FACILITY LAYOUT DESIGN WITH SIMULATION-BASED OPTIMIZATION

A holistic methodology including process, flow, and logistics requirements in manufacturing

DOCTORAL DISSERTATION

FACILITY LAYOUT DESIGN WITH SIMULATION-BASED OPTIMIZATION

A holistic methodology including process, flow, and logistics requirements in manufacturing

ENRIQUE RUIZ ZÚÑIGA
Informatics

1977
UNIVERSITY OF SKÖVDE

Enrique Ruiz Zúñiga, 2020

Title: FACILITY LAYOUT DESIGN WITH SIMULATION-BASED OPTIMIZATION

A holistic methodology including process, flow, and logistics requirements in manufacturing

University of Skövde 2020, Sweden
www.his.se

Printer: Stema Specialtryck AB, Borås

ISBN 978-91-984918-9-0
Dissertation Series, No. 35 (2020)

ABSTRACT

Adaptability and flexibility are becoming key concepts in manufacturing. Today manufacturing companies often have to deal with random disruptive events, which necessitates significantly more complex manufacturing systems. Mass customization (manufacturing customized products with mass production efficiency) has also considerably increased the complexity of facility layouts, that is, the physical arrangement of the different aspects required to create products in a factory. Design and improvement of facility layouts is considered a major industrial problem as it affects so many aspects of business. Even in industrialized countries with a long manufacturing history, it is common to find facility layouts that lack optimized flows of materials and products. The main reason for this state of affairs is usually a lack of long-term planning, commonly due to continuous changes and adaptations of the production systems in the layout. These problems are exacerbated by today's shortened product life cycle.

Simulation and optimization are well suited to improve complex manufacturing systems in which several events occur at the same time with unpredictable situations. Thus this thesis aims to investigate how simulation and optimization, and their combination – called simulation-based optimization – can support the redesign and improvement process for existing facility layouts. A literature review shows there is a gap in the field relating to a holistic approach to optimizing facility layouts taking into account production processes and internal logistics. "Holistic" as used here refers to the consideration of the processes and flows occurring in the facility layout, namely machining, assembly, and internal logistics. The aim of this thesis thus includes proposing a holistic methodology based on discrete-event simulation to optimize processes, flows, and internal logistics related to the facility layout.

A methodology is defined as a logical set of methods, and in this thesis the methodology has been developed using a case study method with a design and creation strategy. This approach has been successful in identifying and overcoming both theoretical and empirical challenges in simulation-based optimization of facility layout design. The methodology was evaluated using functional resonance analysis method and industrial case studies, and it has proven to be effective for optimizing facility layouts. These results can thus serve as a guideline for engineers and staff involved in this type of layout project, and as a guideline for managers and stakeholders to support strategic decisions.

SAMMANFATTNING

Anpassningsförmåga och flexibilitet är nyckelbegrepp för konkurrenskraft i den tillverkningsindustrin. Tillverkande företag står inför en ständigt förändrad omvärld som kräver betydligt mer komplexa produktionssystem än tidigare. Massiv kundanpassning av produkter (dvs. tillverkning av skräddarsydda produkter med massproduktionseffektivitet) är en av de faktorer som bidrar till en ökad komplexitet, inte minst i fabrikslayouterna. Framtagning och förbättring av fabrikslayouter anses vara en stor utmaning inom tillverkningsindustrin eftersom det påverkar så många olika aspekter av verksamheten. Även i länder med en lång tradition av industriell tillverkning är det vanligt att fabrikslayouter inte är optimerade med avseende på flödet av material och produkter. Den främsta orsaken till detta är ofta brist på långsiktig planering, vanligtvis på grund av kontinuerliga förändringar och anpassningar av produktionssystemen. Med alltjämt kortare produktlivscykler ökar problemen än mer.

Simulering och optimering är väl lämpade för att hantera komplexa tillverkningssystem där flera händelser oförutsägbart inträffar samtidigt. Denna avhandling syftar till att undersöka hur simulering och optimering, och deras kombination – så kallad simuleringsbaserad optimering - kan stödja omdesign och förbättringar av befintliga fabrikslayouter. En genomgång av litteraturen visar att det finns få studier särskilt vad gäller en helhetssyn på optimering av fabrikslayouter, i denna avhandling benämnt med begreppet ”holistisk”. Med en holistisk ansats avses en samtidig inkludering av de processer och flöden som uppstår i fabrikslayout, produktion och intern logistik. Syftet med denna avhandling är att föreslå en holistisk metodologi baserad på diskret händelsestyrd simulering för att optimera fabriklayouter med hänsyn till processer, flöden och intern logistik.

I avhandlingen har metodologin utvecklats baserats på fallstudier med en så kallad ”design and creation strategy”. Detta tillvägagångssätt har framgångsrikt lyckats identifiera och överbrygga både teoretiska och empiriska utmaningar i simuleringsbaserad optimering av fabrikslayouter. Metodiken har utvärderats med hjälp av funktionell resonansanalys och industriella fallstudier, och den har visat sig vara effektiv för att optimera fabrikslayouter. Resultaten från avhandlingen kan fungera som en riktlinje för ingenjörer och personal som är involverade i layoutprojekt, och som ett stöd för chefer och andra intressenter som tar strategiska beslut.

ACKNOWLEDGMENTS

First of all, I would like to thank the Swedish Knowledge Foundation, the University of Skövde, Xylem Water Solutions Manufacturing AB, and the IPSI Industrial PhD School in Informatics for funding me, welcoming me, and giving me the chance to develop my research career.

That would not have been possible without the help of Matias Urenda Moris and Magnus Holm, my first contacts at the University of Skövde, who shaped my mind to appreciate Skövde and its university, and who encouraged me as I learnt an almost impossible language for Spanish-speaking people.

I would like to express special thanks to all my supervisors – Anna Syberfeldt, Matias Urenda Moris, Jan Oscarsson, Masood Fathi, and Leif Pehrsson – for allowing me to develop a really interesting project, for always being available to help me with any questions I had, and for trying to understand my poor Swedish: “practice makes perfect,” perhaps.

I would also like to acknowledge the help of my mentors and colleagues at Xylem Water Solutions – Ola Gustavsson, Johnny Fält, and Madelene Thörnblom – as well as Urban Kjellin, Nicklas Mårtensson, Mika Petersson, Nicklas Rydqvist, and the staff of the factory in Emmaboda. Without them, the project could not have achieved its aim, and my time in Emmaboda would have been much more boring.

The working environment is crucial for career development. So I would like to thank all my colleagues at the School of Engineering Science and all my fellow PhD students over the last few years.

Special thanks to my parents and sister for their push and support to study abroad, their moral support, and the Spanish food survival packages to help me survive in cold Sweden. Special thanks also to Ignacio Zúñiga for his huge effort in the precise review of the last drafts of the thesis, and to Ana Isabel Gómez Merino and Juan Carlos Rubio-Romero for welcoming me and supervising my thesis at the University of Malaga during my research stay.

Finally, I want to thank my friends for all their help, advice, and unconditional support while I have been working on this thesis. Without them, it would have been much tougher to survive, missing the warming sun and life of the south of Spain.

PUBLICATIONS

APPENDED PUBLICATIONS IN THE THESIS

1. Production Logistics Design and Development Support: A Simulation-Based Optimization Case Study. Ruiz Zúñiga, Enrique; Urenda Moris, Matías; Syberfeldt, Anna. Summer Simulation Conference, 2016, p. 1-6
2. Integrating Simulation-Based Optimization, Lean, and the Concepts of Industry 4.0. Ruiz Zúñiga, Enrique; Urenda Moris, Matias; Syberfeldt, Anna. Proceedings of the 2017 Winter Simulation Conference, IEEE, 2017, p. 3828-3839
3. Improving the Material Flow of a Manufacturing Company via Lean, Simulation and Optimization. Goienetxea Uriarte, Ainhoa; Ng, Amos H.C.; Ruiz Zúñiga, Enrique; Urenda Moris, Matías. Proceedings of the International Conference on Industrial Engineering and Engineering Management, IEEE, 2017, p. 1245-1250
4. Simulation-Based Optimization for Facility Layout Design in Conditions of High Uncertainty. Flores Garcia, Erik; Ruiz Zúñiga, Enrique; Bruch, Jessica; Urenda Moris, Matias; Syberfeldt, Anna. Procedia CIRP, 2018, Vol. 72, p. 334-339
5. Challenges of Simulation-Based Optimization in Facility Layout Design of Production Systems. Ruiz Zúñiga, Enrique; Flores-Garcia, Erik; Urenda Moris, Matias; Syberfeldt, Anna. Advances in Manufacturing Technology XXXIII: Proceedings of the 17th International Conference on Manufacturing Research, incorporating the 34th National Conference on Manufacturing Research, IOS Press, 2019, Vol. 9, p. 507-512
6. Holistic Simulation-Based Optimization Methodology for Facility Layout Design with Consideration to Production and Logistics Constraints. Ruiz Zúñiga, Enrique; Flores-Garcia, Erik; Urenda Moris, Matias; Syberfeldt, Anna. Part B: Journal of Engineering Manufacture, 2020. [Resubmitted with minor changes]
7. Simulation-based Optimization Methodology for Production System Layout Design in Manufacturing. Ruiz Zúñiga, Enrique; Urenda Moris, Matias; Rubio-Romero Juan Carlos; Syberfeldt, Anna. IEEE Access, 2020, p. 1-11

ADDITIONAL PUBLICATIONS

8. System Design and Improvement of an Emergency Department using Simulation-Based Multi-Objective Optimization. Goienetxea Uriarte, Ainhoa; Ruiz Zúñiga, Enrique; Urenda Moris, Matías; Ng, Amos H. C. Journal of Physics, Conference Series, 2015, Vol. 616, no 1, article id 012015
9. A Simulation-Based Multi-Objective Optimization Approach for Production and Logistics Considering the Production Layout. Ruiz Zúñiga, Enrique; Urenda Moris, Matias; Syberfeldt, Anna. Proceedings of the 7th Swedish Production Symposium, 2016
10. The Internet of Things, Factory of Things and Industry 4.0 in Manufacturing: Current and Future Implementations. Ruiz Zúñiga, Enrique; Syberfeldt, Anna; Urenda Moris, Matías. Advances in Manufacturing Technology XXXI: Proceedings of the 15th International Conference on Manufacturing Research, 2017, p. 221-226
11. How can Decision Makers be Supported in the Improvement of an Emergency Department? A Simulation, Optimization and Data Mining Approach. Goienetxea Uriarte, Ainhoa; Ruiz Zúñiga, Enrique; Urenda Moris, Matías; Ng, Amos H. C. Operations Research for Health Care, 2017, 15, p. 102-122
12. A Genetic Algorithm for Bi-Objective Assembly Line Balancing Problem. Nourmohammadi, Amir; Fathi, Masood; Ruiz Zúñiga, Enrique; Ng, Amos H. C. Advances in Manufacturing Technology XXXIII: Proceedings of the 17th International Conference on Manufacturing Research, incorporating the 34th National Conference on Manufacturing Research, 2019, Vol. 9, p. 519-524

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INTRODUCTION

CHAPTER 1
INTRODUCTION

This chapter presents the background, problem description, aim, research questions, scope, and limitations of this thesis. The relationships and main contribution of the appended papers are also summarized. This research was done in close collaboration with an industrial partner and the Industrial PhD School in Informatics of the University of Skövde (IPSI) and the Swedish Knowledge Foundation (KK-Stiftelsen). The main focus of the IPSI Research School is on how advancements in engineering and computer science can support the development of information technology systems that are beneficial for individuals, organizations, and society in general.

An industrial research thesis aims to contribute to scientific knowledge while taking into consideration the utility and implementation of the research results. It is important to distinguish between research and innovation. "Innovation" implies that the outcome of the research is new to the recipient, for example an industrial partner, but not necessarily to the scientific community. "Research," however, requires a clear contribution to science. In this thesis, the industrial partner is the main beneficiary of some innovations that can be directly implemented in their manufacturing facilities. At the same time, the solutions provided to the industrial partner are analyzed in terms of their applicability to other companies and industries to ensure that the proposed solution can be generalized to serve as a guideline to others and as a base to increase knowledge in the scientific community. The industrial partners, in this case, are the main potential users of the research findings of this thesis; however, extrapolation to other manufacturing companies is also expected.

To facilitate the reading of the thesis, it is important to begin by defining some basic terms such as production system and manufacturing system According to the CIRP Dictionary of Production Engineering, a manufacturing system can be defined as a combination of humans, machinery, and equipment that is bound by a common material and information flow. On the other hand, a production system is a more generic term that also includes the organization and technological aspects related to the conversion of inputs into outputs. Therefore from here on, the term that better suits this thesis is manufacturing. However, production system is also used to denote subsystems of the main manufacturing system, or the making or growing of goods to be sold.

Another key distinction for the understanding of this thesis is the difference between design and redesign. In this thesis the focus is on redesign of facility layouts; however, the literature commonly refers to facility layout design (FLD), and so the term FLD is used in this thesis. Furthermore, a key distinction is made between facility layout and shop floor layout. A facility layout is the physical arrangement of the different aspects required to 0create products in a factory, including the way the equipment is organized. It refers to the physical positioning of people, departments, and subsystems relative to each other including their interconnection [1]. On the other hand, the shop floor or shop floor layout of a facility is the main part or location where the physical manufacture of goods takes place. Since in this thesis some parts of the facility layout design are not related directly to the physical manufacture of goods, from now on the term facility layout is used, which includes the meaning of shop floor layout. “Holistic” means related to or concerned with the complete system rather than focusing only on the analysis or treatment of dissected parts or subsystems [2].

Additional common terms in this thesis are internal logistics, simulation, and optimization. “Internal logistics” is the process of planning and organizing to make sure that resources are in the places where they are needed so that an activity or process happens effectively [3]. “Simulation” is defined as the imitation of the operation of a real-world process or system over time. Simulation has huge potential for developing and improving manufacturing systems [4]. It is an analytical tool to create, maintain, evaluate, or improve a system or process. “Optimization” is the process of making something as good or effective as possible; finding an alternative with the most cost effective or highest achievable performance under the given constraints by maximizing desired factors and minimizing undesired ones [3]. “Constraints” are defined as limitations or restrictions while “requirements” are defined as something wanted or necessary or a compulsory condition. Requirements are usually fulfilled while constraints are usually obeyed.

Finally, a “methodology” can be defined as a logical way to perform a study, the study of methods, linking assumptions regarding the world and how it may be examined [5]. A distinction should be made between “method,” this is, a systematic approach, and “research method”, that is, an established approach gathering the greatest possible amount of knowledge of something unknown [5]. Having made these definitions, the next sections of this introduction are the background and problem descriptions, before presenting the aim and research question of the thesis.

1.1 BACKGROUND

Many companies are trying to conquer a larger share of the market by improving the efficiency of their manufacturing processes. In other words, they seek to minimize the use of resource (time, materials, or labor) while maximizing performance aspects (throughput, lead time, or work-in-progress) and reducing waste [3]. Great effort is required to achieve the level of efficiency needed to stay competitive [6, 7], especially in manufacturing systems that produce goods in large quantities in factories and usually involve a large number of products, variants, and production variables [3]. The large number of variables means that manufacturing systems are usually characterized as complex, as also does the fact that several events may be occurring at the same time in sometimes unpredictable situations [8]. This intrinsic complexity, combined with current levels of competition, shortened product life cycles, and globalization, increases the overall complexity of manufacturing systems around the world.

The competition manufacturing companies are facing is becoming increasingly fierce. They need to work toward continuous improvement in order to stay profitable, especially with the increase of low-cost manufacturing in developing countries [6, 9]. This challenge is highlighted in the agendas of countries with a long tradition of manufacturing, where the manufacturing sector usually represents a significant share of the GDP [6, 7]. Yet manufacturing companies that have existed for a long time often lack efficient and optimized flows of materials and products. This is a consequence of a process of continuous adaptation and modernization over time, often without an overall long-term strategy for adapting or redesigning facility layouts [10, 11].

It is common for manufacturing companies to undergo modernization and adaptation in order to improve efficiency. However, the integration in facility layouts of production subsystems (e.g., foundries, machining areas, and assembly lines) and internal logistics systems (e.g., incoming flows from internal and external suppliers, internal transports, storage, and buffers) makes manufacturing systems even more complex. This complexity is increased by the high number of variables involved in these systems and their stochastic behavior [12]. Furthermore, changes in a country and in the world may have severe consequences for manufacturing industries – a point that has been driven home in the recent pandemic which has forced companies to adapt their manufacturing and suppliers' networks while also accommodating changing product demands and changing national economies. Some of these problems can be solved by cost-cutting approaches, high-precision production, new technology for parts suppliers, or trying to shrink manufacture without raising cost [13].

Additional common problems that characterize manufacturing systems and the integration of their subsystems are the large number of automated and manual processes to be coordinated and the high number of product families and variants. These variables result in high variability in processing times, large storage and buffer requirements, space constraints, the need for specialized resources, and dependence on external suppliers. A very large number of possible configurations result from this complexity. It is common for facility layout designs to be constructed using a combination of intuition, common sense, and systematic trial and error [1].

Despite the large amount of time and resources invested in the layout design process, the high number of production processes and different kinds of products together with facility changes over time are common reasons for inefficient FLD. Dynamic facility layout problems with unequal areas are one of the non-deterministic polynomial-time hard problems that are part of a complexity class used to classify the solving feasibility of decision problems [14].

Apart from the major challenges posed by complexity and variability, there can also be high levels of uncertainty associated with the design of improved facility layouts. "Uncertainty" is the difference between the information available at the time of the initial design of conceptual models and the information one needs to achieve the final proposed solutions [15]. "Conceptual modeling" is abstraction of a real or proposed system to reach an increased level of understanding [16]. Restrictions in the conceptual modeling constrain the range of values or types of models in the analysis of uncertainty [17]. Other challenges are related to the coordination of the engineering teams working on large-scale projects, a lack of knowledge of available technological tools, and poor usability of the tools and methods intended to support the layout redesign process.

Additionally, several limitations have to be taken into account in the redesign and improvement process of facility layouts. These include a lack of free space in the layout, excessive traffic or the large number of transporters required for logistics, the extensive and diverse amounts of labor needed for every process, and the difficulties of interrupting the system. All these problems have to be addressed when analyzing and proposing alternative facility layout designs. Facility layout decisions can therefore be difficult and expensive; hence operation managers are reluctant to do them often [1, 15].

Discrete-event simulation (DES) is a way to handle the complexities and overcome the shortcomings of traditional methods of improving facility layouts. DES provides the results of specific what-if experiment scenarios and is a convenient tool when a large number of different system configurations are considered. Recently, simulation approaches have been widely used for system improvement and design in manufacturing. However, with increasing system complexity, the numbers of products and variants to be taken into account, and adaptation and flexibility requirements, the application of simulation alone is reaching its limits.

This thesis proposes that a better approach that enables DES to analyze several scenarios in the search for optimized solutions is a combination of simulation and optimization known as simulation-based optimization (SBO). SBO has been applied in the design and improvement of complex systems or subsystems consisting of several interconnected parts. However, it has not commonly been used in manufacturing for FLD. Yet when working with facility layout problems, SBO can take into account the optimization, constraints, and requirements of subsystems and allows the analysis of large numbers of variables and scenarios that can otherwise become tedious and time-consuming when using DES on individual what-if scenarios. The problem description that motivated this thesis is presented in the following subsection.

1.2 PROBLEM DESCRIPTION

Manufacturing systems around the world have long been adapting to new requirements and standards to meet the demand for mass customization and smooth flows of materials and products [18]. Mass customization occurs when a company produces large numbers of products and differentiates those products according to the preferences of several customers, resulting in a product mix with high variance [3]. This often results in the extension of existing facilities with aggregated installations, mainly due to continuous expansion, adaptation, and modernization of the manufacturing systems over time. The specifications of constraints limiting facility performance and its improvement or design objectives can often be fuzzy [19]. Therefore this thesis addresses the process of analysis and possible redesigns.

Changes in the organizational structure of the company, in product designs, processing sequences, demand, and schedules; the replacement of equipment or procedures; and the elimination or addition of products are common situations that demand the redesign of facility layouts [19]. A large number of product families and variants often translate into tedious, simultaneous, and complex design processes. There are often several assembly lines with adaptable processes, ineffective transport procedures, transport-related accidents, and increased lead times and levels of inventory. One of the most common objectives of researchers and practitioners working with the design of facility layouts is to minimize the distance between departments with common flows of materials or products. However, this approach ignores limitations such as the design and performance of the manufacturing systems, the density and frequency of traffic between departments, buffer and storage requirements, and internal logistics flows of materials and products. Thus this thesis will consider internal logistics systems and their relation to the manufacturing systems, as well as different flows of material and products in relation to FLD.

