the goal has been to maximize the simulation performance for quick iterations. Adding more visual elements to the model will slow down the simulation speeds and do not serve the purpose of studying material flows.

4 DISCUSSION AND RECOMMENDATIONS

As expected from the popularity of simulation tools in engineering purposes in manufacturing (Jahangirian et al 2010), this research showed that it is possible to bring useful information for layout decision making by simulating production processes with a digital twin. Even if the digital twin created for this purpose during the research process do not meet the strictest requirements set for digital twins by Tao et al. (2018) it can become a helpful tool for multiple use cases in the factory. These can be for example process design and improvement, scheduling, and resource allocation suggested by Jahangirian et al. (2010) in addition to facility layout design.

4.1 Using the digital twin

Currently there is two clear use cases for the digital twin developed during this study: the layout evaluation purpose, which it was originally designed for and in addition verifying purposes to compare the real-life situation to the situation in the simulation which strictly follows the routing data from the ERP system. For the layout evaluation use case it is important to schedule a long enough production run. This is because so many different products are produced that having a representative sample from the operations of the factory is impossible with a short simulation period. This concept of representative sample is in line with the emphasizing of input data quality by Tao et al. (2018) and Uhlemann et al. (2017). In the production schedule, there should be multiple batches of high runners produced and some of the low demand products have to be picked to the production schedule in order to have cover enough different situations the production can face. For the verifying use case it is advisable to compare data from a real production run from the history by generating a simulation run with similar specifications.

4.2 Designing the layout

When starting the process of developing a layout the first thing is to recognize which layout type is the right for the specific production: product-oriented layout, process-oriented layout, or cell layout as Heizer and Render (2014) stated. In the context of the case company the decision is most probably made between product-oriented layout and cell layout, or characteristic of both are utilized. The vision of the company to shift towards mass customization would support the decision about cell layout, but the cost leaderships as a competitive advantage would promote the product-oriented layout in the future.

After the suitable layout type is determined it is time for creating a simulation and running that same simulation with those different layout configuration options. At this point it is important to remember to design the options so that they meet the space requirements of the facility which is an important component of layout design (Stevenson 1999), but ignored by the digital twin model. When the simulation is run with all of the layout candidates the results can be compared using the statistics provided in the user interface of the digital twin. Overall transportations (number, distance, and time) should be the main performance measure to concentrate on. When the best layout candidate is found it can be iterated before making the final decision. When making iterations it is advisable to first look at the data of transportations between individual inbound and outbound locations. The locations with highest transportation statistics could be the key for minor improvements by bringing those closer to each other.

4.3 Other recommendations

Currently the same loading bridge serves both the inbound and outbound materials. This also leaves some of the purchased materials far away from the work centers where those are consumed. Just by having the loading bridge and the warehouse for arriving materials at the other side of the building compared to the departing materials could have a big effect on the efficiency of the material flow.

Processes performed by human are very difficult to simulate accurately. Therefore, it would be beneficial to continue taking the digital twins into use with processes with high level of automation. Machines can naturally also offer more data about the operations, and this is also very useful for simulating purposes.

4.4 Validity and reliability of the study

Validity represents the credibility to truthfulness of the study (Denzin 2009). Threat for validity of this study is the low number of interviewed persons by the area of focus. Usually only one person per area of focus was interviewed. However, the information and data gathered during interviews set the framework for creating simulation from the operations of the factory. This simulation has been investigated by multiple different experts that are familiar with the operations and few errors were detected and those were corrected. Also, the characteristics of the output data of the simulations make it simple to compare to real-life both as a whole but also in smaller components. This increases the validity of the study. Outcomes of the study can be applied widely in the situations where developing material flow is a significant factor. However, this kind of digital twin and data created by it can be utilized only in the case company

Reliability represents the coherence and repeatability of the study (Denzin 2009). The interview questions of this study were not recorded since interviews concentrated on finding out how the operations happen in practice and often this required conversations to specify certain things and illustrate operations in the factory. In management system interviews the need for data in each interview was unique and similar structure for these interviews would have been unnecessary. However, the goal of the interviews was to gather the data needed to simulate operations as well as possible so the reliability of the study can be drawn from the performance of the simulation. All of the categories of data required for the simulation is documented in the study which makes it possible to create corresponding research setup also in the future and in different facilities.

5 CONCLUSIONS

The main objective for this study was to develop a methodology for layout evaluation for the case company. The methodology should use data to provide information for experts to make decisions about layout designs. Approach to meet this objective was to develop a digital twin about the assembly operations of the case company. The digital twin utilizes input data gathered from the information systems of the case company in order to simulate the production in the assembly department. Following research questions were set in the beginning of the research in order to meet the objective of this study.

RQ1: How does the layout affect value creation in manufacturing?

RQ2: What are the key factors of process simulation for layout decisions?

RQ3: How can the effectiveness of layout designs be measured in the case company?

Research questions one and two were answered with the literature review. Understanding value creation and tools for evaluating that in a value stream is a key requirement for developing operations. The wrong layout type for production can create a vast amount of waste in the process. When a suitable layout type for production is already in use the layout can be developed mainly by reducing the waste of transportation.

The key factors for the process simulation were understanding the input and output variables which are required for a comprehensive simulation. Input data for a digital twin can be divided into three components: resource management, production plan, and process control. Resource management consisted for example the work centers and the workforce available at a given time. The most important data from the production plan component is the routing data. Process control includes data such as the production schedule and storage data.

The performance measure for the layout effectiveness is primarily the amount of the waste of transportation. Digital twin provides data about the number of transportations, transportation distance, and transportation time. This data can be investigated both in total and individually between each inbound and outbound location.

Three main ideas for continuing the research rise during this study. One for generally developing this kind of methodology for layout evaluation, one specifically for the case company and one as a long-term goal for digital twins from the layout optimization point-of-view. Generally, the material flow evaluation should be combined with the space requirement evaluation in order to fully understand the effectiveness of different layout configurations. The case company specifically could expand this material flow evaluation to its injection molding department. This could reveal synergies between work centers in different departments of the facility. As a long-term goal for digital twin could be the ability for optimizing the layout in the software. Optimization would require much more precise simulation and also setting the constraints to the model for each variable.

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