There is very little in the research literature regarding a methodology involving simulation and optimization to make decisions regarding FLD, especially taking into account production and logistics requirements [10, 20]. Most of the approaches and methodologies in the literature focus on the resolution approach for simplified facility layouts, focusing primarily on the reduction of distances between departments and the reduction of associated material transport costs. Manufacturing subsystems such as assembly lines and storage facilities are usually not considered. In addition, these approaches or methodologies rarely define the resources and steps needed for FLD projects. Several challenges have also been identified in the literature regarding FLD with SBO, including the high complexity and stochasticity of the systems and a lack of expertise, resources, time, and project planning.

To fill this research gap, the thesis proposes to offer a holistic methodology for FLD with SBO that includes optimization of the production and logistics systems related to facility layout. An analysis was performed to identify the specific aim and research questions that could contribute to solving these problems.

1.3 AIM AND RESEARCH QUESTIONS

The aim of this thesis is to propose a holistic simulation-based approach to the redesign of facility layouts taking into account process, flow, and logistics optimization. Based on this aim, three research questions (RQs) have been formulated:

RQ1. What are the challenges for the design and improvement of facility layouts taking into account process, flow, and logistics requirements?

RQ2. How can SBO address these challenges to support FLD in manufacturing systems taking into account process, flow, and logistics requirements?

RQ3. How can a methodology based on SBO be developed for FLD in manufacturing taking into account process, flow, and logistics requirements?

The next subsection details the contribution of the appended papers to these three RQs.

1.4 RELATIONSHIP AND MAIN CONTRIBUTION OF APPENDED PAPERS

The relationship between the papers, the RQs, and their contribution is presented in this subsection to facilitate understanding this thesis and its structure. The list of high-relevance papers, sorted in chronological order, specifies which RQ each paper answers and its contribution. Table 1 summarizes how the different RQs are answered by the appended papers:

Table 1. Contribution of appended papers to research questions.

	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5	Paper 6	Paper 7
RQ1	x	x			x		
RQ2			x	x			
RQ3						x	x

Paper 1, *Production Logistics Design and Development Support: A Simulation-Based Optimization Case Study* was presented at the Summer Simulation Conference in July 2016. The authors present an SBO case study for the design and improvement of a recently adapted assembly line of the industrial partner. The aim was to use simulation to analyze the existing line and find potential improvements supported by simulation and optimization, taking into account the different processes on the line, its needed resources, line buffers, and material feed system. The paper investigated the benefits of using simulation and optimization in industrial case studies with low volumes of customized products. Some major challenges were also highlighted, such the lack of information, mixed manual and automated processes, and difficulties in the data collection process. A bottleneck analysis was performed and the main limitations of the line were identified. The results showed that the throughput of the line could be increased significantly. Optimization was then implemented to double-check whether the buffer capacity would be sufficient for increased production. The main advantage of this approach was that the project could be developed without stopping production. The project showed that improvements to the assembly line could be implemented without major changes in the system, allowing implementation from one day to the next in cases of peak of demand.

The main contribution of this paper to this thesis was an increased understanding of simulation and optimization techniques in manufacturing, of important challenges in data collection and data availability, and of the possibility of implementation without interrupting production. The importance of key performance indicators in manufacturing and their association with simulation models was also highlighted. The findings were used to identify what practical knowledge is required when working with SBO and FLD in real industrial case studies, highlighting the challenges of data collection, the process, flow, and logistics simulation, and the validation aspects with respect to RQ1.

Paper 2, *Integrating Simulation-Based Optimization, Lean, and the Concepts of Industry 4.0* was presented as part of the Proceedings of the 2017 IEEE Winter Simulation Conference. It addresses the importance of integrating simulation and Lean approaches to increase efficiency in manufacturing systems. It also identifies the lack of communication between the respective experts or departments involved in system improvement in manufacturing. The paper introduces integration with the new paradigm of Industry 4.0 and how this can serve as a link between Lean and simulation. The main contribution of the paper is to highlight the importance of Industry 4.0 for the improvement of process, flow, and logistics in manufacturing as a base for overcoming the challenge of data collection. It also shows that Lean support can overcome the challenge in the planning and communication process among team members. The paper uses an optimization case study to analyze the performance of three different layouts while maximizing throughput and minimizing buffers and resources. The results highlight the benefits of integrating Industry 4.0 from the beginning. This integration facilitates the development of Lean approaches (e.g., just-in-time and pull systems), data availability, and collection processes. It also helps to analyze the performance of the lines, especially regarding material and production control and internal logistics. This paper was the base for understanding the importance of Lean tools, primarily for waste reduction and continuous improvement, and the paradigm of Industry 4.0, highlighting its benefits for digitalization, data collection, and project planning, thus helping to identify and overcome the challenges of RQ1.

The third paper, *Improving the Material Flow of a Manufacturing Company via Lean, Simulation and Optimization*, was presented as part of the Proceedings of the International Conference on Industrial Engineering and Engineering Management, IEEE, in 2017. This paper aims to analyze the implementation of an improved material handling system in a manufacturing company following an SBO framework combined with Lean. The optimization problem included several material flows in the layout. The optimization focused on sizing the length of the required conveyors in every area to minimize their use of shop floor space. The results highlight a significant reduction in the waiting time of materials to be transported and transport times. It contributes to answering RQ2 by presenting a process that combines Lean, simulation, and optimization to improve material flow in a manufacturing company. The main contribution of the paper is an analysis of how these three approaches can be combined to improve the facility layout while taking into account the production and internal logistics flows and addressing their requirements.

Paper 4, *Simulation-Based Optimization for Facility Layout Design in Conditions of High Uncertainty*, Procedia CIRP 2018, analyzes the implementation of simulation and optimization in real manufacturing FLD problems with significant levels of uncertainty regarding data and outcomes. The paper identifies different conceptual modeling activities when working with simulation in this kind of system. Furthermore, a classification criterion for manufacturing systems is defined by going through three industrial case studies to reduce uncertainty in FLD problems. The contribution of this paper is the analysis of the uncertainty levels to identify critical moments in the facility layout design process, and the inclusion of the classification criteria in the proposed methodology for FLD. This paper also complements the answer to the second research question by addressing the levels of uncertainty, characterization criteria, and conceptual modeling activities when working with FLD.

Paper 5, *Challenges of Simulation-Based Optimization in Facility Layout Design of Production Systems*, was presented at Advances in Manufacturing Technology XXXIII: Proceedings of the 17th International Conference on Manufacturing Research, incorporating the 34th National Conference on Manufacturing Research. This paper presents an analysis of theoretical and empirical challenges found in the literature and two industrial case studies. The aim of the paper was to identify the challenges of SBO and FLD in manufacturing systems. The main contribution to the thesis, answering RQ1, is a list of theoretical and empirical challenges to be considered in FLD methodology. The paper also discusses some interrelations between complexity, data noise, and standardization, and the importance of not underestimating the complexity of the layout design process and the production systems.

Paper 6, *Holistic Simulation-Based Optimization Methodology for Facility Layout Design with Consideration to Production and Logistics Constraints* was resubmitted with minor comments for the Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture. It presents a methodology for FLD using SBO in manufacturing systems taking into account production and internal logistics requirements. The contribution of this paper, together with paper 7, is the basis for this thesis, answering RQ3 by presenting and analyzing the proposed FLD methodology with SBO.

Finally, paper 7, *Simulation-based Optimization Methodology for Production System Layout Design in Manufacturing Companies*, published in IEEE Access in September 2020, answers the methodology validation aspect of RQ3. It shows how the proposed methodology is evaluated and implemented in two case studies. The aim of the paper is firstly, the evaluation of the methodology by using the functional resonance analysis method (FRAM) and secondly, its applicability in manufacturing. The main contribution of this thesis is the evaluation of the methodology and how it can be used by this kind of manufacturing system to design optimized layouts.

1.5 SCOPE AND LIMITATIONS

The main limitation of this thesis is its focus on existing manufacturing facilities, which is very different from designing facility layouts of new factories being built from scratch. For the final design of a new facility, a detailed level of design is required, including machining and assembly line blueprints; the exact location and shape of additional machining activities; maintenance procedures and spaces; building facades; diverse electrical, gas, and water installations; and physical architectural requirements and constraints. The focus in this thesis is on the redesign of the layout of existing factories with an existing FLD. It focuses on the conceptual block layout problem, taking into account the number, size, location, shape, and interrelations of existing blocks or departments with fixed input and output points, but not the detail level of the blueprints of every one of them.

In most of the case studies presented in this thesis, some boundaries regarding the scope of the production flow have been applied. A prior consideration is to include a generalization of the main product or family of product flows in the facility layout. On the other hand, there is a risk to too much generalization or excessive assumptions regarding production processes and internal logistics related to facility layout. These processes should be analyzed and included when relevant. The requirements for the material handling systems and facility layout should be clear before deciding on their level of consideration in the FLD project. In the following subsection the organization of the remainder of the thesis is presented.

1.6 THESIS STRUCTURE

Chapter 1 has presented the content of the thesis, its background and problem description, aim and RQs, the connection between the RQs and the appended papers, and the scope and limitations of the thesis.

Chapter 2: Frame of reference, presenting a literature review of the state of the art of the main areas of this thesis: layout design, methods for facility layout design, DES in facility layout design, facility layout design with SBO, and theoretical challenges.

Chapter 3: Facility layout optimization methodology with simulation-based optimization. This chapter presents the research paradigm and strategy; the procedures for data collection and analysis; key performance indicators and the importance of Industry 4.0; the introduction of process, flow, and facility layout optimization; empirical challenges; and the proposed FLD methodology with SBO. The methodology is also evaluated in this chapter.

Chapter 4: Summary of results. The answers to the RQs and a summary of the industrial case studies are presented.

Chapter 5: Conclusions and future work. This chapter summarizes the conclusions of this thesis, its contributions to knowledge and practice, and some ideas for future research.

References. All the references used in this dissertation are presented. Some of the references in the appended papers might not appear here; however, they are presented at the end of each appended paper.

Appended papers, in which the appended publications in the thesis are presented.

FRAME OF REFERENCE

CHAPTER 2
FRAME OF REFERENCE

This chapter reviews the literature on the main research areas commonly associated with FLD that fall within the scope of this thesis. In this chapter, these areas are organized in the following sections: FLD, methods for FLD, DES in FLD, and FLD with SBO. The purpose of the literature review is to have a deep understanding of the state of the art of FLD and FLD methods and their challenges. The review enables an investigation of a holistic simulation-based approach for the redesign of facility layouts taking into account process, flow, and logistics optimization, which is the aim of this thesis.

The main research areas of this thesis are shown in Figure 1. Given that the focus of this thesis is their area of intersection, however a deep understanding of each area independently is required.

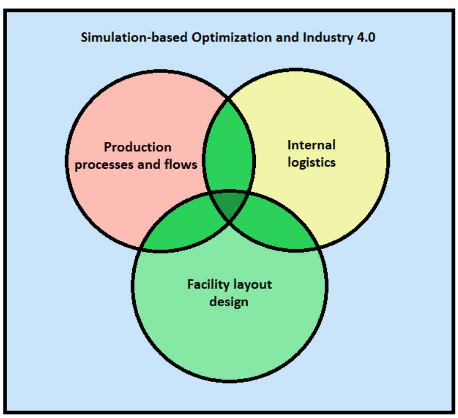

Figure 1. Research areas of the thesis

The central area of overlap between these fields has been the focus during the development of the thesis, with SBO and Industry 4.0 as a base. The thesis especially focuses on FLD, taking into consideration production processes and flows, internal logistics requirements, and constraints. As previously defined, production is the task of making or growing goods to be sold. It includes the systems present in a facility to perform the production, including machining areas, foundries, assembly lines, and their flows of materials and products. Internal logistics can be defined as the transport, management, and delivery of goods and finished products, which is especially crucial in large manufacturing systems. In this research, internal logistics refers to the material handling and storage systems related to production systems located in the layout. Additionally, a change or update in the research direction of FLD and production system design has significantly affected the ways of working with these areas, SBO, and the concept of Industry 4.0.

Industry 4.0 is a promising paradigm based on the emerging technologies of the Internet of Things and cyber-physical systems, bringing together fully or partly autonomous systems and humans to increase efficiency and flexibility in manufacturing [21, 22]. Flexibility enables better reactions to change. Flexibility can usually be achieved by using modular equipment, workstations, and material handling systems, as well as general purpose equipment and grid-based utilities and services systems [19]. Starting with different levels of automation and data generation, collection and analysis, Industry 4.0 has had a tremendous impact on manufacturing, including FLD. The terms "adaptable manufacturing" and "digitalization" are becoming common in manufacturing systems today. A model of the evolution of Industry 4.0 in manufacturing is presented in Figure 2.

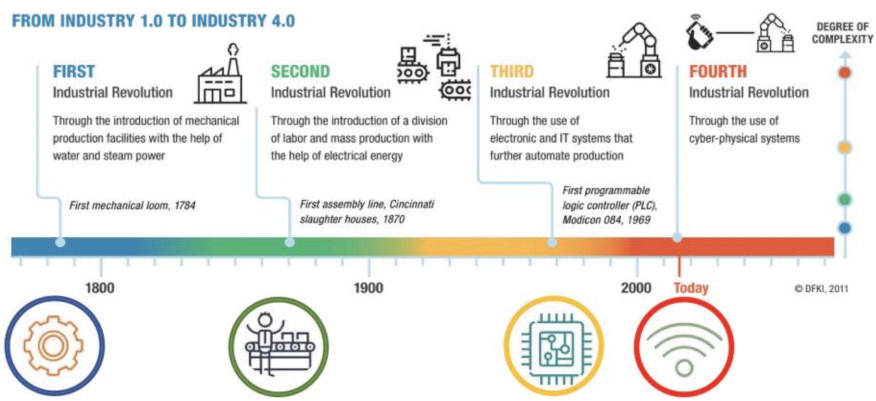

Figure 2. Industrial revolutions until Industry 4.0 (Reproduced with permission of Sisodia et al. [23]).

Industry 4.0 is a game-changer that allows the transition from mass production to mass customization and plays a vital role in the design of new production and logistics systems as well as in the design of facility layouts. After the industrial revolutions of mechanical production, mass production, and automation, the conversion of production processes of manufacturing systems into cyber-physical systems is becoming the current industrial revolution, known as Industry 4.0. The interconnection in real time of these cyber-physical systems through the Internet allows visibility, transparency, communication, coordination, and adaptation of the production and logistics subsystems present in the layout. This generates a large amount of data in real time. When stored and properly analyzed, the data can facilitate manufacturing predictions to support the FLD process and the durability and adaptability of long-term designs. The ways in which this data can contribute to the design of optimized facility layouts is explained in more detail in chapter 3. Using data appropriately ensures an efficient transport system that takes into consideration the large number of factors related to facility layout.

In the literature review in this chapter, the papers are classified as literature review or survey papers, FLD computing approaches, FLD with simulation approaches, or FLD methodologies. Searches of the databases of Web of Science and Scopus for articles in English from 1999 to 2019 resulted in 181 and 110 articles respectively. The key words were facility layout, layout, shop floor layout, workshop, design, simulation, optimization, method and approach, (((facilit* OR shop* OR workshop* OR layout*) W/3 design*) AND (simulat* W/2 optimi*) AND (method* OR approach*)). The majority of the papers overlapped. This search was complemented by simplified search strings in masters and doctoral theses, references in reviewed documents, and some additional articles in German and Spanish obtained using Google Scholar to ensure the accuracy of the literature review process. The abstracts were filtered to classify the articles and reject those that were out of scope. After that, a similar full-text filtering process was applied. The Kumu data organization online platform (https://kumu.io/) was used to classify and map the articles reviewed to enable a clear and structured view of the literature review, as shown in Figure 3. This platform was useful to structure the literature review and to clearly identify borders, key areas, authors, and articles. The review papers were classified using tags assigned to them as characteristics or attributes using this online platform.

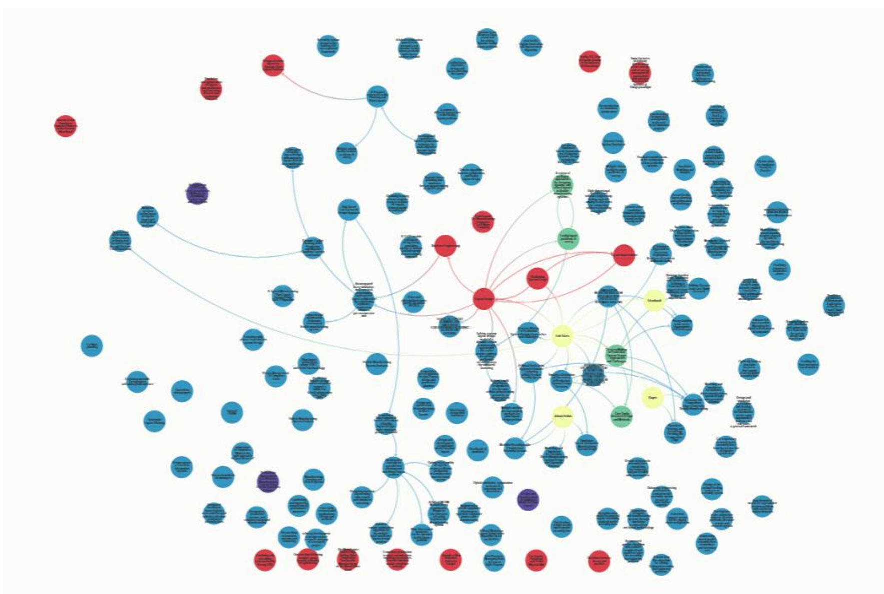

Figure 3. Mapping of reviewed articles.

The classification of the reviewed articles in the Kumu platform was mainly done according to the application areas mentioned to avoid incongruences in the classification. These areas are represented in the tags assigned as characteristics or attributes of every article identified in the chart presented in Figure 3. For example, the articles marked in red and placed at the borders are out of scope, and so define the limits of this research. The structure of the Kumu model is mainly classified into FLD, including production and internal logistics systems, and SBO. From these main areas, some key articles that were used as a starting point are highlighted below:

- Simulation in the production system design process of assembly systems [24]
- Facility layout problems: A survey [15]
- Decision-making in production system design: Approaches and challenges [25]

Working with this Kumu model identified some key papers, serving also as a starting point by having their own element in the chart due to their relevance, references, and literature. All the articles are considered to be supportive of the main areas presented in Figure 1. Additional tags of “Method” and “Application” were used to analyze the articles reviewed at different stages of this research. These classifications make a clear difference between purely theoretical papers and applications or case studies. Case studies in this industrial field can be considered as relevant due to the need for applicability. The classifications used different colors. For example, blue represents articles, green represents key articles, and yellow key authors.

To understand the development of this thesis the frame of reference is structured in the following way: first, an introduction to FLD in manufacturing is presented. Then different methods of working with FLD are analyzed, followed by production and internal logistics application areas, and concluding with the integration of SBO in FLD. These main research areas are presented in the following subsections: FLD, including production and internal logistics systems, FLD methods, FLD with DES, and SBO in FLD.

2.1 FACILITY LAYOUT DESIGN

The layout of an operation is considered to be the physical positioning of its people and facilities relative to each other, and how its various processes are physically allocated for the transforming of resources [1]. It governs how safe, orderly, flexible, and efficient an operation is. Relatively small changes in the layout can significantly affect the flow of the operation and in turn its cost and effectiveness [1].

Different factors make for a good layout. These include inherent safety, security, minimized length of flow, minimized delays, minimized work-in-progress, clear flows of materials or persons, good staff conditions, good communication between staff and between the layout and managers, accessibility, minimized space requirements, minimized use of capital, long-term flexibility, and a good image [1]. The flows of persons, materials, and products are an important consideration in facility layouts.

The relevance of flows of person, materials, and products increases the complexity and number of variables for FLD significantly. Thus internal logistics is one of the key areas when referring to facility layouts. This chapter presents an analysis of methods for optimizing the flow of materials and products, and the way these flows can limit the production of goods and the design of effective facility layouts. However, flows of persons, materials, and products are definitely not the only ones dictating or restricting the design of facility layouts. Effective facility layouts should provide a well-balanced relationship between the objectives of the organization, products, raw materials, equipment, and labor. Layouts should enable customer satisfaction, cost minimization, and a comfortable environment [26]. Common objectives of facility layouts are manufacturing production adaptability and effective use of people, equipment, and energy while minimizing lead time, space, and cost and maximizing the safety of users and convenience of operations [19].

Some of the common reasons for pursuing optimized layout designs are inefficient operations such as high production costs and bottlenecks, inefficient internal logistics and storage systems, short- and long-term adaptation processes without overall long-term thinking and planning, and lack of floor space. Normally it is not easy to achieve a high score in all these objectives. Therefore, optimal solutions are not usually possible or guaranteed. Any one of several good optimized solutions can offer a good balance between the objectives. However, compromising some of the objectives to achieve others is often necessary.

One of the first steps when working with FLD is the selection of the type of the layout. There are four basic types of layout [19]:

- Fixed-position layout
- Process or functional layout
- Group technology or cell layout
- Line or product layout

A classification of the different layout types to be used in different process and service types is presented in Table 2 [1]:

Table 2. Alternative layout types for each process type [1].

Process type	**Potential layout type**		**Service Process type**
Project	Fixed-position layout Functional layout	Fixed-position layout Functional layout Cell layout	Professional Service
Jobbing	Functional layout Cell layout		
Batch	Functional layout Cell layout	Functional layout Cell layout	Service Shop
Mass	Cell layout Product layout		
Continuous	Product layout	Cell layout Product layout	Mass Service

The selection of the proper facility layout is strongly correlated to the flow of the operations, mainly volume and variety. For example, flow is not a major problem when there are low volumes of products and relatively high variety; however, if both volume and variety are high, a trade-off solution is usually required.

For example, consider high volume food production, in which the most suitable layout is a continuous flow or line layout. In this case, the products usually have a low unit cost which allows equipment specialization. When more product variants have to be manufactured while maintaining high volumes of products, cell layout is commonly considered. Some different connections have to be considered to handle the increased number of product variants, with some specialized stations or processes for different products. When the number of different variants or products increases, a functional layout allows a high product mix and high flexibility. This usually decreases the utilization of facility floor and increases the complexity of the flows. Finally, when the number of products is low and the variation is high (as in aircraft manufacture), fixed-position layouts are commonly considered. This allows a very high product mix and flexibility. This last option usually increases unit cost, the scheduling of activities and space become quite complex, and may require intense moving of staff and equipment.

However, it is common for different areas or departments on the shop floor to have different requirements or necessities. Therefore, a combination of different production layouts is common. From case to case, even in different manufacturing systems with similar product families, the layout distribution can be dramatically different, depending on the interconnections of the systems and the individual flows of products and materials.

Krishnan et al. present an additional classification of facility layout design: robust layouts [27]. Robust layouts are able to address multiple production scenarios depending on uncertainties, and are classified into single or multiple time periods. According to the same authors, other classifications are redesign layout, redesign layouts subclassified for various time horizons, and multiple layouts, that can address multiple production scenarios in various periods [27]. This classification aims to consider long-term variation in layout designs. For example, layouts may have to capable of handling peaks in production before production is stopped for vacation, normal production, and low production during the summertime.

In this thesis, the focus is on robust and dynamic layouts that can handle all the peaks of production during the year and are able to adapt to future defined scenarios. These could include, for example, a 20% increase of production in five years' time. The focus is therefore on the worst-case scenario, peak production, but also considers the feasibility of the layout in case of drastic production reduction. Drira et al. [15] present a complete classification of the layout problem. They surveyed facility layout problems and suggested a general framework to analyze the literature in the area and existing solution approaches [15]. They present a remarkable tree representation of facility layout problems with resolution approaches, constraints, objectives, layout formulations, material handling systems, manufacturing systems, and facility shapes [15].

Moslemipour et al. [28] wrote another remarkable review article regarding the design of dynamic and robust layouts in flexible manufacturing systems. They classified and analyzed the different solution methods such as mathematical approaches, and hybrid algorithms. A summary of the methods used for FLD is presented in the following subsection.

2.2 METHODS FOR FACILITY LAYOUT DESIGN

Due to the formulation of the problem, FLD is considered to be an NP-hard problem and optimal solutions are nearly impossible to achieve [29]. The minimization of utilized space, distance between departments, material handling cost, work-in-progress, and lead times for effective flows of materials, products, and persons are common objectives for FLD.

There are several approaches to finding a trade-off solution for suitable facility layout designs. A common traditional approach is systematic layout planning as presented by Muther [30]. Several more recent automated approaches are based on this approach. These include Apple's plant layout procedure; Reed's plant layout procedure; exact methods such as branch and bound, cutting plane, and dynamic programming; intelligent approaches such as genetic algorithms, Tabu search, simulated annealing, ant colony optimization and fuzzy systems; and hybrid algorithms [1, 28, 31].

Until recently, two approaches have been commonly used to find optimized solutions in facility layout problems, namely the quadratic assignment problem approach and the graph-based method [29]. The quadratic assignment problem approach focuses on minimizing the traffic intensity between departments on the shop floor, while the graph-based method primarily focuses on maximizing the adjacency of departments. This last method has been commonly used as a basis for more advanced computerized FLD procedures. They are explained in the following subsections.

GRAPH-BASED TRADITIONAL METHOD

In the graph-based method, the number of areas or departments to be included in the layout design and their area and shape requirements are first defined. Then fixed constraints on the layout are also defined (e.g., immovable areas, facilities, or departments), and the degree and direction of the product flows (e.g., number of journeys, loads and cost of flows per distance traveled). Finally, the desirability of departments or areas being closer, or together, or close or together with other fixed parts of the layout (e.g., doors, buildings, and installations) is included [1]. A flow record chart and an activity relationship chart are usually used when determining the number of departments, their areas or surfaces, and the distances between them. The information in these charts is usually obtained by surveys or communication with the persons responsible for each area. An example with ten different departments (A–J) is shown in Figure 4.

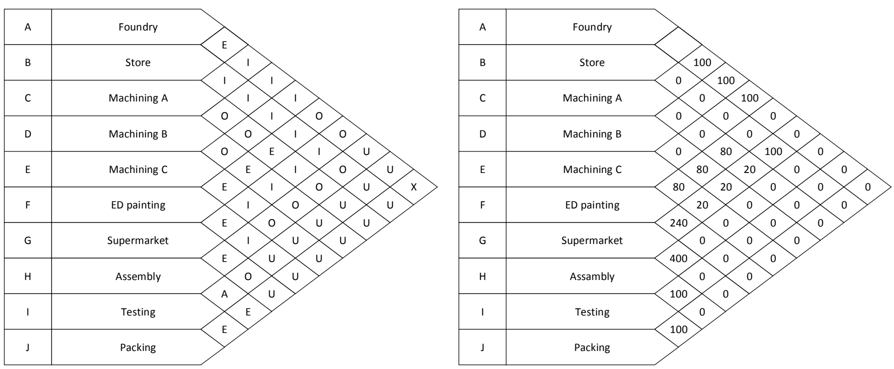

Figure 4. Example of activity relationship chart and flow record chart for FLD.

The left part of the figure represents a classification matrix of the relationships between departments. The importance of adjacency between departments is determined on the basis of the following criteria:

- A – Absolutely necessary
- E – Especially important
- I – Important
- O – Ordinary closeness acceptable
- U – Unimportant
- X – Undesirable

This classification can be customized depending on the size and nature of the facility. On the right, a similar chart shows the volumes of material or product flows between departments, in this case the number of pallets transferred per month. Alternative, the chart could represent the number of trips between departments per time period (hour, day, or week). Mileage charts or from-to charts can also be used for this purpose. Using this information, traditional approaches try to maximize the value of effectiveness of the layout with the following formula [1]:

$$\text{Effectiveness of the layout} = \sum F_{ij} D_{ij} \qquad \text{for all } i \neq j$$

where F_{ij} is the flow in loads or journeys per period of time between departments, from center i to center j, and D_{ij} is the distance between departments from center to center.

One way to represent these charts is to draw a schematic chart, in which every department is represented by a dot or circle and the flows between different departments are represented by lines connecting the dots. Additional classification can be applied. For example, non-existence, low, medium, and high flows of products or materials can be represented by lines with different thicknesses or different patterns, as shown in Figure 5.

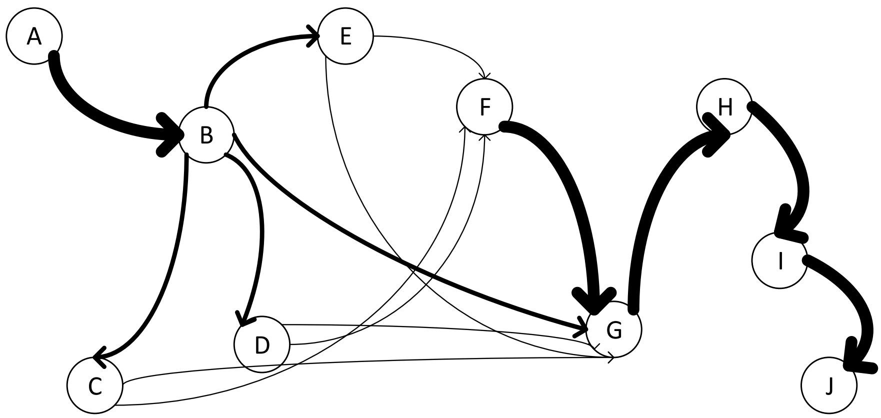

Figure 5. Example of schematic layout chart.

Figure 5 presents the same information as Figure 4 on the right. The flows between departments are represented by arrows of different thickness. Using common sense, the above chart can then be reorganized, trying to minimize the length of the thickest connections while trying to be realistic in terms of the area and shape of the facility and the considered departments. One possibility is shown in Figure 6.

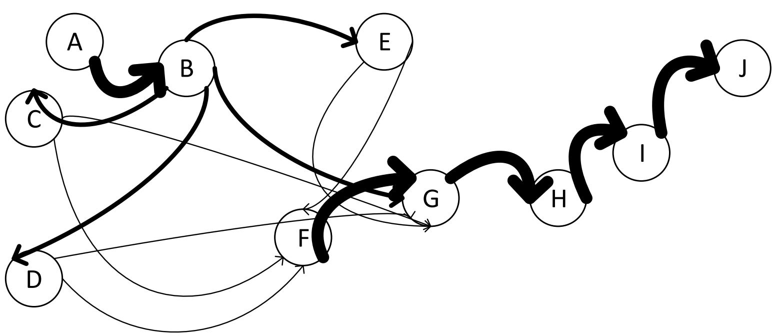

Figure 6. Reorganized schematic layout chart.

The next natural step is to substitute the dots representing the departments with squares or rectangles representing the shape and size of the departments considered, as can be seen in Figure 7.

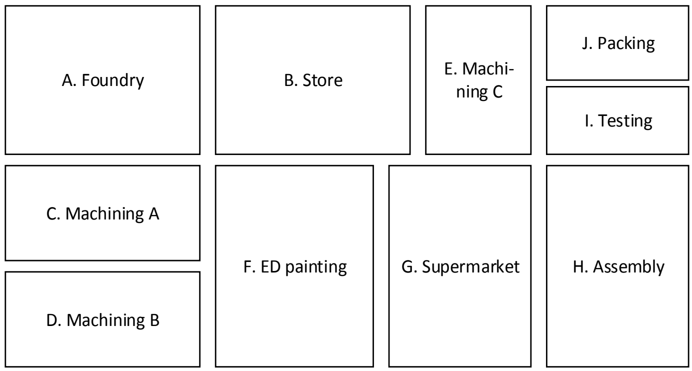

Figure 7. Adjusted facility layout obtained from the reorganized schematic chart.

This figure shows the distribution of departments in the current facility layout. The surface and shape of the original layout were respected, and the departments were located with the knowledge obtained from the reorganized schematic chart taking into account the approximate surface area necessary for every department. Finally, in the testing stage, the layout configurations obtained should be validated to ensure they are feasible taking into account all the necessary aspects (such as strategic objectives, products, market, production, and decision interrelations). This graph method has evolved considerably as a basis for computerized optimization of facility layouts. The most relevant methods are summarized here below.

COMPUTERIZED METHODS

The combinatorial complexity of manufacturing facility layouts has given rise to the development of several computer-based heuristic procedures to aid the design process. These include CRAFT (computerized relative allocation facilities technique), which is a simulation method to generate layout designs based on a pairwise exchange method improvement algorithm. It starts with a predefined layout design and proceeds to find better configurations by minimizing the distances between departments. CRAFT does not search for optimal solutions, but it might find one by chance. Usually, this type of computerized heuristics technique focuses on the reduction of material handling costs, omitting or underestimating production aspects such as machining and assembly line limitations, storage and buffer capacity and location, and long-term changes or adaptations of the facilities. Although CRAFT is the most popular tool for the design of industrial layouts, the results are usually limited to designs showing only the minimum total transfer cost between departments [32].

More advanced versions of CRAFT, such as Micro-CRAFT or MCRAFT, allow non-adjacent exchanges. However, management of constraints and requirements is still one of their main limitations. MCRAFT allows non-adjacent and unequal department exchanges for the design of optimized layouts. However, unmovable departments or obstacles in the layout cannot be defined, and there is no consideration of non-rectangular shapes of departments. Other procedures such as BLOCPLAN and LOGIC provide a combined approach to improvement using a construction algorithm. However, they still cannot handle constraints and non-rectangular department shapes, and they cannot be customized when the complexity of the system is considerable.

Some authors who have reviewed facility planning and plant layout design [10, 15, 33] mention potential work on risk and accident analysis and reduction. Other authors have recently analyzed different approaches such as exact methods, intelligent approaches, hybrid algorithms, multiple attribute decision-making methods, and a combination of intelligent computational techniques: clustering, genetic algorithms, and ant colony algorithms [31, 34]. Wanniarachchi et al. propose a framework that simplifies the facility layout planning and data collection process for food processing facilities [35].

Kia et al. use simulated annealing and genetic algorithms to analyze the layout design of a dynamic cellular manufacturing system with alternative process routing and lot splitting [36, 37]. Simulated annealing and genetic algorithms can be used for layout construction, but are more common for layout improvement. The fundamental concepts of simulated annealing are based on using the analogy between statistical mechanics and combinatorial optimization problems, based on the concepts of gradient and lowest energy points, to find optimal solutions related to the search space and objective functions [19].

Genetic algorithms, on the other hand, are based on a survival of the fittest approach, evaluating the characteristics of a population (optimization objectives) and generating candidate solutions using combinations of the population. These candidates are generated by combining parents (two individuals from the existing population) and randomly crossing the characteristics of both parents to obtain two offspring. These offspring become part of a new population from which the best candidates are selected. In addition to this cross over, mutation is also commonly applied randomly to some of the individuals in the population. Similarly, the concept of elitist reproduction is also commonly applied in genetic algorithms to automatically copy the best 10% to 20% of the individuals to the next population [19]. The main limitation of genetics algorithms is the computing power required to evaluate the large number of solutions generated when the size and complexity of the system is considerable. Parallel computing is often used for its implementation [19].

Azadeh et al. present an integrated fuzzy simulation-mathematical programming approach for layout optimization of a maintenance workshop in a gas transmission unit, taking into account resilience engineering factors [38]. Their integrated fuzzy simulation approach was considered for the development of the FLD methodology in this thesis. Zhang et al. present interesting research on finding the optimized locations of warehouses on the shop floor, taking into account production planning [39]. They used a mixed-integer linear programming model with the objective of minimizing the cost of production and warehouse operations [39]. Derhami et al. presented an SBO with DES for the design of block stacking warehouses, determining the number of aisles and cross-aisles, bay depths, and cross-aisle types in a beverage industry [40].

Pongamorn Wangta and Pupong Poncharoen compared Tabu search and simulated annealing algorithms for non-rotable and non-identical rectangular machine layout design in multiple rows to minimize the traveling distance for a material handling system [41]. They concluded that while the Tabu search performed up to 50% faster, the solutions obtained from simulated annealing were marginally better.

Semih Önüt et al. present a particle swarm optimization algorithm for multiple-level warehouse layout design in which the design of shelves and storage spaces is defined with the objective function of minimizing the distance of picking and putting away the palletized products [42]. Alan R. McKendall Jr. and Wen-Hsing Liu also present an improved Tabu search heuristic for the dynamic space allocation problem, assigning maintenance activities and their required resources to workplaces and storage locations at a nuclear facility [43]. Their improved method outperformed other heuristics in the literature. Shanshan Zha et al. also propose a hybrid particle swarm optimization and simulated annealing algorithm to solve the unequal-area dynamic facility layout problem [14, 44]. They tested their approach using some test problems as well as a new aircraft assembly shop floor taking into account material handling costs. In a more recent paper, they tested a multi-criteria decision-making method for facility layout selection in manufacturing. Their method integrates Delphi, fuzzy set theory, ANP, Entropy, and the PROMETHEE II method [44]. They tested their approach in an aircraft assembly workshop, applying different weights to the variables and objectives.

Id Jithavech and Krishna Kumar Krishnan present an interesting mathematical approach with simulation of risk assessment under stochastic product demands [45]. They analyze the instances of the departments and the flows between them to perform the facility layout risk assessment with a genetic algorithm, taking into account possible changes in the flow intensity. Kar Yan Tam presents a coding scheme for facility layout with slicing trees using genetic algorithms taking into account shape and area constraints, an improved CRAFT method [46]. He states that according to [19], CRAFT, CORELAP, and ALDEP allow specifying facility shapes.

Sanli and Eldemir present the construction and improvement of a facility layout heuristic, spiral facility layout generation and improvement (SFLA), based on the concept of the CRAFT heuristic procedure for FLD. They compared it with existing layout design methods such as MCRAFT and MULTIPLE [29]. Their approach focuses on locating the most related departments in the center of the facility layout to reduce the distances between departments and facilitate material handling. However, they concluded that there is no clear difference between SFLA and MCRAFT, the upgraded version of CRAFT. To complement these tools, some authors added simulation techniques to the FLD approach, adding more information to the layout designs.

Smutkupt and Wimonkasame present an approach for the design of plant layouts based on CRAFT and supplemented with Microsoft Visual Basic routines to obtain the best plant layout [32]. They then used the Arena simulation software tool to complement this design with production information such as product lead time, waiting time, and machine utilization.

Several approaches in the literature focus on reducing the cost of material handling. Shah et al. state that traditional optimization methods are impossible for FLD when taking into account capacity and logistics constraints [47]. This task can become even more tedious task when the size and complexity of the system are considerable, and especially when the system's behavior is considered to be dynamic in terms of changes in product demand and mix.

Balamurugan et al. propose an interesting mathematical approach for the economic evaluation of the compactness of optimal facility layouts taking into account material handling, breakdown of machines, and unusable space on the shop floor [48]. Their proposed approach was also considered for the development of this thesis. Jiang and Nee present a novel methodology for FLD with augmented reality tools developed in a software tool for fast three-dimensional modeling [49]. They consider space utilization and distance minimization or maximization as well as customizable constraints, such as material handling and personnel costs in existing facilities. Their solution approach was drawn on in for the development of the steps of the methodology in this research.

In summary, different types of facility layouts and methods have been analyzed. Most of the algorithms presented here were developed as part of research projects. Some commercial packages are available for layout design; however these packages are intended for representation purposes only (based on the methods presented here), or are designed as evaluation tools [19]. The complexity of manufacturing systems often makes mathematical modeling challenging, especially when the number of variants, variability, and stochastic behavior are considerable, thus underlining the importance of DES [50]. Due to the size and complexity of the facility layouts considered in this thesis, a combination of some of the above facility layouts and approaches is necessary to find trade-off solutions. The main approach in this thesis is based on genetic algorithms, which have more recently been applied to facility layout problems. These algorithms use a survival of the fittest approach, commonly used in decision-making, optimization, and machine-learning problems [19]. From now on the focus will be on computer simulation techniques such as DES complemented by SBO.

2.3 DISCRETE-EVENT SIMULATION IN FACILITY LAYOUT DESIGN

FLD is a crucial task in the development of allocation plans for machines and equipment on the facility layout of manufacturing systems [11]. Traditionally, this has been done using mathematical modeling approaches such as mixed-integer programming and the quadratic assignment problem model [11]. However, when the size and complexity of the system are considerable, FLD problems can be intractable for mathematical approaches without simulation and optimization [11].

Some authors state that optimized FLDs can save up to 50% of the total operating costs [19]. Simulation can be one of the key approaches in finding the best optimized solutions [51]. Simulation is the imitation of the operation of a real-world process or system over time. “Whether done by hand or on a computer, simulation involves the generation of a model or artificial history of a system and the observation of that artificial system to draw inferences concerning the operating characteristics of the real system” [4]. During the 21st century, simulation started to be a key technology to support and improve manufacturing systems. Simulation has considerable potential for production flow development and improvement [52].

The availability of special-purpose simulation languages, the massive computing power at a decreasing cost per operation, and the advances in simulation methodologies make simulation one of the most widely applied and accepted tools in operations research and system analysis [53]. Simulation models are usually analyzed by numerical methods instead of applying analytical methods. “Analytical methods employ the deductive reasoning of mathematics to ‘solve’ the model; numerical methods employ computational procedures to ‘solve’ mathematical models” [53].

Today there are different techniques for process improvement with different applications for a variety of more specific purposes, such us process improvement, design, or feasibility studies. Some examples of process improvement approaches are linear programming, Markov chain analysis, DES, system dynamics, Monte Carlo simulation, value stream mapping (VSM), and some other Lean approaches. It has been demonstrated that simulation techniques are the most suitable approach for process improvement of complex systems with high variability; the variability and difficulty of the processes within complex systems demand the analytic power of DES [51]. When the complexity and variability of the system increases, DES is often necessary to model and represent the complex and stochastic flows in manufacturing systems. Manufacturing systems are often too complex to be modeled mathematically, highlighting the importance of DES [50].

Almost all systems can be categorized as discrete or continuous. Few of them are entirely discrete or continuous, but usually they are classified according to the predominant category [54]. An event is a change in the system state. When the state variables of a system change only at a discrete set of points in time (which may occur at random time points), the system is considered a discrete system [53]. The discrete set of time points are known as event times [4]. A simulated clock, provided by the simulation software, records the time points at which events occur on a DES.

One of the highlighted characteristics of DES are "what-if" questions. These questions allow the creation of "what-if" simulation scenarios, representing variations of existing systems, making system analysis possible without disturbing the existing system. New alternatives, ideas, systems, and procedures can be tried out without disturbing the real system, or can be developed even before a system is constructed [4].

As shown in Figure 8, a DES simulation project usually consists of several steps [4] that have to be carefully performed during the building of the simulation model in order to obtain an accurate model providing accurate results.

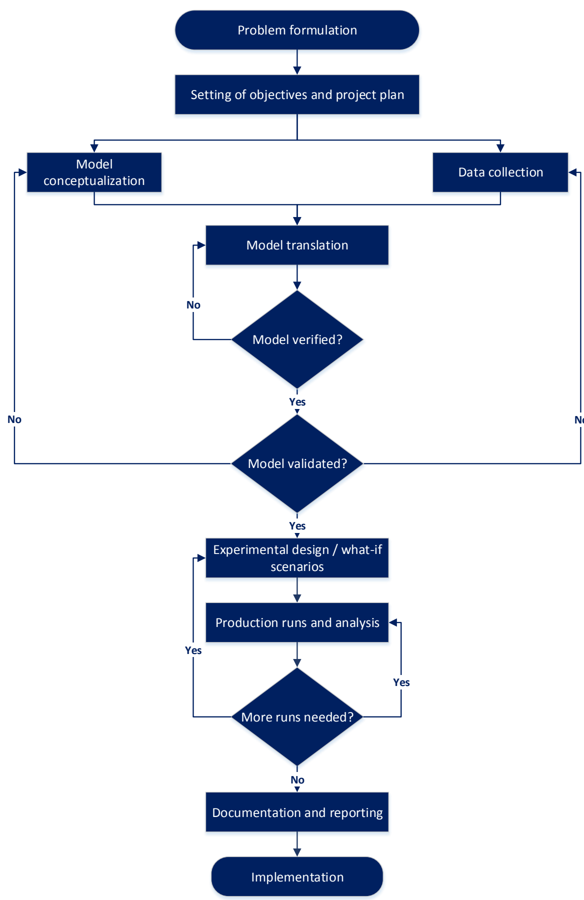

Figure 8. Simulation steps [51].

The flowchart in Figure 8 shows that the first step in building a simulation model is to have a clear problem formulation. The problem should be perfectly understood by the client and the simulation analyst. It is then possible to start setting objectives and the overall project plan. The objectives should be the answers that will be obtained by implementing a specific simulation project. If simulation is the appropriate approach for the project, an overall project plan is needed to study how the project will be developed and implemented depending on the available resources and time. Another consideration is whether the model will be used in future for other specific studies of the same system; if so, other processes or resources may need to be taken into account when developing the model.

Once the problem, objectives, and project plan are clear, it is possible to start with the next steps: model conceptualization and data collection. Both of these steps are key to creating a good model to obtain accurate results. "The art of modeling is enhanced by an ability to abstract the essential features of a problem, to select and modify basic assumptions that characterize the system, and then enrich and elaborate the model until a useful approximation results" [53]. The data collection step usually needs more time to be performed. Time studies may be needed, and time standards may need to be applied to different processes to obtain accurate data from each part of the real system.

Model construction can start once the required data have been collected and the conceptual model of the system is clear. Construction consists of translating the conceptual model into a computer language using a simulation software tool. This model has to represent all the key factors that need to be considered. Once the models have been built and are working properly, they have to be verified and validated. These two processes ensure that a simulation model accurately represents the system. Verifying the models means checking that everything represented in the model is done correctly. Validation is checking that the behavior of the model represents reality accurately; for example, checking that simulated processes take the same time as real processes.

Once the model has been verified and validated it can be analyzed and possible weaknesses and potential improvements of the system can be determined. Finally, when the obtained results are satisfactory, they can be presented to decision-makers and stakeholders to serve as a decision support system.

Several authors have described the use of DES for the modeling facility layouts. For example, there is a study to design the facility layout of an automotive part manufacturer taking into account operation processes [55], a decision support system for supply chain configuration [56], and a DES model of a repair facility layout to optimize production [50]. Their studies aim to decrease the length of material flows and their effect on material handling cost, labor, and throughput. Some other authors have used simulation to assess risk in the FLD process under stochastic situations of product demand [45], for assessing innovation deployment readiness in manufacturing [57], and to support the plant layout design process [32].

DES can be a good approach for the construction of a detailed model for facility layout design when the complexity (number of variables) or size of the system is considerable. The customizability of simulation software tools make them easily adaptable to different systems. When the standard libraries are not enough for a high level of customization, programming options are usually available in many of the most common simulation software tools.

The results of specific what-if scenarios can be obtained using DES. However, when several what-if scenarios are considered, increased amounts of time and resources may be needed. Combining simulation and optimization into SBO improves the search for optimal or nearly optimal solutions when the number of possible scenarios or possible combinations of a system is significant. A literature review SBO in production and logistics systems taking into account FLD is presented in the following subsection.

2.4 FACILITY LAYOUT DESIGN WITH SIMULATION AND OPTIMIZATION

The size and complexity of production and logistics systems today require the use of simulation for their design and improvement. However, when the number of possible solutions to be analyzed is significant, generating hundreds or thousands of individual scenarios can be a tedious task. Integrating simulation with optimization is thus a promising approach for system design and improvement.

When multiple objectives are simultaneously considered, SBO is the most promising approach for it facilitates the search for trade-offs between several conflicting objectives [58]. Simulation by itself is not an optimization tool; therefore the combination of simulation and optimization is considered when several possible combinations of the system are analyzed. In operations research, simulation and optimization have traditionally been considered to be different approaches [59]. Integrating simulation and optimization enhances the use of the detailed system behavior of simulation with the ability of optimization to reach optimal or close to optimal solutions [59]. It has been demonstrated that the combination of optimization and simulation tools allows decision-makers to quickly determine optimal system configurations, even for complex integrated production facilities [51].

Different optimization methods can be used in combination with simulation depending on the type of problem. Several options are presented by Figueira and Almada-Lobo [59]. Metaheuristic optimization is a flexible approach to examine any solution space and is characterized by quickly achieving good quality solutions. It has therefore usually been used in combination with DES [59].

As mentioned in the introduction, common problems that characterize manufacturing systems are the large number of automated and manual processes, the large number of family of products and variants, the high variability of processing times, the capacity and location of storage and buffers, space constraints, the need for specialized resources, and dependence on external suppliers. To approach these problems, Amos et al. proposed the design and analysis of factory flows with SBO and automatic model generation. They also present some papers about bottleneck and production system analysis using this method [60-62].

Yang et al. analyze the design of a Lean production system supported by SBO [63]. Lean philosophy involves never-ending efforts to eliminate or reduce waste or any activity that consumes resources without adding value in design, manufacturing, distribution, and customer service processes [3]. Some authors have used the Lean approach to design facility layouts of production systems to improve overall efficiency [64]. Roser et al. summarize a combination of methods for a holistic manufacturing system analysis using bottleneck detection and buffer optimization [2]. Their research was developed by the Toyota Central Research and Development Laboratories to detect bottlenecks and shifting bottlenecks, based on a holistic analysis of machine working times and buffer times. One of the papers appended to this thesis is by Goienetxea Uriarte et al. presents an approach using simulation, optimization, and Lean to improve the material flow of a manufacturing company [65].

Internal logistics can be considered as the transports necessary to maintain the material flows by feeding the storage, machining, and assembly areas of a manufacturing system. One of the main objectives of FLD is to design effective workflows to make equipment and workers more productive [11]. Internal logistics is a key aspect contributing to effective workflow. As previously mentioned, material handling costs are usually considered a measure of the effectiveness of layout design. According to some authors, handling costs can represent from 20% to 50% of total operating cost, and 15% to 70% of total manufacturing costs [19].

Xiaomei Hu presents an interesting paper regarding a workshop layout optimization algorithm based on particle swarm optimization and simulated annealing and used to optimize the layout of equipment taking material handling cost and distances between equipment into account [66]. A relevant paper including plant layout design and production planning by Zhinan Zhang et al. presents a framework with a simulation-based approach integrating mathematical algorithms and heuristic methods to balance operational performance and planning cost [20]. Their approach and framework, systems architecture using simulation-based lean layout, and production planning have contributed to the development of the methodology in this thesis.

Some other papers are focused on more specific aspects of internal logistics. For example, a heuristic solution procedure was developed by Golz [67] to minimize the required number of drivers for in-house shuttle trips between parts storage and delivery areas in an automotive factory. In another study in the automotive sector focused on logistics, Wenping et al. [68] consider the optimization of a mixed-model assembly line. Battini et al. [69] also define an interesting approach to parts and component management by optimizing the degree of centralization in warehouses, minimizing storage costs, and choosing the right feeding policies.

A well-known problem of internal logistics is the part feeding problem, delivering the necessary parts, at the right time, to different locations, with the appropriate transportation methods through the facility layout. The part feeding problem has been widely studied in manufacturing sectors and especially in the automotive sector. For example, automotive part logistics has been deeply studied and analyzed by Boysen et al. [70, 71]. Ziarnetzky et al. [72] have an extensive literature review and description of the different logistics types, in which they analyze an aircraft assembly line simulation model using DES.

Very little of the literature related to the line feeding problem includes appropriate in-house transportation methods and routing as well as different types of production lines (with different automation levels). One of the closest papers involving these three principles is that of by Battini et al. [69], who introduce the line feeding problem and analyze different solutions for optimally locating logistics areas to facilitate just-in-time supply of mixed-model assembly lines. However, they do not consider different production methods for different lines, or the facility layout design itself.

The part feeding problem has also been analyzed by the mentioned Golz et al. [67]. They divide this problem into the planning of the transportation orders and the assignment of those orders to the shuttle system subject to transportation capacity restrictions. They mention that the main objective in feeding the parts to the production line is to ensure the efficiency of the logistics processes. They state that one of the key problems according to the just-in-time principle is retrieving the parts in their respective containers from a central storage system and assigning them to the designated assembly locations, with the proper transportation route. Exact timing of the material supply is of utmost importance to avoid interruptions in production.

Emde and Boysen [73] summarize the problem of locating the logistics areas optimally to facilitate just-in-time supply of mixed-model assembly lines. They point to the ever-increasing challenge of feeding mixed-models production lines due to the ever-rising product variety in modern manufacturing systems. They also propose a mathematical model with an exact dynamic algorithm to analyze the pros and cons of the supermarket concept.

The concept of supermarket can be defined as a decentralized in-house logistics area close to the assembly lines that serves as immediate storage for parts delivered with a just-in-time approach [73]. Faccio et al. [74] provide a framework to design the supermarket and feeding system for automotive mixed-model assembly lines. In their case, the decision to choose a central kitting area to supply all the production lines was based on the amount of available space on the shop floor. They analyzed both the option of having dispersed storage areas to feed the lines located close to each production line, or having a central storage supermarket area. It was demonstrated that a centralized supermarket would free much more space, especially at the production lines, and would drastically reduce the traffic around the production lines where operators usually have to walk. Many manufactures around the globe are adopting this supermarket concept to supply parts to assembly lines.

Emde et al. [73, 75] defined the location of in-house logistics on the shop floor to facilitate materials flows. They developed an exact solution for the optimal scheduling and routing of transportation with tow trains between a central supermarket storage and the assembly lines in the automotive industry. Some other authors have proposed similar solutions for in-house logistics, such as Zhang et al. and Nourmohammadi et al. [39, 76]. However, simulation and optimization of this kind of production and internal logistics system were commonly implemented independently and often assume static systems. That might lead to non-optimal results in cases in which high variability of demand products and variants is significant.

Some authors have used SBO to optimize production and logistics systems as a whole. Some have used mathematical modeling, such as Petri nets [12, 77]. Heilala et al. present two case studies in which they applied an ongoing and interesting modeling and simulation project of manufacturing system design including operation planning, programmable logic controller (PLC) code validation, distributed simulation using high level architecture (HLA), and value network analysis. However this case is more focused on real-time production planning and connection to the enterprise resource planning system, not layout design [78]. Bortolini et al. present a general framework for assembly system design in the Industry 4.0 era [79]. Their framework was considered for the FLD methodology presented in this thesis.

Some other authors have analyzed how simulation combined with optimization techniques can improve production and material handling systems [51, 52, 60, 80]. As previously mentioned, many of the relevant papers are related to the automotive sector. Different automation, production, and logistics methods in the manufacturing sector and their main characteristics and limitations were analyzed in depth by Groover [81].

F. Azadivar and J. Wang present a FLD approach with simulation and optimization taking into account dynamic characteristics and qualitative and structural decision variables [82]. They consider operational policies, resources, and time requirements such as production rate, cycle time, number of transports, and machine capacity to overcome the limitations of traditional methods focusing on material handling cost reduction, with the objective of reducing cycle times. Pourhassan et al. used an SBO approach for dynamic facility layout planning with internal logistics with a validated case study [11]. They constructed a simple simulation model of five machines to test their technique and used the NSGA-II algorithm for optimization. Their computation flowchart and SBO approach were considered for the analysis of the optimization parts of this thesis.

Yi-Shan Liu et al. present an interesting methodology for FLD of a TFT-LCD module cell with simulation and fuzzy multiple attribute group decision-making. [83]. Shah et al. present a methodology with heuristics and simulation for the design of facility layout design with dynamic constraints of product demands and material handling requirements for each time period [47]. Their proposed methodologies were analyzed for this thesis.

One of the most relevant papers for the development of the FLD methodology presented in this research is by Kikolski and Ko [84]. They present a methodology for the facility layout problem taking into account basic optimization methods for the distribution of workstations on the shop floor, depending on the application studied. Their methodology consists of a description of stages and activities to describe how to optimize the design of workstations, including a set of methods to be applied depending on the characteristics of the manufacturing processes considered.

All these methodologies, approaches, or techniques were taken into account for the construction of the FLD methodology presented in this thesis. Several challenges are commonly associated with the use of simulation and optimization in facility layout design. The literature survey found many challenges when working with DES and SBO. A list of challenges found in several case studies was compiled and is presented in the next section.

In summary, there are no cases in the literature with a methodology with DES and SBO applied together to design optimized facility layouts taking production and logistics systems into account, even while industry is becoming more highly collaborative, globalized, customer-oriented, eco-efficient, and knowledge efficient [20]. In most of the analyzed papers some of the problems mentioned above are addressed specifically, sometimes analyzed from an overall perspective, but few of them include facility layout design, internal logistics, and production systems. In the following subsection, a list based on the analyzed papers summarizes the theoretical challenges of using SBO for FLD.

2.5 THEORETICAL CHALLENGES OF SIMULATION-BASED OPTIMIZATION AND FACILITY LAYOUT DESIGN

This subsection summarizes two lists of challenges when working with FLD and SBO. These challenges are presented based on results in appended paper 5, *Challenges of Simulation-based Optimization in Facility Layout Design of Production Systems*. The challenges classified as theoretical in the literature review are presented in Table 3 and Table 4 regarding FLD and SBO in FLD. Another list of empirical challenges identified in two in-depth industrial case studies will be summarized in Table 9 of chapter 3, together with a brief introduction of the case studies. Table 3 lists the theoretical challenges when working with FLD.

Table 3. Challenges affecting facility layout design reported in literature.

Challenges inherent in the nature of facility layout design	
Complexity	Much of the existing layout literature relies on simplifications to represent the interrelation of elements in a production system [31, 78].
Dynamicity	It is difficult to represent the consequences of changing material flows resulting from product diversity and demand in FLD [10, 78].
Randomness	The stochastic nature of production systems may not be accurately represented in FLD [38].
Simultaneity	Problems in FLD are addressed simultaneously instead of sequentially [85].
Challenges affecting resources supporting facility layout design	
Cost	Justifying a new FLD depends on demonstrating an increase in competitiveness that exceeds the high cost of implementation [47].
Integration	Difficulty integrating different information sources to provide a quick response when evaluating alternative layouts [78].
Process	Relying on individuals instead of standardized processes for FLD [78].
Safety	Favoring operational performance over human and safety factors [10].

The table shows that complexity, dynamicity, randomness and simultaneity are challenges in manufacturing systems. These challenges significantly affect the resources involved in this kind of FLD layout project. The cost of changes like vertical and horizontal integration and improved performance can be difficult to justify.

Table 4. Challenges affecting simulation-based optimization reported in literature.

Challenges inherent in the nature of simulation-based optimization	
Complexity	Translating practical problems into explicit mathematical formulations, understanding the interaction, conflicts, trade-offs of objectives, determining conclusively the primacy of a solution in a stochastic system, capturing essential production processes with sufficient detail [86] .
Noise	Dealing with imperfect estimates in a stochastic simulation [86].
Search	Locating and distinguishing between local and global solutions, or determining the limits of a solution space [86, 87].
Evaluation	Failing to recognize an optimal solution, the primacy of input values or decision scenarios [87].
Challenges affecting resources supporting simulation-based optimization	
People	Lack of understanding or technical competence in the use of simulation and optimization [87].
Process	Deficiencies for changing routines and processes related to SBO including simulation processes, modeling standards, or integration of SBO in production system design [86].
Technology	The nature of SBO makes it hard to determine its potential benefits, generating doubts about its use [87].

Table 4 shows that when using SBO in FLD, there are also important challenges in terms of complexity, noise or variability, the search for near-optimal solutions, and limitations when evaluating the proposed solutions. The challenges of using SBO in FLD may change over time and may depend on understanding and technical competence in the use of SBO. High complexity, noise, and a lack of knowledge and competence for its implementation and the evaluation of the results are commonly identified issues.

Due to the high degree of complexity, variability, and stochastic behavior of the systems in consideration, this thesis is based on simulation and optimization with DES modeling. As there is no current methodology to overcome these challenges with simulation and optimization for the design of facility layout, the aim of this thesis is to create such a methodology. The proposed methodology is presented in the next chapter.

FACILITY LAYOUT DESIGN METHODOLOGY WITH SIMULATION-BASED OPTIMIZATION

CHAPTER 3

FACILITY LAYOUT DESIGN METHODOLOGY WITH SIMULATION-BASED OPTIMIZATION

In operations management, the term “research process” refers to the systematic gathering of evidence by following clear steps with the aim of analyzing a system and reaching some kind of scientific conclusion [88]. In this industrial thesis, these steps have involved both the development of scientific research on the academic side and development with the main partner in this project on the industrial side. Therefore, a challenging aspect of this research was to avoid losing track of which steps to follow and getting into loops taking too much time or effort on one side or the other. Some basic steps were followed, some more focused on one side than on the other, and some on both sides. These steps were identifying the research gap correlated to the industrial gap, definition of the objectives and preliminary project plan, deciding on the research approach of the thesis, data collection and analysis, the identification of key performance indicators and the paradigm of Industry 4.0, and the development of empirical case studies regarding process, flow, and layout optimization.

Starting with the industrial gap, the aim of this industrial PhD thesis as identified by the main partner was to support the development of production and logistics flows and plant layout. This development involves new parameters for FLD including production and logistics optimization. The development also includes the implementation of changes in the existing facility of the industrial partner, with all the planning problems that this raises. In this initial step, a list of gaps, common assumptions, and references pointing to the need for more research was identified. A summarized list is presented here:

- Several dynamic layout planning methods use from-to charts, focusing on the distances between departments and ignoring material handling and capacity requirements and constraints [47].
- Unlimited capacity as regards material handling and production resources is commonly assumed [47].
- When production capacity constraints and material handling capacity requirements are also considered, traditional optimization approaches are impossible [47].
- A combination of continuous models with dynamic location problems is lacking [10].

- There is a lack of analysis to reduce risks and accidents in industry by taking risk into account as an objective in facility layout design [10].
- It is difficult to work with specific variables in layout designs that change over time [10].
- New methodologies for layout design with optimization for large-scale dynamic problems are not yet in use [10].
- Methods need to take decision variables such as production, inventory, and shipment quantities as well as constraints, requirements, and key performance indicators into account [89].
- There is a need for a quick response tool to evaluate alternatives and scenarios before decisions are made (required for the operational use of DES) [78].
- Manufacturing systems have to be flexible and able to react to changes in production capacity requirements [78].
- A shared base of robust, validated models for all materials and manufacturing processes needs to be developed to enable fast, accurate modeling simulation of any combination of the processing steps [78].
- Methods should be developed to provide the ability to create and apply scalable product life cycle models in every phase of the life cycle and across the supply chain [78].
- There is a lack of general frameworks and algorithms with simulation to guide the process of designing optimized plant layouts and production processes to maximize throughput [20].
- Even though there are algorithms for computer generation of "optimal" or near optimal facility layouts, the implementation of studies in real-world industrial applications is limited [48].

This list of common assumptions, gaps, and limitations of current research in FLD points to a lack of consensus and methodology for FLD, especially when taking into account dynamic conditions and production and internal logistics constraints and requirements. The research aim of this thesis was defined in combination with the technical gap identified by the main industrial partner as being to propose a holistic simulation-based approach for FLD taking into account process, flow, and logistics optimization.

The generalization of this research is an interesting area for manufacturing companies with a long industrial history and tradition without optimized flows in their production systems. This deficit in turn limits future capacity planning and adaptation in production, as well as competitiveness and growth in Swedish industry. The following subsection presents the paradigm on which this research is based and the research strategy followed during the development of this thesis.

3.1 RESEARCH STRATEGY AND PARADIGM

Collaboration between industry and academia has proven to be beneficial for both sides, by creating innovation and technological research useful in industry while at the same time expanding knowledge in the scientific community [5]. A distinction between basic research, applied research, commissioned research, and experimental development should be made here [5]:

- Basic research is experimental or theoretical effort seeking new knowledge about the causes of phenomena without focusing on specific applications.
- Applied research also pursues the acquisition of new knowledge but with a clear practical objective.
- Commissioned research is the extension of applied research. The party commissioning the research has priority access to the use of the research, and controls the development of the research to a higher extent.
- Experimental development does not seek to obtain new knowledge but mainly contributes to practical experience.

Thus the use of technological research, that is, applied research oriented to engineering applications, can be the basis for industrial development. However, the proper and clear formulation of societal or industrial problems can be a limitation on the research if these are defined too narrowly and not associated with simplified and generalized technological problems. In other words, technology-driven development can undertake research without identifying the basic need for improvement. New technologies can find potential implementations to contribute to solving existing problems. In many cases in manufacturing the need for improvement can be identified; however, the tools and methods to contribute to that improvement are not clearly identified.

The research strategy of this thesis is based on the design and creation research strategy, aided by action research for the development of the industrial case studies [90, 91]. Design and creation research aims to develop new IT products or artifacts, such as constructs, models, methods or methodologies, and instantiations [91]. An artifact is something artificial, not naturally created, something made that may be physical or some other form of artificial phenomena [5]. The selection of this research strategy is based on the creation aspect in the aim of this thesis which is to investigate a holistic simulation-based approach for FLD taking into account process, flow, and logistics optimization. However, the research strategy is complemented with aspects of a case study research strategy as the research has to be applicable to the industrial partner. This process follows from established science and scientific approaches in the natural sciences. The new knowledge found in this process is useful for both practice and theory. It is summarized in the form of a methodology that is considered to be the artifact of the design and creation research strategy. The main principles of the proposed research strategy are presented here:

- Design as an artifact
- Problem relevance
- Design evaluation
- Research contributions
- Research rigor
- Research as a search process
- Communication of research

This artifact is based on several analyzed simulation and FLD methodologies. It relies on DES and SBO tools to address the analysis and improvement of different logistics and production systems taking facility layout into account. In manufacturing, simulation has been widely used in feasibility studies and to analyze potential improvements to support decision-makers and increase efficiency [39]. By complementing a design and creation research strategy with a case study research strategy, different areas related to production or logistics at the main factory of the industrial partner have been analyzed with SBO, redesigned, and improved. However, this kind of project can become a pharaonic project if there is a lack of expertise, time, and resources, as is often the case. Despite the increased use of SBO, facility layout design is recognized as a challenging task with a significant impact on manufacturing performance [15].

The FLD design proposed is the artifact outcome of the design and creation research strategy. This artifact is also based on the simulation methodology presented by Banks, Law, Uriarte, and Skoogh [53, 54, 92, 93]. The artifact is validated and implemented in different case studies together with research partners to show the real-world applicability of the methodology. Additionally, the validation is supported by the functional resonance analysis method (FRAM) to identify the critical steps for the application of the methodology in manufacturing.

The research paradigm of this thesis is positivism. Three common research paradigms in engineering and IT are positivism, interpretivism, and critical research [91]. A research paradigm, or the philosophical paradigm of research, is based on the different views about the nature of the world we live in and how it is investigated [91]. A research paradigm can usually be described in terms of its views regarding the following four attributes [5]:

- The nature of reality (ontology)
- How knowledge is achieved (epistemology)
- What constitutes “good” research
- What ethical guidelines apply to research

The underlying strategy for the research reported in this thesis is the design and creation research strategy within the philosophical paradigm of positivism. Positivism can be regarded as representing the traditional scientific approach when research in the social sciences tries to mimic the ideals of the natural sciences [5]. Reality is seen as objective and independent of the observer. The researcher usually looks for cause-effect relationships between different concepts as the basis for predictions [5]. The classification of this research as falling within the positivist paradigm is due to the nature of the problem and the use of mainly quantitative and analytical methods [91]. The choice of this research strategy is based on the creation aspect of the aim of this project. Another reason for choosing this research strategy is the need for methodical documentation of the procedures in the different steps of this project to produce a properly defined and evaluated artifact.

The focus of this research is in applied and quantitative research as the outcome must meet the specific application needs of the industrial partner and also be capable of being generalized to make it applicable to other manufacturing companies and sectors. Quantitative research, that is, research that is numerically based, is strictly necessary due to the nature of the problem and the results in this case. It is based on the data collected through interviews, observations, and time and frequency studies, and on measurements related to the real processes and knowledge often considered in manufacturing systems. The research is implemented in several case studies to show the industrial applicability of the methodology. Some industrial case studies are presented in the results chapter.

Figure 9 shows the research strategy design and creation as defined by the interrelations of the three main bodies that can be included in this research (environment, design science, and knowledge base):

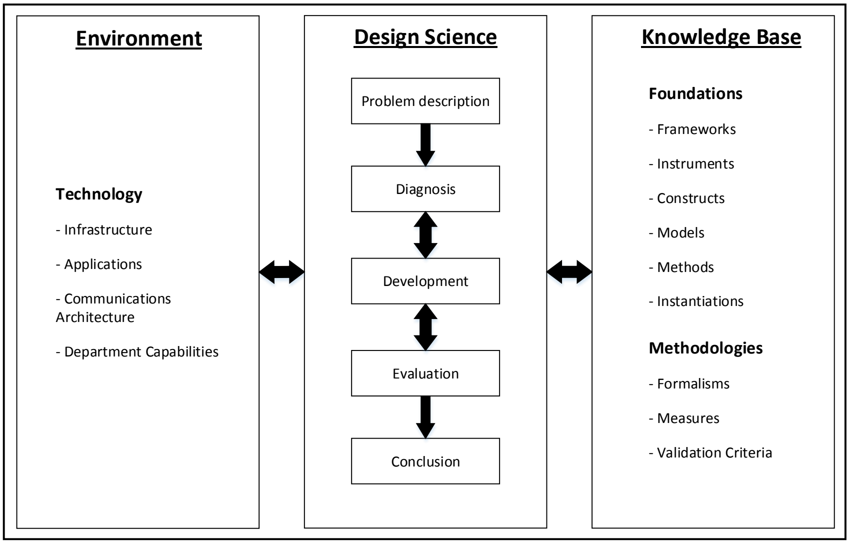

Figure 9: Information systems research framework [94].

Figure 9 shows that the first main body to consider in this research strategy is the environment, the application area. In the present case, this is the facility layouts of manufacturing systems, existing technology present in the system, and its evolution to new systems and capabilities. The environment considered in this industrial thesis was mainly that of the main industrial partner. These current and potential environments are the main input to the central design science development phase, based on the problem description of the system and its current and target state. The knowledge base is the other input to the design science central body. This knowledge base includes several methodologies and improvement methods and approaches such as simulation methodologies, Industry 4.0, and data collection approaches. The knowledge base consists mainly of foundations and methodologies. All the explicit research, the case study material, and related information are considered within these foundations. The different measures to evaluate the basis of the implementation, formalization, and validation of the analyzed knowledge are addressed within the methodologies. During the development phase, the iteration between new suggestions for implementation, the development phase, experimentation, and its evaluation are performed until a solid conclusion is reached. If the conclusion is satisfactory enough, that knowledge should return to the knowledge base and to the environment bodies to enrich them, closing the cycle of the base of design science.

In this case, the proposed methodology for FLD with SBO is the created artifact, taking into account the industrial environment and the different system improvement approaches and methods such as simulation and optimization. The proposed methodology contributes back to the knowledge base with its contribution to science and to the industrial environment through its application in case studies.

A proper evaluation of the overall thesis is performed to finally address the fulfillment of its purpose by using the FRAM method. After this the documentation and data generation phases are implemented, including case study implementations and real result data, which is useful for the research partners and is used for the assessment and evaluation of the research project. Figure 10 presents the research approach followed with the main industrial partner.

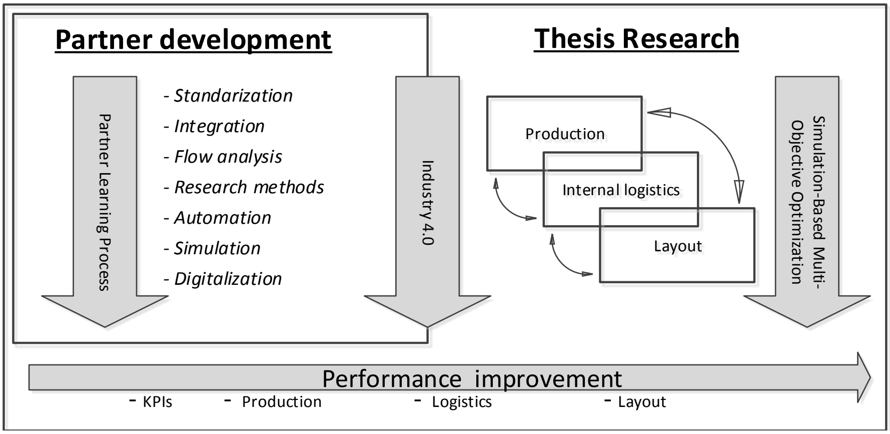

Figure 10: System development and thesis research approach.

Figure 10 represents the development of this research project in parallel with the development of the main industrial partner. A common base at the partner is required for the current and target facility layout designs and production and logistics flows and processes. This base may include certain levels of automation, standard processes, digitalized information, knowledge about simulation, and availability of data. This base is developed by supporting the research partner with knowledge, technologies, procedures, and methods via workshops, benchmarking visits, and engineering thesis projects. One of the main tasks here was the integration of a simulation and optimization culture at the partner. This required the removal of skepticism and reluctance to change, and also providing technical competence. At the same time some research regarding key performance indicators (KPIs) and Industry 4.0 was undertaken to support the base for digitalization and data collection, which are key aspects for using simulation in production, internal logistics systems, and facility layout.

The figure shows some developments on the partner side that occur in parallel with the development of this research. Some the major issues identified at the beginning of this research were a lack of data or difficulty in obtaining data on such matters as example production times, logistics performance, and capacity. To obtain the data necessary to analyze the system and to construct the simulation models, digitalization was used as a base and keystone for the development of this thesis, as shown in Figure 11.

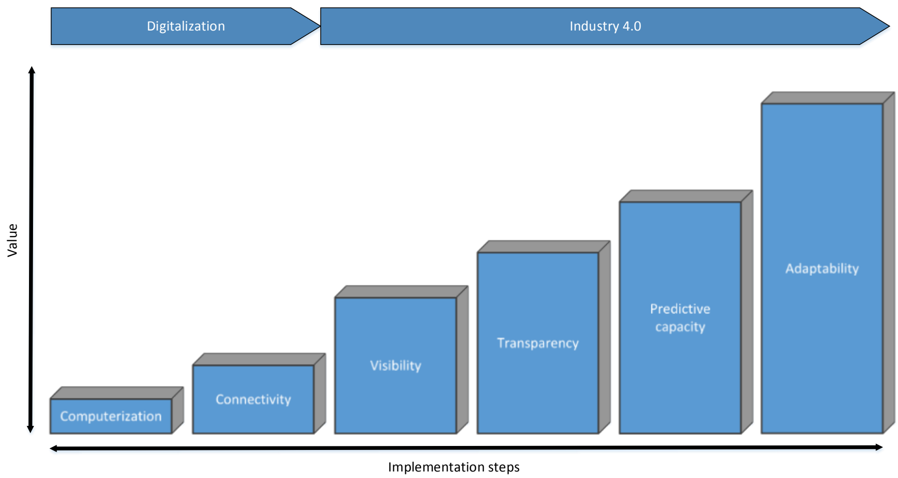

Figure 11. Maturity index of Industry 4.0 [95].

Figure 11 shows the maturity index for achieving an Industry 4.0 system, presenting several major steps in Industry 4.0. Industry 4.0 is a promising paradigm based on the emerging technologies of the Internet of Things and cyber-physical systems that should increase efficiency in manufacturing. Digitalization is the base and a key area for improvement in production and logistics systems related to facility layout. Digitalization focuses on computerization and connectivity, while the Industry 4.0 stages focus on visibility, transparency, predictability, and adaptability [95]. The implementation of Industry 4.0 concepts can significantly increase or improve production quality, efficiency, flexibility, and security [21].

Once data is available and manageable, its visibility increases, especially to managers, engineers, and stakeholders, promoting transparency in the system. It thus becomes possible to draw a clear picture of the current state of the system. Good access to data also allows managers to take the necessary measures to achieve possible desired target states by adapting the entities involved in the system, such as machines, suppliers, internal logistics, assembly, packing, and painting lines.

The fifth and sixth steps in Figure 11 are predictive capacity and adaptability, and involve simulation. Simulation is a key approach in the design and improvement of manufacturing systems. The simulation methodology in this research combines Banks's and Law's simulation methodologies, and is supported by the LeanSMO framework of Goienetxea Uriarte [53, 54, 96]. It also uses the data management methodology of Skoogh and Johansson [95]. The methodology is presented in Figure 12.

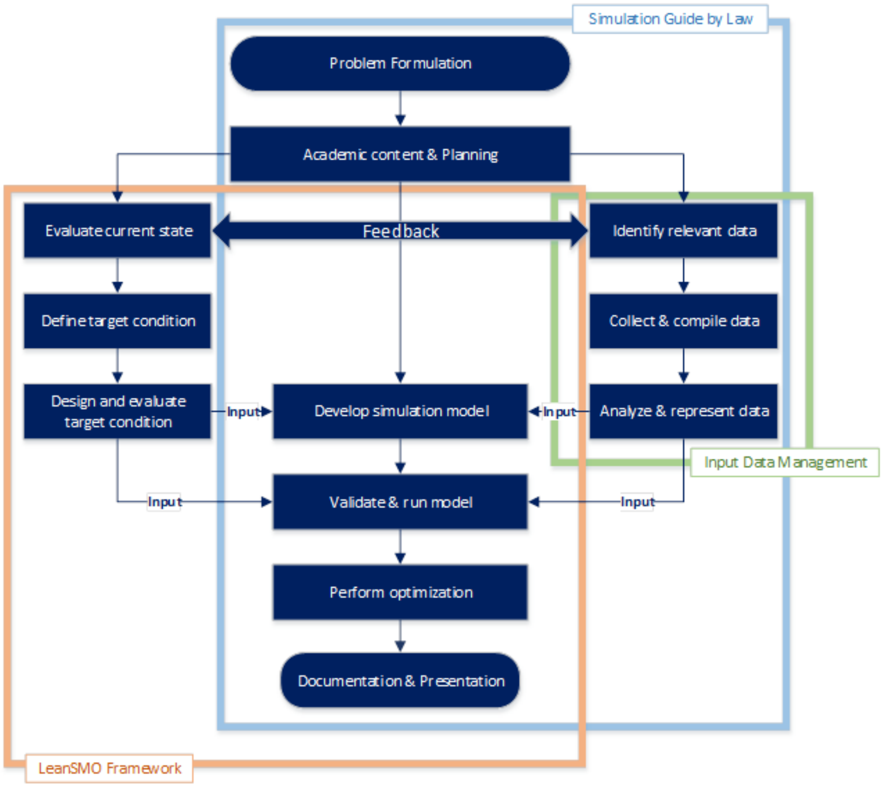

Figure 12: Combined simulation, Lean philosophy, and data management methodologies.

The aim of this thesis is approached by constructing a methodology based on these system improvement approaches with DES, SBO, Lean principles, the research approach previously presented, and the research strategy. One of the main steps when working with this kind of improvement is to have a clear picture of the current and the possible target states of the system. This requires data. Information about data collection and analysis is presented in the following subsection. Further definition and adaptation of these approaches and methodologies are presented later in this chapter.

3.2 DATA COLLECTION AND ANALYSIS

Once the problem has been formulated, the next step is obtaining the necessary data. Data collection can become one of the most tedious tasks in a simulation project. Usually the main question is what kind of data will be necessary, what data exist or are available, how to collect the data, and how to process it. These are issues explained in this subsection.

Most of the data analysis in this project is quantitative. Some data can be considered qualitative or nominal (e.g., product color, vehicle type, or production method). However, this data can be classified and treated as ordinal data for simulation and optimization purposes by assigning a numerical value to it. Most of the data in this project were quantitative. Due to the complexity and specific characteristics of the systems, all the data were considered discrete. This also facilitated using the data in the simulation models and handling the results.

It became clear that some triangulation of data was going to be necessary, combining different techniques for data collection due to the vast and diverse amount of data required for this project [97]. There are several techniques or strategies for data collection, including experiment, surveys, analysis, history, case studies, samples, measurements, observations, interviews, questionnaires, workshops, and document studies [5]. The strategy selected may vary depending on the availability and nature of the data.

In this project, extensive data collection was required and therefore most of the above-mentioned data collection strategies were used. The data were necessary to analyze the current state of the system, and an extensive data collection process was necessary to be able to build simulation models with the desired level of accuracy. Some of the key data collection strategies applied during this project were document studies, using secondary information in the form of documents and statistics that were available at the company. Observations were made of system parameters such as production and transport processes, facilities, and product information. Data were acquired from sensors or computers used to gather the required information. Frequency studies and time studies were conducted for those manual processes where automatic data logging was not possible.

Observation was a key data collection strategy for system improvement. Several manufacturing companies and institutions were visited for study visits or for benchmarking. The companies and institutions were chosen based on their levels of innovation in manufacturing and were mainly located in three countries: Sweden, Germany, and Japan. Documentation was obtained before, during, and after the visits. Field notes, information from experts, comments, and opinions were also documented.

Manufacturing provides a significant institutional foundation for learning and developing process skills and enterprises related to research. Hence benchmarking some manufacturing best practices from industries around the world can help to identify improvement opportunities and create a competitive environment. The following three tables present a list of the companies and research centers visited as part of this industrial PhD research. Employee numbers are approximate.

Table 5. Companies and institutions visited in Sweden and Norway.

Company/institution	Description
SwePart Transmission	220 employees. Produces gearboxes and components.
Xylem Water Solutions Manufacturing	1200 employees. Produces all technology needed for turning wastewater into drinking water. They produce Flygt pumps at the factory visited.
Väderstad	650 employees. Produces farming machines for cultivation, seedbed preparation, and seed placement.
Nordic Brass, Gusum	130 employees. Produces different brass alloys. Produces three main types of products: ingots, rods, and nuts.
Höganäs	1800 employees. Produces steel and metal powder.

Magcomp	12 employees Produces inductors and induction heating systems by using soft magnet materials. A spin-off from Lund University.
Scania AB, Södertälje	9140 employees. Scania AB headquarters, research and development and main production plant.
Volvo Car Engine, Skövde	2000 employees. Produces car engines.
Volvo Group Truck Operation	2800 employees. Produces truck engines.
Bring Warehousing (Norway)	238 employees. Warehousing and storage industry. Part of the Bring Warehousing AS corporate family.

Table 6. Companies and institutions visited in Germany.

Company/institution	Description
Siemens, Bad Neunstadt	450 employees. Casting, machining, and assembly of electrical motors. One of the top three companies within the Siemens group based on the audits that include Lean and digitalization.
Garching Campus, Technical University of Munich	7500 employees. Largest center for science, research, and teaching in Germany.
Ludwig Bölkow Campus	Research and technology hub for innovation in aerospace and security sectors, including companies and institutions such as Airbus, Bauhaus, iABG, Siemens, Technical University of Munich, and the University of the German Federal Armed Forces.
BMW Group Recycling and Dismantling Center	Car recycling and research into the environmentally compatible and efficient recycling of vehicles.
BMW Welt Car Plant	8000 employees. Main BMW group's plant. Produces about 1000 cars and over 2000 engines every day.

Table 7. Companies and institutions visited in Japan.

Company/institution	Description
UD Trucks Corporation	6210 employees. Produces medium and heavy-duty trucks.
Makino Milling Machine	4600 employees. Produces milling and electro-spark machining, EDM, and machines tools.
Toyota Kaikan plant	364,450 employees globally, 69,000 employees in the Toyota City area. Company headquarters of the car manufacturer in Japan.
Denso Corporation	168,810 employees, 39,000 of whom are based in Japan. Produces wheel-speed sensors and air-bag sensors.
Yamazaki Mazak Manufacturing Corporation	4000 employees. Produces different types of machining centers, e.g., milling and laser processing machines.
DMG Mori	12,000 employees in the entire company. Produces machine tools, machining centers, and turning centers.
Asahi Beer	30,000 employees globally. Produces beer, spirits, and wine.

Mitsuboshi Diamond Industrial	324 employees. Produces tools for hard and brittle materials such as glass and sapphire.
Panasonic Eco Technology Center	Part of Panasonic, which employs almost 275,000 globally. Recycles used home appliances such as TVs and refrigerators.
Kyoto Tools	195 employees. Produces hand tools and measurement instruments.

The main objective of these visits was to search out the best manufacturing practices from various industries around the globe, analyze their practices, and compare methods in current manufacturing. The implementation state of Industry 4.0 and FLD in the German companies was analyzed. Several aspects were evaluated in the Scandinavian and Japanese companies, including FLD, digitalization, and Industry 4.0, KPIs, sustainability, quality assurance, integrated product and production development, research integration/institutes, and production processes. These areas were considered as a base for constructing the methodology developed in this research, providing a guideline for strategists and engineers in manufacturing planning and development focusing in FLD.

Workshops were organized during these visits, and periodically with the main industrial partners to obtain additional information and validate the data collected. These workshops often involved stakeholders, operators, and engineers. Subject matter experts were consulted periodically to corroborate the collected data and information with the main industrial partners, Xylem Water Solutions, Volvo Truck Operations, and Volvo Cars. In addition, input from engineering theses and machine operators was valuable in developing case studies and in the data collection process.

The collected data were then analyzed and summarized in the form of tables, charts, histograms, or statistical distributions. The statistical distributions are usually the key information to be translated or programmed into the simulation models. Data analysis software tools such as ExpertFit and EasyFit were commonly used for this purpose when the complexity of the data required further analysis than was possible with spreadsheets. Access to some confidential documents was provided, including common procedures for layout design and operations management for Volvo Group Truck Operations, Volvo Cars, and the Toyota Corporation, as well as layout principles, procedures, and guidelines for Ford Motor Company.

Finally, interviews were used to validate the methodology. Research interviews are a suitable data collection strategy when perceptions and experiences need to be gathered [5]. As the data of the partner companies were classified as confidential in all cases, some protocols for management, storage, and publication were defined at the beginning of the project. A data management plan was developed with the library of the University of Skövde. In the following subsection, the way the data was collected is usually represented in KPIs. The way the new paradigm of Industry 4.0 affects the data collection is also presented.

3.3 KEY PERFORMANCE INDICATORS AND INDUSTRY 4.0

As previously stated, data collection can be considered as the base for defining the current and target state of the system to be improved, in this case facility layouts in manufacturing systems. However, layout KPIs are usually limited to square meters, number of departments, and the distance between them. A holistic perspective on the layout design is needed to obtain a broader picture. This holistic perspective also considers the production and logistics systems related to the layout, and so needs considerably more data in the KPI.

KPIs are used in almost every company today to monitor and control the production processes, goals, and costs and to make sure decisions and improvement projects are in line with company strategy. KPIs are usually quantitatively used to assess manufacturing performance [98]. In many cases, KPIs are used as a system improvement reference and as a production measure. They can be considered as routine and effectiveness measurements of manufacturing planning and control as well as tools for auditing and benchmarks [99]. KPIs are usually used as a base for bottom-up improvement approaches.

KPIs commonly used in facility layouts by manufacturing companies around the world were analyzed. Japan and Germany are considered two of the most advanced manufacturing countries. Analyzing their KPIs was a key step in understanding the importance of KPIs and their relation to production processes and flows, internal logistics, and facility layout. The focus of this benchmarking was primarily midsize and large companies (considered as companies with more than 50 and 250 employees respectively).

The companies studied use different kinds of boards in their daily production to represent and analyze KPIs. In Sweden and Germany, most of the companies had digital boards showing the number of parts produced and the daily target in their factories. In many cases these digital boards were supported by status lights on most of the stations in the production processes indicating whether the machine or station was running smoothly (green), having problems in finishing the parts on time (yellow) or stationary (red). This gives the team leaders in charge of production a good overview of the processes and station status. Some companies use more advanced computerized monitoring of their machines, allowing the collection of performance statistics; however, this was not the most common method.

In Japan quality is a high priority KPI; however, very few quality measures were found in the production area. The main reason is that quality is commonly built into the process with manual quality control stations. If any quality problem is found, the line is stopped and the problem analyzed to avoid producing defective parts. A common KPI visualized on digital boards is OEE (overall equipment efficiency), which is a combined indicator of quality, utilization, and availability. Additionally, Japanese workers need to achieve high skill levels in their work and this is clearly visible in Japanese factories. Many of the companies clearly show the certifications and degrees of their employees on boards, showing their ability to perform different tasks and move up in job positions. One interesting finding in Japanese companies was that when questioned about their next step toward Industry 4.0, the main answer was "knowing how to use the data," which indicates that the focus is shifting from performance measurement and monitoring to performance management with those measures; hence the importance of having digitalized KPIs and technical tools to analyze them.

The Swedish and German companies were classified into three groups: low automation level, high automation level, and small companies. This classification was done on the basis of different levels of use and representation of KPIs. The first group were companies with a significant number of manual processes and operators working on the shop floor. They commonly made use of Lean-inspired visual management boards for daily production control and management. However, the reliability of the data could not be ensured due to the use of different data collection methods and procedures, and the different persons in charge. Thus it is important to double-check this information. These whiteboards commonly showed indicators of quality such as defects, complaints, delivery reliability, produced and planned products, and resource availability including machines and operators. There was also often information about ongoing improvement work. The status of ongoing projects was visualized close to the boards showing the KPIs. An important KPI as regards safety indicators was the number of incidents. Additionally, clear indications of potential accidents and risks were shown in production cells and machines on the facility layout. Digital boards usually show the status of some main KPIs in real time. In some of the cases, KPIs were shown in centralized areas or rooms on the shop floor. The information shown in these locations was usually gathered by different team members every morning (e.g., area supervisor, production managers, and operators) and was summarized on whiteboards. These whiteboards usually focus on quality, service level, electricity consumption, and production materials.

The second group of European factories were those with a high level of automation, commonly with very few operators working on the shop floor. In these companies, production control is centralized and the status of processes can be visualized on computer screens, in many cases almost in real time. Whiteboards with more long-term indicators were also common. In some cases, the KPI data of the main product articles per production cell were available. Several companies used Axxos as a communication platform to show the KPIs on different screens on the shop floor. Axxos is a production monitoring software tool for the collection and management of data [100]. Usually product quality and accidents play a large role in the analysis of KPIs in these companies. Other KPIs such as throughput, work-in-progress, and lead time were also continuously monitored.

The third group were small companies with less than 50 employees. These companies at minimum had digitalized whiteboards with information regarding production planning, and in some case performance indicators, focusing on throughput and machine status.

To summarize: European midsize and large companies commonly use Lean-inspired visual management boards for daily production control and management. This information is usually presented on monitors or screens distributed around the facility and sometimes also centralized for production monitoring purposes. On the other hand, in many of the Japanese companies analyzed, Lean-inspired visual management boards were integrated into daily production. Pen and paper information boards were also used. The general impression was of a lack of the high technology of Industry 4.0 on the shop floor.

One of the main KPIs on the shop floor is throughput or produced parts. Throughput is commonly shown per hour, per day, per week, per month, or per year, depending on the production volumes of each product or manufacturer. In some of the Japanese companies, this throughput KPI was substituted with a “line moving speed” value. The line moving speed is how fast the products are moving on the assembly line, usually measured in meters per minute to measure productivity. The line speed can usually be adapted depending on the workforce on the line at any moment. The work stations and tools of the different operations move together with the products of the line, at the same speed, on something called the “magic carpet.” These magic carpets are platforms moving on both sides of the line at the same speed as the products. The operators are able to work with the products on those platforms. After the station or operation is finished, the platforms quickly return to their original position to begin the operation for the next product. The material was commonly delivered to the line by automated guided vehicles (AGVs), following the specific products or magic carpet at a coordinated speed. A high line moving speed means there are no failures or stops in the assembly line, and thus high throughput.

Another KPI commonly present in manufacturing is related to the quality of products. It can also be referred to as the product failure rate or product rejection rate. In Japan, a so-called “check person” commonly performed a manual inspection of every product for quality after every key operation. On the other hand, in European companies the weight of the quality KPIs was considerably more relevant at the end of the production process, measuring the quality of finished goods. A general impression was that European companies prominently displayed their KPIs for quality, defects, complaints, and delivery reliability on boards or screens on the shop floor. However, at the Japanese companies, these KPIs were less present on the shop floor, mainly due to the general policy of not accepting or allowing a product to continue processing without the required quality.

To conclude, in the European factories visited, there is an extensive focus on quality, electricity consumption, and accidents, something that seems to be absent in Japan, especially on the shop floor. On the other hand, in the Japanese factories there is usually a focus on target objectives for the day, especially regarding the amount of produced parts and finished products, and on the workers’ expertise and education. KPIs such as throughput, work-in-progress, and lead time were commonly analyzed and summarized. Additionally, the methods used to collect this information were a mix of automatic data logging systems (such machines or cells connected to a central monitoring system like Axxos) and manual systems (noting the values collected manually on whiteboards and then entering them in a computer system). Nevertheless, with some exceptions, Europe seems to more commonly use an automated approach, while in Japan the approach is manual. This offers European companies a clear advantage when it comes to increasing digitalization and the trend to Industry 4.0.

In terms of visualizing KPIs, the manufacturing companies visited showed growing interest in data processing for production processes such as assembly and machining. Some of the manufacturing companies did not use data visualization on the manufacturing shop floors. The high cost of the techniques and tools for data visualization was a main factor. Additionally, some traditional manufacturing companies believed that there was no demand for data visualization.

Data visualization in large manufacturing companies was commonly applied in the production and assembly of components. The manufacturing process was commonly visualized by Kanban systems, which allow communication between processes and workers during a production process to establish the order of utilization of materials and parts. The production schedule, machining status of components, status of machines and workers, information on the production plan and execution, and production exceptions are visualized and monitored in real time on the digitalized interface. This can significantly contribute to decision-making for system improvement. However, the use and analysis of visualized data in the manufacturing companies seemed to be at the primary level regarding Industry 4.0.

As stated in paper 2, *Integrating Simulation-Based Optimization, Lean, and the Concepts of Industry 4.0*, Industry 4.0 is considered to be the next step in the evolution of industry, integrating information technology and automation systems in manufacturing [101]. It aims to integrate the new technology of the Internet of Things to build cyber-physical systems, allowing the interconnection of different actuators on the shop floor (e.g., machines, robots, processors, computers, and workers) with the surrounding environment, databases and the outside world. The objective is to interoperate and cooperate to achieve individual as well as jointly aggregated goals, helping to achieve increased flexibility in production to adapt the capacity to a more variable and customized demand [102]. An example is shown in Figure 13.

Figure 13. Example of a smart factory showroom in a manufacturing company.

Some of the data visualized in the figure were used to display the digitalization level of manufacturing companies. Much emphasis was placed on commercial aspects, that is, selling products adapted for Industry 4.0 or Industry 4.0 production. However, the added value of data processing and data mining for the manufacturing process did not seem to be deployed in most of the companies visited.

In most cases, it was hard to find strategies for using big data or data to drive their decision-making. The awareness of Industry 4.0 also varied between the companies, suggesting that most of them do not have a strategy aligned with it. It was not clear what their ambitions were related to connecting their production such as knowing their processes better, for example with more sensors collecting data. Most companies were computerized and had data presented on visual boards or dashboards with KPIs to follow up their production goals. In terms of the chart in Figure 11, most of the large and medium enterprises were at least at level 1 with computerization. None of them really reached level 4, where the data collected is transparent to the organization and can drive decision-making. Level 2, connectivity, mostly involved connection to internal information systems. There were no mobile connections, mainly due to data security issues. The few existing connections were stationary for machines or production cells. Level 3, visibility of data, was present to some extent in most medium to large enterprises. For level 4, transparency, it was not clear how real-time data can be or are being used. Here again, security issues regarding data and IT systems are commonly a limitation. Some companies stressed their intention to transform into relying more on production data when making decisions. Sharing data seemed to be becoming a trend, but usually just among suppliers and from the customer to the organization, especially for product feedback and maintenance purposes.

One of the major issues when it comes to digitalization and Industry 4.0 are conservative IT departments, who are usually protective of their data. They inhibit external collaboration by, for example, limiting connection between organizations and customers and lacking data management and visualization standards for different companies, and by not enabling connectivity and data visualization from computerized devices such as external computers, tablets, and smartphones. In most companies Supplier A would not be allowed to access data related to Supplier B for competitive reasons. However, within the production networks, information sharing was often enabled by IT systems with an Industry 4.0 maturity index close to stages 3 and 4 for critical processes. Nevertheless, the use of digitalized Kanban systems, maintenance systems, work orders, and scheduling seem to be good directions for data visualization and management to reach levels 5 and 6 in the maturity model of Figure 11. More precise order picking and fulfillment, and the importance of having better information and control automation levels are recognized for internal logistics. At the same time, there are difficulties in identifying the right physical level of automation and its trade-offs with flexibility.

One aspect of Industry 4.0 production adaptability that should be highlighted is the better use of data visualization to improve manufacturing performance and monitor production processes, and the utility of predicting demand and maintenance of products by connecting customers to the data management system of the company. This access to information can significantly contribute to FLD with data availability, flexibility, and adaptability, enormously facilitating the ability to predict production performance. This highlights the importance of adaptable and reconfigurable manufacturing systems and the need for more dynamic facility layouts and therefore continuous redesign.

This subsection presented an analysis of common KPIs and how they are commonly visualized and analyzed in manufacturing. The next subsection will address how to proceed with the design and improvement of the flows present in facility layouts.

3.4 PROCESS, FLOW, AND LOGISTICS OPTIMIZATION FOR FACILITY LAYOUT DESIGN

The first decision to be considered regarding layout types is to decide on a suitable layout (Table 2). A workshop meeting can be a good approach to determining this. A workshop is a meeting to discuss and plan practical work, commonly used in engineering. In this case, it should involve managers and stakeholders, as well as engineers and technicians in charge of the areas or departments being considered. The outcome should be a clear picture of the existing facility layout and a draft of the possible desired and ideal layout designs. This first step when working with FLD is considered the base for the proposed methodology.

The literature review showed there are no common procedures for designing these different types of layouts. Some existing generic procedures such as the graph-based method are not commonly applied nowadays due to the very large number of different layout alternatives, complex shapes of layouts and departments, and numerous constraints and requirements. Hence it is common that layout designs are created by a combination of common sense, intuition, and systematic trial and error. A brief investigation of the conceptual modeling activities in production system design is necessary to have a broad view of the FLD task. This is provided by the example presented in appended paper 4, *Simulation-Based Optimization for Facility Layout Design in Conditions of High Uncertainty*, as shown in Figure 14.

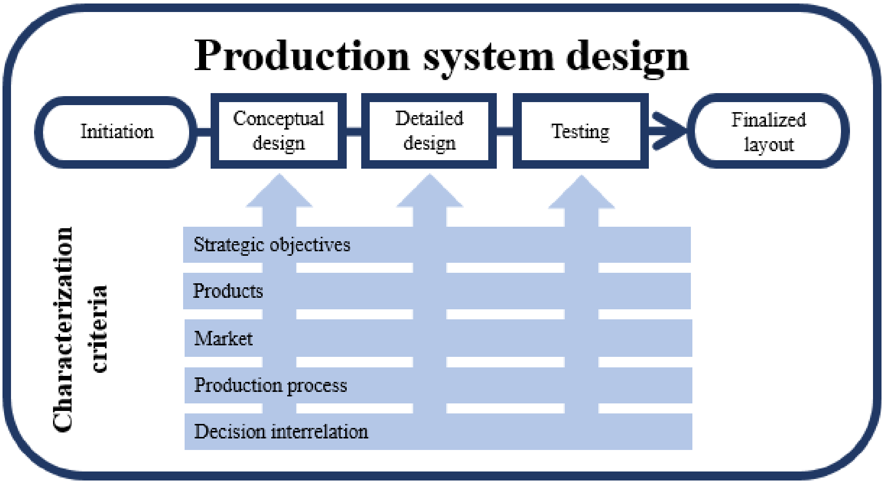

Figure 14. Conceptual modeling activities and characterization criteria for facility layout design.

This figure shows three stages between initiation of the project and the final layout: conceptual design, detailed design, and testing. A conceptual model is the point of origin for the abstraction of a real or proposed system to reach an increased level of understanding [16]. The concept is transformed into a flowchart or VSM, acting as the conceptual model of the system. A VSM is a key component of the Lean toolbox for visualizing, representing, and improving production flows in manufacturing systems. A clear image of the system is required for its development, not necessarily in every detail. However, all the relevant processes and relations in the production chain should be clearly identified. This conceptual model has to be verified and validated by subject matter experts. These may be persons responsible for production, managers, or related engineers. Once this conceptual model is verified and validated, data collection is required to provide information related to every process represented in this conceptual model. The objective is to have a more detailed model design that represents the current system.

An important step here is to properly define the aim and objectives of the project and the project team, analyze possible constraints and requirements, and possible future expansion plans, visions, or strategies of the company in question. This can be crucial in determining which processes, data, and information are relevant for the analysis of the current state and the target desired states. This information can be related to the strategic objectives of the company, the type and number of products and future predictions, the status of the market, the required production processes for the identified products, the competence of the team, and the interrelations of the decisions of different departments involved at different levels.

The next step is translating the model into a simulation model that represents the current state of the system, taking into account the existing layout design, main production areas, and internal logistics. Robinson et al. [16] present a useful guide:

Table 8. Conceptual model activities [16].

Activities	Description
Understand the problem situation	Definition of the need to improve a problem situation
Determine the modeling objectives	Purpose in terms of achievement, performance, and constraints
Identify the model output	Model responses
Identify the model input	Experimental factors. Data changes may be required to achieve objective
Determine model scope	Model boundaries in terms of entities, activities, queues and resources
Establish level of detail	Specification of entities, activities, queues, and resources
Formulate assumptions	Beliefs about real-world being modeled
Look for simplifications	Essential information for rapid model development

Once all these activities are clearly defined and a conceptual layout design has been defined by some of the traditional approaches, an appropriate simulation software tool must be selected. An analysis of available software tools can be performed as indicated by Guimarães et al. [103]. In many cases, the selection of the software tool is determined by the availability of simulation software tool licenses or expertise at the company. Once there is some familiarity with the software tool in the project team, it is possible to translate the previously obtained conceptual design into the simulation model. It is not strictly necessary for all members of the team to be familiar with the software, but the simulation experts should act as a link with the rest of the team. This is done by representing the relevant objects on the flowchart or VSM in the simulation model and introducing the appropriate data collected about them. If the data are not available, time studies, frequency studies, observations, or assumptions double-checked with matter experts can be considered. Proper documentation of the data collection process is always necessary.

As presented in appended paper 1, *Production Logistics Design and Development Support: A Simulation-Based Optimization Case Study*, the simulation process can be based on Banks's simulation steps. These were presented in Figure 8 of the Frame of Reference chapter of this thesis. The simulation model or models have to be verified and validated to show that they are accurate and appropriately detailed. This is usually done with the support of the engineers and people in charge of the project.

Once the system is verified and validated, the existing production system can be analyzed and some what-if scenarios can be tested to determine possible target states. With this knowledge about the current and target states of the system, the existing facility layout can be analyzed. The process of designing an improved facility layout can be started considering the number of areas and departments, their interconnections, the constraints of the layout such as shape, surface, unmovable equipment, and fixtures. An example of such a simulation model is shown in Figure 15.

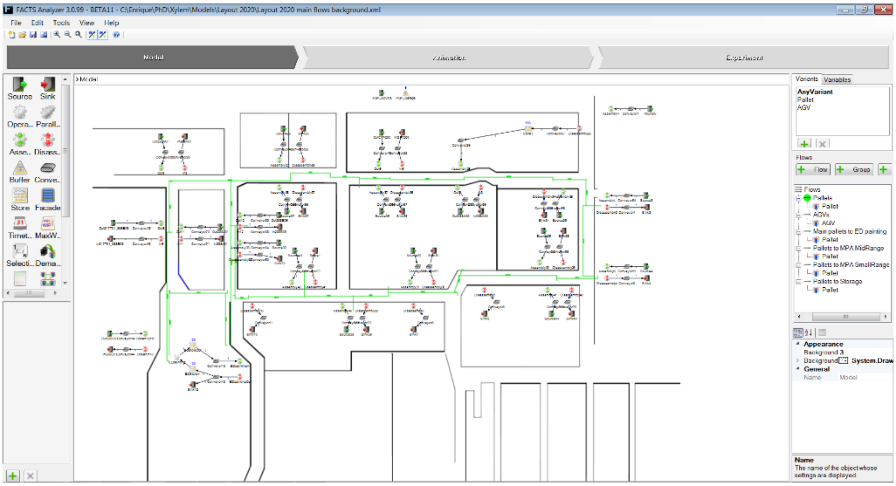

Figure 15. DES simulation model of facility layout.

The common reality in manufacturing facility layouts does not allow complete freedom to rearrange departments; several constraints usually have to be considered, such as the impossibility of moving some or many of the departments; adjacency rules; and facility, logistics, and production requirements.

The evolutionary multi-objective optimization algorithm Non-Dominated Sorting Genetic Algorithm “NSGA-III” was selected for solving the optimization problem. It is preselected in the simulation software tool FACTS Analyzer. The basic framework of the NSGA-III remains similar to the original NSGA-II, with significant changes in the internal mechanics [104]. The fundamental difference is the sorting of the solutions and the way the niche preservation operation is performed [104]. Kalyanmoy Deb introduced this algorithm and proved its effectiveness in the field of multi-objective optimization. The NSGA-III performs as follows, in the sequence shown below [104, 105]:

- The algorithm starts with an initial population based on the range of the problem. The parent population is initialized, which relates to the input variables. Then a new population is created by creating an offspring population and parent population where the child population is produced by genetic operators such as crossover and mutation.
- A non-dominated sort of the initial population takes place to ensure that elitism from the previous generation is preserved.
- Application of the crowding distance comparison for the same rank, which does not fit entirely in the next set of the parent population.
- The best solution selection process is carried out after sorting all individuals based on non-dominated and then crowding distance value. The selection is done using a crowded-comparison-operator or crowded tournament selection.
- Applying the two genetic operators for simulated binary crossover and polynomial mutation.

NSGA-III is important because it can handle up to 15 conflicting objectives. Using DES and SBO allows several different combinations of the production systems to be tried out and visualized. For example, new assembly lines or machining centers can be merged or created, future production for specific products can be increased, new products or new material handling systems can be introduced. The outputs of the simulation models and optimization engine are usually represented and analyzed in bar and pie charts as well as histograms and scatter graphs. When further analysis was required and the amount of data was considerable, data mining techniques were used to find hidden correlations in the optimized solutions.

The combination of DES and SBO allows the consideration of variables or parameters to be customized and allows the programmer to modify the layout easily without interrupting the system. However, the lack of a generic methodology for working with simulation and optimized solutions of FLDs was a gap identified in the literature search. A list of theoretical challenges to using DES and SBO was presented in subsection 2.5 in the frame of reference chapter; in the next subsection, a list of empirical challenges is summarized before introducing the proposed methodology.

3.5 EMPIRICAL CHALLENGES OF SIMULATION-BASED OPTIMIZATION AND FACILITY LAYOUT DESIGN

Having understood the theoretical challenges and way of working in the fields of SBO and FLD, an analysis of empirical challenges was required. The research relied on a case study method to understand the context of the study, even though behavioral events cannot be controlled [97]. As mentioned in paper 5, *Challenges of Simulation-based Optimization in Facility Layout Design of Production Systems*, two cases were selected (A and B) based on the following three criteria: the manufacturing company was planning an FLD project; SBO would be used in the FLD project; and the staff anticipated that the SBO models would face serious challenges.

Data were collected between 2016 and 2019, focusing on the challenges identified in Table 3 and Table 4. The data included company documents and field notes of informal conversations with staff responsible for FLD projects A and B. The descriptions by the staff of the factories, company documents, and field notes data were analyzed bearing in mind the challenges in Table 3 and Table 4. Then a cross-case analysis was performed and empirical data were compared to the literature at every step of this process. The case studies are briefly presented below.

Case A involved an FLD project including SBO at a medium-sized manufacturing company specializing in the production of electrical cabinets. The project gave precedence to operational performance, including factory floor space and production flow to meet increasing demand and product variety. The staff developed a simplified alternative to the existing FLD that addressed existing issues sequentially. The new version was a static representation based on the production process, material flow, and equipment used to produce its most popular electrical cabinet. The FLD process did not include SBO. However, management contacted an external partner specializing in developing DES models to verify and validate the FLD project. The simulation experts determined that the existing information represented only a partial understanding and was insufficient to develop an SBO model. Simulation experts and staff from the company met repeatedly to acquire data from diverse sources, analyze stochastic data, and develop an SBO model. This model indicated that the initial alternative would not achieve its objective. In response, critical factors for achieving a desirable outcome were identified and a new FLD was drawn up based on the optimization of these factors. The project did not come in on budget or on time. However, the staff rated the project favorably because SBO had enabled them to avoid a poor choice. They had considered SBO necessary to progressively introduce changes in the factory floor space. However, Case A was limited by a lack of access to and understanding of SBO. The existing FLD process was not revised to include SBO after the project.

Case B involved an FLD project including SBO at a large manufacturing company specializing in the production of water pumps. The objective was to increase quality while minimizing the cost of a layout redistribution on the main shop floor. The problem was the need for space to install a new assembly line to increase production, as well as a new painting system to improve painting quality, and to have the capacity to introduce new products. The production requirements and material handling system were also considered in the layout design. Nine project teams with nine project leaders under two production development managers were created to subdivide the project into more specific subprojects. The time frame was one year from signing the purchasing contract with a painting line supplier to production start-up. At the beginning, a draft layout was proposed with the main objectives of feasibility and moderate cost. The possibility of working different shifts to achieve the production goals was then considered. The flexibility of the outcome was key to being able to adapt to future changes in the factory. Another issue considered was the impossibility of stopping production. SBO was used locally in some of the subgroups to determine some parameters and scenarios, and no generic FLD method was followed during this project. Table 9 identifies the challenges of using SBO in FLD of manufacturing systems for cases A and B.

Table 9. Challenges of using SBO in FLD for cases A and B. ○ and ● represent Case A and B respectively.

Challenges of FLD	**Challenges of SBO**						
	Complexity	Noise	Search	Evaluation	People	Process	Technology
Validity	○ ●	○ ●	○				
Randomness	○ ●	○ ●			○		
Dynamic	○ ●	○ ●					
Simultaneity	○ ●	●	●	●	●	●	●
Cost	●	●					
Safety	○ ●	●	●	●	○ ●	●	●
Standardization	●		○ ●	○ ●	○	○ ●	●
Integration	○ ●	○ ●			○		

These results show the relation between SBO and FLD challenges, usually studied independently. The challenges of complexity, noise, and standardization took precedence in the cases studied. These challenges are not technological in nature but emerge from the complexity of modern manufacturing systems. This indicates that problems with the systemic nature of manufacturing systems, including facility layouts, continue to affect manufacturing companies despite decades of research on these topics. This result is also encouraging for those manufacturing companies working with standardized processes and systemic thinking, trying to obtain information about essential production processes in sufficient detail. The case data show that such companies may benefit from utilizing SBO in FLD. The challenges in Table 9 could be minimized by performing risk analyses at the planning stage, or involving increased SBO resources alongside the FLD project. To overcome these challenges the methodology for FLD with SBO is presented in the next subsection.

3.6 PROPOSED METHODOLOGY

The following FLD methodology with SBO is presented to overcome the challenges identified above and the lack of a generic methodology for layout design with simulation and optimization, and taking into account internal logistics and production requirements. The proposed methodology fulfills the requirement of the design and creation research strategy shown below:

- Design as an artifact
- Problem relevance
- Design evaluation
- Research contributions
- Research rigor
- Research as a search process
- Communication of research

As previously mentioned in the Research paradigm and strategy subsection, the artifact in this thesis is the proposed methodology for FLD using SBO. The problem is relevant for manufacturing industry due to the high uncertainty associated with FLD. This was identified with the partner companies, by benchmarking, and study visits. An analysis of theoretical challenges when working FLD and SBO was performed to further identify the relevance of the problem.

A clear methodology for FLD with SBO to overcome the number and magnitude of these theoretical and empirical challenges is presented in Figure 16 as the proposed artifact:

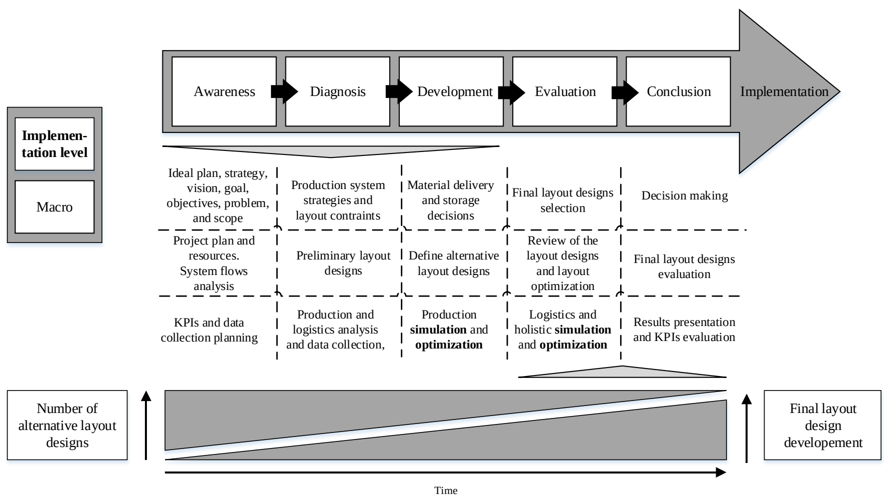

Figure 16. Methodology for design of facility layouts using SBO.

To guide an FLD project using simulation and optimization, the methodology represented in this figure is structured in five development stages along the X-axis: awareness, diagnosis, development, evaluation, and conclusion. These stages were defined according to the research steps in several of the articles reviewed in the Frame of Reference, but primarily by the research methodologies defined by Oates, Säfsten and Gustavsson, and Rösiö and Bruch [5, 91, 106]. The different implementation levels of the methodology, both at macro and micro levels, are shown on the Y-axis; macro in Figure 16, and micro in Figure 17.

The awareness development stage refers to an informal start, the definition of a project proposal, and the initiation and planning of the project. The diagnosis stage mainly refers to the pre-study, data collection, and conceptual design with VSMs. Development focuses on the translation of the conceptual design into the simulation software tool, including the definition of the detail design of the facility layout with the simulation software tool. Before the conclusion, the evaluation stage focuses on the definition of possible what-if scenarios and optimization to obtain the desired target stages. The conclusion stage involves analysis of the designed, verified, and validated what-if scenarios and optimization results to facilitate the decision-making process. These five stages are explained in more detail below.

The order of implementation regarding the classification on the Y-axis in Figure 16, micro, might depend on the application case. Based on experience in different case studies, a top-down approach is common for the stages of awareness, diagnosis, and development, and a bottom-up approach for the final stages of evaluation and conclusion. Further industrial case studies would be required to refine the order of application of these three implementation levels. This could be done, for example, by analyzing the implementation order in both midsize and large companies to analyze their differences at the micro and macro levels. The general perspective is presented in Figure 16, and the micro implementation level in Figure 17. The description of the different development stages presented here is based on paper 6, *Holistic Simulation-Based Optimization Methodology for Facility Layout Design with Consideration to Production and Logistics Constraints*.

Awareness: Several case studies, studies of benchmarked companies, and interviews were performed to define this first stage. A common conclusion was that there was a lack of planning and time to perform FLD projects. Picturing an ideal plan of the company or site and its strategy and vision are key aspects to ensure the project is properly defined. Clear definitions of the goals, objectives, problem description, scope, departments, and divisions facilitate visualizing the expected results of the project and defining a detailed and realistic project plan. Especially when the size of the project is considerable, it is important to allocate sufficient time to plan from the moment of identifying the problem until the definition of a preliminary project plan. This first stage requires the involvement of at least the management team, stakeholders, those responsible for the layout, engineering/technicians team involved, and simulation and Lean experts, if any. The scope has to define such matters as whether to include possible changes or improvements in the manufacturing systems (e.g., machining and assembly processes). The scope must also include the logistics systems (e.g., internal and external logistics, material storage, and material handling system), as well as the need for and availability of resources and data for the development of the project. The person chosen as project manager can be key to the success of the project [107]. Once this awareness stage has established the aim, objectives, boundaries, time frame, and resources of the project, it is time to move on to the diagnosis stage.

Diagnosis: At this stage, the preliminary information obtained during the first stage must be supplemented by a more specific data collection process, involving consideration of possible strategies and methods for the improvement of production and logistics systems. This additional information is required to develop a realistic project plan and to obtain the first preliminary draft layout designs. This design should include different production system alternatives and their required logistics alternatives, taking into account constraints and requirements regarding the layout.

Determination of the different areas or departments in the layout (number and required space), aisles, plant services, and the identification of the workstations, products and variants, lead times, and storage requirements should be the key step at this stage. The use of VSMs of the current and target state to identify the relevant processes and data is strongly recommended to facilitate this process. The system should be analyzed to determine whether simulation is required before moving on to the next stage of the methodology, development. More specifically, one should determine whether DES is required due to the nature and complexity of the systems in the scope of the layout project. If not, traditional methods might be sufficient for the FLD.

The conceptual models of the production and logistics systems, production and logistics constraints and requirements, and key questions that the layout design project will help to answer have to be clearly defined at this stage. Possible scenarios that can be planned at this stage include an increase of 30% in production in five years, or renewing the internal material handling systems due to the high number of accidents and delays resulting from the use of forklift trucks. The appropriate KPIs and different types of transports should be considered in the conceptual models at this stage. Once the current and target states of the system and their conceptual models are defined, as well as clear project planning with some preliminary layout designs on the table, the development stage is the next step.

Development: The main part of this objective is to build, verify, and validate the simulation models of the production and logistics systems related to the layout design. Once verified and validated, these simulation models will be considered in an aggregated, holistic model of the entire system in which different alternative layout designs can be tested to define specific parameters for constructing the final layout design.

Some preliminary designs of the future or target layouts are required here. A first draft can be obtained using the existing layout design. An initial block diagram can be created using one of the previously mentioned graph-based methods and relationship diagrams. The diagram should include the existing situation as well as identifying the fixed locations of the areas or departments that cannot be moved and defined layout constraints. Then the layout design can be constructed with the simulation software tool to add the production and logistics system to it.

The simulation software tools selected for this project were Flexsim and FACTS Analyzer. They were selected due to their intuitive interfaces, optimization engines, and 3D/2D representation capabilities, respectively. However, there are several commercial simulation software tools in the market with similar characteristics [103]. In many cases, the simulation software tool is selected on the basis of the existing expertise or software tool available at the company. The selection of 2D or 3D software tools is usually a trade-off between the need to gain credibility among managers and stakeholders, and the difficulty of programming simulation models that have to look like the real environment purely for credibility. Whether DES is required in the simulation software tool depends on the complexity and size of the systems to be analyzed. The simulation approach can be guided by a simulation methodology such as Banks's or Law's simulation methodologies [53, 54]. At this stage the conceptual models of the existing production systems, such as machining and assembly, can be translated into the simulation model.

The simulation models have to be verified and validated; this is usually done by comparing the outcome of the model with reality and analyzing whether the results are accurate enough for the purpose of the study. After the simulation model or models have been verified and validated, it is possible to analyze the model in order to find weaknesses of the system and potential improvements. This allows possible alternatives for the improvement or adaptation of these production systems regarding the desired target state to be modeled.

For example, the identification of bottlenecks, the balancing problem of the assembly lines, and their shape distribution on the shop floor can be of great importance in visualizing the future facility layout, as presented in the appended paper 1, *Production Logistics Design and Development Support: A Simulation-Based Optimization Case Study* and in these papers [76, 108, 109]. Some other possible improvements identified by large automotive manufacturers include redesigning the position of the material or products when being assembled (e.g. side-by-side rather than bumper-to-bumper), redefining the material handling systems in the assembly lines, or optimizing the number of steps per product every operator has to perform [13].

Similarly, once the production system has been simulated to visualize the current state and possible improvements for the target state, the material handling system can be added to the production system model or be simulated independently, depending on the complexity and size of the system. Different alternatives and scenarios in the internal logistics can be tried. These alternatives include the type of material handling system (e.g., conveyors, AGVs, forklifts, tow trains, and manual transports), different routes, vehicles capacities, capacity, number of buffers, length of conveyors, and containers needed.

These problems (both production and logistics) can become significantly large (NP-hard) depending on the size and complexity of the system. Thus simplifications or assumptions must be considered without compromising the accuracy of the results. For example, the number of products and variants can be the simplified by working with product families rather than with individual products. The implications of this for the logistics also has to be verified and validated by subject matter experts or the responsible persons.

Depending on the nature of the production and logistics systems simulated, the future layout type required for each area of the shop floor can be defined as one of fixed-position layout, functional layout, cell layout, and line or product layout (Table 2). After narrowing down the options, an approach to obtain a final set of optimized layout designs is the application of common sense in combination with the constraints and requirements previously defined. This layout should be revised at this stage, using items such as [110]:

- Double-check building and site constraints and requirements such as available area, height, and location of the buildings, existing and possible input and output flows, accessibility, natural lighting, ventilation, and electrical and hydraulic installation.
- Determine whether the requirements of production design can be met: variable demand, equipment capacity, processes, lines, stores, and buffers, taking into account current and future variability of products and demand.
- Consider the analyzed material handling system alternatives and their requirements (space required on corridors, paths, turning, loading and unloading, and charging and/or repair areas).
- Minimize the financial demands such as investments in equipment and material handling cost.
- The safety, comfort, and quality of life for employees.

Once all the constraints and requirements have been considered, a limited number of possible layout alternative designs and production and logistics systems can be considered. Using SBO can support the FLD decision process better than traditional methods if the complexity of the system is considerable and if simulation experts are involved in the layout project. Multi-objective optimization can be applied to resolve conflicting objectives of the different simulation models by, for example, minimizing the number of required transports and lead time while maximizing or keeping a certain throughput.

Evaluation: The fourth stage is based on the optimized logistics and material storage systems that fulfill the requirements of the previously simulated production system. An aggregated holistic simulation model of the entire system is built. Modeling the production system in an aggregated manner and adding the material supply and storage systems allow the optimization engine to work with the objective parameters, such as area, throughput, storage, work-in-progress, and lead times. This stage might require going back to the conceptual and analysis stages to address missing data or changes in the conceptual designs until the final holistic model can be verified and validated. This holistic simulation model can be represented in different layout designs to analyze the performance of the system with the new distribution of the system. For example, alternative layout scenarios can have different locations, shapes, and sizes of some of the departments; different input and output flows of materials and products; or different material handling systems; or different aisles for workers and transports. The results of the analysis of the simulation models and the optimization results of the comparison between alternative layout designs can then be evaluated in the last stage of the methodology by managers and stakeholders.

Conclusion: The fifth stage consists of the evaluation of the holistic simulation model and the optimization results by analyzing the KPIs to arrive at a final selection of the best layout design. Commonly, a Pareto front is used to evaluate the optimized layout alternatives. The Pareto fronts obtained from the optimization approach in the previous stage can be a useful tool for comparing such things as the number of required transports against the lead time or work-in-progress in the different layout alternatives. An additional step is the introduction of approximate budgets for the required changes (e.g., for moving departments, machines and lines, changing transportation systems, or constructing new facilities).

The methodology presented above can serve as a guideline for managers and stakeholders, and also for engineering teams and simulation experts involved in FLD projects. More detail is shown in the micro implementation level (Figure 17). These activities have been defined based on the methodologies in the literature review, analyzed case studies, and benchmarking visits, and the planning process analyzed by Tompkins at al. [19].

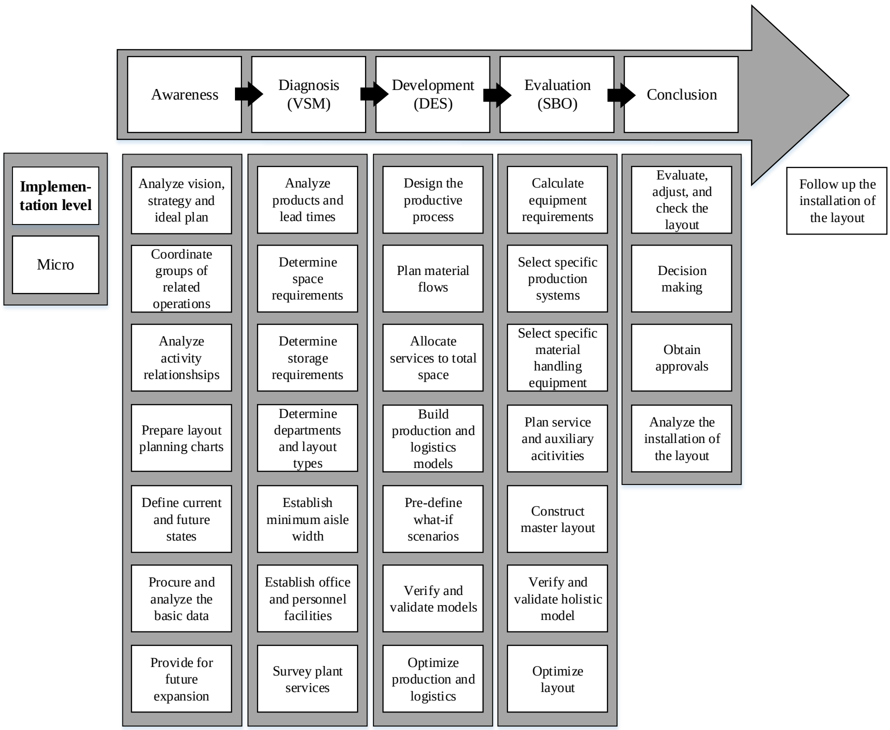

Figure 17. Methodology for design of facility layouts using SBO, micro implementation level.

The same stages as in Figure 16 are represented in Figure 17 and are explained in detail in the following paragraphs. As before, the implementation order of the tasks in each column depends on the implementation case. Although a logical structure going from the first element on the top of every column downward has been considered in this micro level, the implementation order may change from case to case. As mentioned before, further analysis of different industrial case studies may change this aspect. The different stages at micro-level are explained below:

Awareness: Data collection for the diagnosis stage should be planned to analyze the availability of the required data and its format, starting with the collection of the existing layout planning charts. This process comprises gathering and analyzing the available production data, coordinating resources and working teams, and establishing the main interrelations of the processes occurring on the layout.

At this stage, it is also time to analyze the possible contribution of simulation and optimization in the layout design project with the simulation expert if the complexity or the size of the system require it [51]. Some of the Lean toolboxes are useful at this stage to establish a Lean working environment and to involve different levels of staff to promote vertical integration and continuous improvement. The involvement of the responsible staff from different areas in the layout in the form of a Kaizen workshop is strongly recommended. In this workshop, brainstorming and defining requirements and analyzing constraints are the basis for drawing up the first layout alternatives [111]. Including Gemba visits to the different areas of the shop floor can be useful to understand the scope of the project and for team-building purposes [112]. Analyzing the existing layout of the current shop floor in light of the aim and scope of the project is an important step toward picturing the final desired solutions. A set of requirements for the production and logistics systems must be defined to lay the basis for possible alternative future layout designs.

Involving Lean is highly recommended if there is some room to work with the improvement or redesign of some of the production systems. Some basic knowledge of a Lean production system and the use of the Lean toolbox can lead to major improvements, especially when integrated with the simulation methodology, as demonstrated by Goienetxea Uriarte et al. in their LeanSBO framework [92]. One of the key steps here is the identification of the current and target states of the system. Some meetings, Kaizen workshops, and Gemba visits are usually required to accomplish this. A preliminary holistic VSM of the production chain present in the layout should be defined. As an outcome of this first stage, a preliminary version of the current, future, and ideal states should be defined, as well as the main constrains of the facility layout such as shape, available floor space, inputs and outputs, and flows of materials, products, and people.

Diagnosis: During the second stage of the methodology phase, the production and logistics systems are the main focus of the layout. A conscious current and target state analysis is necessary to avoid dedicating effort to a layout design that will not be able to handle new production or logistics adaptations. Firstly, a clear vision of the production system focusing on the machining and assembly aspects should be identified to realize how far these systems have come regarding the objective, vision, strategy, and ideal scenario of the facility defined in the diagnosis stage.

At this stage a key step is determining the different areas or departments in the layout, aisles, and plant services, and identifying the workstations, products and variants, lead times, and storage requirements. A detailed VSM of the current and target states highlighting relevant processes is strongly recommended before continuing to the next stage. DES may be needed depending on the nature and complexity of the systems.

The main outputs of this stage are a defined project team; project plan; data collection plan; some first draft alternative layout scenarios with clearly identified flows of materials, products, and people; and clear pictures of the current, target, and ideal states with their VSMs. Important points to consider are the use of project management tools such as Microsoft Project and the seven management and planning tools referenced in [113]. Peter Stumpf offers some recommendations regarding managing risk in projects with limited resources, increased technological complexity, and stakeholder demands [114]. His paper highlights the engagement of all team members, collaboration, Lean project management techniques such as Obeya rooms for visual project management boards, and brainstorming. Design reviews, management and customer feedback, short design cycles, supply chain risk analysis to minimize unpredictable situations, and continuous review and assessment of the designs [114] are also important. Good project planning can facilitate the allocation of enough time buffers between the main tasks in the project plan to avoid excess non-desired overlapping when delays occur. It can also facilitate analyzing future predicted demand increases or decreases in the short and long term, as well as estimation of the batch sizes and containerization of parts and products [107].

Development: During the third stage, a few possible alternative layout designs should be on the table as well as a decision by the simulation experts on whether to use simulation and/or optimization. If simulation will be used, the availability of the data in the system and selection of the simulation software tools should be analyzed. A simulation expert or team should be assigned to pre-define the time needed to obtain the data for the simulation models, and to translate the conceptual models or VSMs into the simulation modes. The time to verify and validate the models, and create alternative layout scenarios that include the production and logistics systems modeled should also be included. The KPIs at this stage are the time and resources needed, as well as the KPIs commonly used in systems analysis (e.g., throughput, work-in-progress, numbers of transports, defects, and areas).

To be able to detail the process of simulation at this development stage in Figure 17, some previous simulation expertise is necessary. An engineering background or similar and some basic training or a course in DES can be enough to start modeling simple production or logistics systems. Some of the common software tools used in manufacturing include Flexsim, PlantSim, Promodel, and FACTS Analyzer [20, 103]. In many cases, the selection of the simulation software tool is based on the existing expertise at the company. The process of working with simulation can be guided by a simulation methodology, such as Law's methodology in combination with a data management methodology for the data collection and a LeanSBO consideration for the integration of Lean, as presented in Figure 12.

Some of the key steps for a successful development of the project are data collection and detailed VSMs of the current and target states of the system. Emphasis should be placed on the flows and value chain of materials and products in the facility. Value-adding activities and flow strategies such as pull-system and first-in-first-out strategies should be clearly identified. The root cause of defects should be determined, and systematic quality checks for the target state should be in place to minimize the creation of defective parts or products and their continuation downstream.

Once again, the simulation models have to be verified and validated to double-check that all the data in the model is correct and that the model properly represents the conceptual model. Expert support is essential. The validation process to ensure that the model accurately represents the real system for the purpose of the study is usually done by comparing the outcome of the model with reality, analyzing whether the results are accurate enough for the project development.

At this micro-level of implementation, it is also important to analyze the model results to find weaknesses and potential improvements to the system. The identification of bottlenecks (the line and process balancing problem), and analysis of different assembly line shapes or distributions on the shop floor are common examples that can help to visualize the future facility layout [76, 108, 109, 115, 116]. Similarly, once the production system has been simulated to visualize the current state and possible improvements in the target state, the material handling system can be added or simulated independently, depending on the complexity and size of the system. Different alternatives scenarios can be tested, such as the type of material handling system (e.g. conveyors, AGVs, forklifts, tow trains, and manual transports), different routes, vehicle capacities, capacity and number of buffers, length of conveyors, and containers needed.

Depending on the size and complexity of the system, these problems can become significantly large. Hence, assumptions must be considered without compromising the accuracy of the results. When the number of possible solutions or what-if scenarios is significant and becomes time-consuming, multi-objective optimization tools can save time. For example, some conflicting objectives for optimization can be defined, such as lead time vs. number of transports for example, and then a Pareto chart of optimized solutions (alternative scenarios) can be obtained to select the most suitable solutions of the subsystems being analyzed. The optimization process can also be divided into levels. A possible approach is to start modeling the lower level, for example the machining areas and assembly lines. Then the number of operators, operations and buffers between them, lead time, and throughput can be optimized at that level, locally for the subsystems modeled. The next level of optimization is usually the internal logistics system, feeding machining centers or assembly lines, and transferring materials or products after processing. The previously optimized parameters can then be considered as fixed values or requirements at the second level of optimization. The main parameters can be the type and number of transports, storage capacities, and required safety buffers. When the production and logistics systems have been defined, or at least some final candidate solutions or scenarios have been obtained, it is possible to go to the next stage of the methodology, evaluation.

Evaluation: In this fourth stage, some draft layout alternatives have been selected at the planning stage and some alternative production and logistics optimized scenarios have been identified at the development stage. Hence, the requirements, constraints, and possibilities of the current and target states of the production and logistics systems have been thoroughly analyzed and potentially improved with the help of Lean, DES, and optimization if required. It is now time to build the holistic simulation model including the optimized production systems, the final alternatives of internal logistics systems, and some candidate solutions of target and ideal layout designs. Some of the main KPIs used at this stage are a refined number of transports, lead time, work-in-progress, and storage capacity. Layout-related parameters can be the size, shape, size of the departments and distances between them, as well as minimum/maximum throughput of products, lead times, and buffer capacities. It is important that there should be continuous communication between all members of the Lean staff, simulation experts, project managers, and logistics and production staff.

Once there is a clear picture, the selection of final alternative layout designs can be narrowed down. The data obtained during the initial stages such as shape, available surface areas, possible inputs and outputs, and connection with other buildings should be compared. All the data and insight obtained during the third stage of the project regarding production and logistics systems should be reviewed. Then it is time to design the best suitable layout design that will suit the defined production and required logistics systems.

The first step is to consider how the different KPIs for the different layout alternatives differ from one another. These normally relate to items such as production area, distances between different related operation and areas, flows of materials, products, labor, throughput, work-in-progress, and buffer capacity. Common objectives that good designs should include are inherent safety, security, minimized length of the flow, minimized delays, minimized work-in-progress, clear flows of materials or persons, good staff conditions allowing communication between staff and between the layout and managers, accessibility, minimized space required, minimized use of capital, long-term flexibility, and good image [1]. Other important parameters are the location of the stores, supermarkets, or material preparation areas [117, 118].

The so-called “matrix of distances” method is a good tool to double-check the location of the main departments. With some alternative layout designs on the table, this matrix is applied by measuring the distances between the different departments or areas to ensure the best location of the different departments. Usually, the main departments are the input areas from internal and external suppliers, assembly lines, supermarkets, machining areas, painting lines, packing stations, and delivery of goods. Due to the complexity usually prevalent in this kind of layout design, the results obtained from the matrix of distances cannot directly dictate the selection of the definitive final layout design, but it can serve to further narrow down the final selection process of the layout alternatives or to reconfigure the best candidates.

An improvement or construction algorithm such as the graph-based method or the CRAFT method can be used to incrementally improve the initial block layout proposed. Some other tools that can be used to reduce the possible layout alternatives are exact methods such as branch and bound, and dynamic programming. Other options are heuristic algorithms such us construction algorithms and improvement algorithms; intelligent approaches such as genetic algorithms, Tabu search, simulated annealing, ant colony optimization, and particle swarm optimization, meta-heuristics, hybrid meta-heuristics; and mathematical optimization modeling approaches. All are usually based on traditional approaches [110, 119].

Experience with several layout design case studies has shown that mathematical modeling can be a good approach if competent resources are available. The size and complexity of the layout design should be within reasonable bounds, avoiding complex shop floor and department shapes, significant numbers of flows of products or variants, and complex diverse flows of transports, persons, or materials.

Double-checking the final solutions by traditional approaches such as CRAFT can drastically narrow down the number of possible scenarios. In the ideal scenario, the simulation software tool will handle the complexity of the production and logistics models together. If not, objects representing the production systems (e.g., machining and assembly areas, foundries, and packing or painting stations) can be modeled as "black boxes". The black boxes can be modeled with simplified inputs and outputs while respecting their physical location on the layout. This results in a logistics model that can handle production. The final layout alternatives are built in a simulation model in which the production systems are represented in a simplified manner while keeping their input and output parameters (the KPIs of the simulation models at the third stage). By using this black-box modeling procedure, the complexity of the model does not escalate while the simulation software tool can perform properly on a regular computer. Thereafter, the selected suitable logistics system is added to the simulation model to feed and remove material from the production systems (machining areas, production lines, painting and packing areas, etc.). In some cases, more scenarios could be added if there is more than one final transport alternative (e.g., tow trains or AGVs). In the same way, some other scenarios could be put in place for production. However, the limitations of the black-box approach have to be kept in mind. For example, changing production quantities is a reasonable scenario, but changing assembly lines from linear to U-shaped is not, as that level of detail should have been dealt with during the development stage. It is crucial to double-check that all the systems work as a whole and to analyze the performance of the final layout alternatives with the selected production and logistics systems in the final layout designs. The location of some specific areas or departments among the possible locations and material preparation locations can be optimized by maintaining the production requirements (e.g., minimum throughput, maximum work-in-progress, and lead times) and logistics requirements (e.g., number and routes of transports and buffer and conveyor capacities and size).

Conclusion: At this final stage of the project, some useful tools and methods to validate the final alternative layouts must be identified. First, the constant involvement of the management team and subject matter experts in this stage is the key to success. The feasibility of the final layout scenarios should be analyzed, verified, and validated in a workshop. There the Pareto fronts obtained from the optimizations can be analyzed and the importance of the different KPIs can be evaluated. An additional step is the introduction of approximate budgets for the required changes (e.g., for moving departments, machines, lines, changing transportation systems, or constructing new facilities). As stated in paper 6, other aspects to consider here are the feasibility of the solutions regarding implementation times and plans, with questions like: Can line A be shut down for two weeks to be moved to the new location? Is there enough space for the buffer of line A to keep production running? How would those products and materials be transported during the two-week moving period? Finally, it is up to the managers and stakeholders of the project to choose the most suitable optimized layout design.

This micro evaluation level may be more suitable for the technical team in charge of the layout design, without needing to involve managers and stakeholders in the details. The potential results of this research can enable engineering, managers, stakeholders, and decision-makers to increase the productivity and efficiency of different and complex manufacturing systems around the world. The proposed methodology can also be used as a guideline for similar production systems in other sectors, adapting the order of application and the needed resources at the different methodology stages. To ensure the validity of this proposed methodology, an approach to evaluating it is presented in the next subsection.

3.7 APPROACH TO EVALUATING THE METHODOLOGY

The approach to evaluating the FLD design methodology proposed in this research has three major steps. The first step was identifying the utility of the methodology in manufacturing. Layout engineers in several companies were interviewed to discuss the applicability of the methodology, resulting in high interest when discussing the different stages and steps and levels of the methodology.

The second evaluation method was through a detailed case study following the methodology, identifying which steps were missing, and which steps were not suitable or understood by the different team members.

Finally, the methodology was evaluated using the functional resonance analysis method (FRAM) to ensure that the connections between the different steps were represented logically. The different possibilities of those connections were analyzed to identify the variability of the stages and steps of the methodology. Critical activities that can have fatal repercussions if insufficient resources and time are allocated properly were identified.

FRAM is a tool for the design, management, and analysis of series of actions, representing them reliably and systematically using a well-defined format. It was first developed to understand safety procedures such as Safety I. It was developed further for Safety II, determining the root cause of adverse outcomes and understanding how procedures go well. The FRAM approach aims to understand in which conditions the performance variability of a process or procedure can cause the process to become difficult to control [120]. It is a method used to produce a model of how a set of activities are carried out.

FRAM is a way to describe outcomes using the idea of resonance arising from the variability of everyday performance. It identifies and describes essential system functions, and characterizes each function using six basic connection aspects. These aspects are the inputs and outputs of every activity, preconditions, control (keeping track of the development of an activity by another function or activity), time requirements such as temporary conditions, and resource requirements such as matter, energy, or competence. They are represented in Figure 18 with the different letters around the hexagon representing each activity.

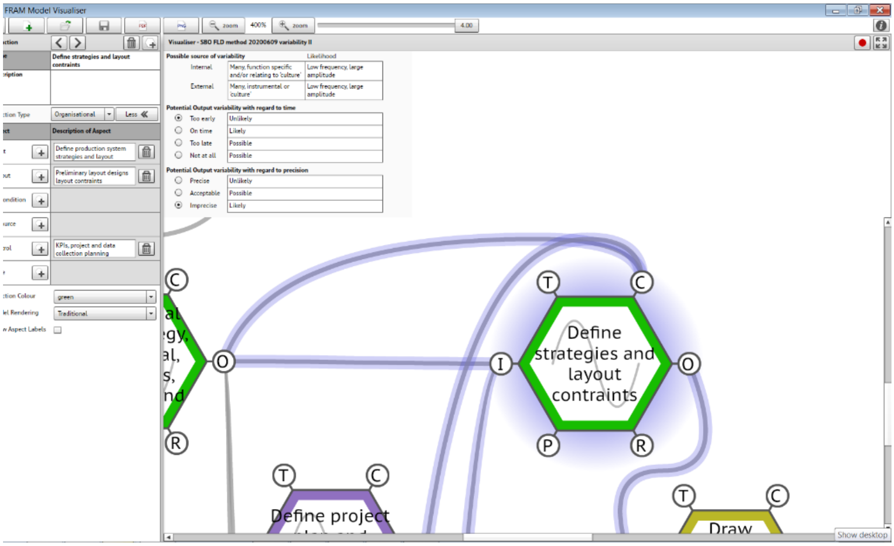

Figure 18. Activity characterization in the functional resonance analysis method.

To build a FRAM model, a set of system functions are first defined and characterized using the above six-aspect characterization criteria. A function represents the necessary means to achieve a goal, or the acts or activities needed to produce a certain result. It can describe something an organization does to achieve that goal, something that people have to do to achieve that goal, or what a technical system has to do to achieve its goal. Then the functions or activities are further characterized by their variability and the possibility of functional resonance based on dependencies or couplings relating to the potential and actual variability of every function presented in Figure 16. Finally, a set of recommendations is developed based on the variability results and coupling of the different activities. By adding or removing more resources or time in the real system, the variability of those activities can be reduced or increased accordingly. Usually allocating more time or resources to a step in the FLD methodology can reduce the variability of the output, for example, by ensuring that the outcome of that step will occur within the expected boundaries of accuracy and time. Subject matter experts should be involved in each step of the methodology for this process.

In this case, using the defined inputs and outputs of every activity as well as the different characterization and variability shown in Figure 18, every activity or function is defined in the model, representing the general activities for the proposed methodology for FLD. These connections with their dependencies/couplings and variabilities allow the variability of the potential outcome to be defined. Using this process FRAM characterizes the potential variability of the FLD methodology, identifying those activities with a higher risk of producing an unwanted outcome. FRAM will also identify processes that may lead to desired outcomes, for example, the proper plan for data collection, or the proper definition of the expected time and accuracy for verification and validation. The FLD methodology with SBO for evaluation with the FRAM approach is presented in Figure 19.

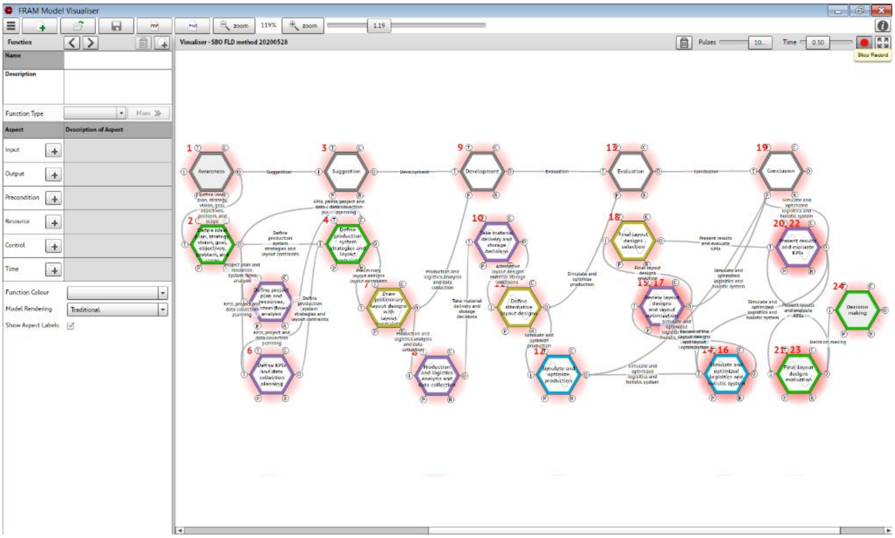

Figure 19. Functional resonance analysis method applied to FLD methodology with SBO.

All activities are also classified by their nature, as technological, organizational, or human. Human activities have the highest variability with a less precise outcome or high amplitude; technological activities the lowest variability with the most precise outcome or lowest amplitude; organizational activities vary with low frequency or variability and high amplitude. The sources of the variability can be external or internal. External variability is related to the variability generated by the work environment such as inappropriate operating conditions, pressure from co-workers, or environmental or legal regulations. Internal variability is related to performance issues, software or machine issues, individual human factors, or organizational group pressures. The characterization of variability is the starting point in understanding how the coupling between functions can lead to unexpected results. Figure 20 is an example of characterizing an organizational activity.

Possible source of variability		Likelihood
Internal	Many, function specific and/or relating to 'culture'	Low frequency, large amplitude
External	Many, instrumental or 'culture'	Low frequency, large amplitude
Potential Output variability with regard to time		
◉ Too early	Unlikely	
○ On time	Likely	
○ Too late	Possible	
○ Not at all	Possible	
Potential Output variability with regard to precision		
○ Precise	Unlikely	
○ Acceptable	Possible	
◉ Imprecise	Likely	

Figure 20. Variability characterization criteria in the functional resonance analysis model.

These characterization criteria allow the definition of the variability regarding time, precision, and the nature of the activity. Activities should be reviewed to pay special attention to their connections, resources, and time constraints. The characterization criteria for this model were defined by continuous communication with the engineering teams in various industrial case studies and by a set of interviews. The interviews included an explanatory survey study asking engineers and project managers in several companies about critical activities. Figure 21 shows the activities with high outcome variability.

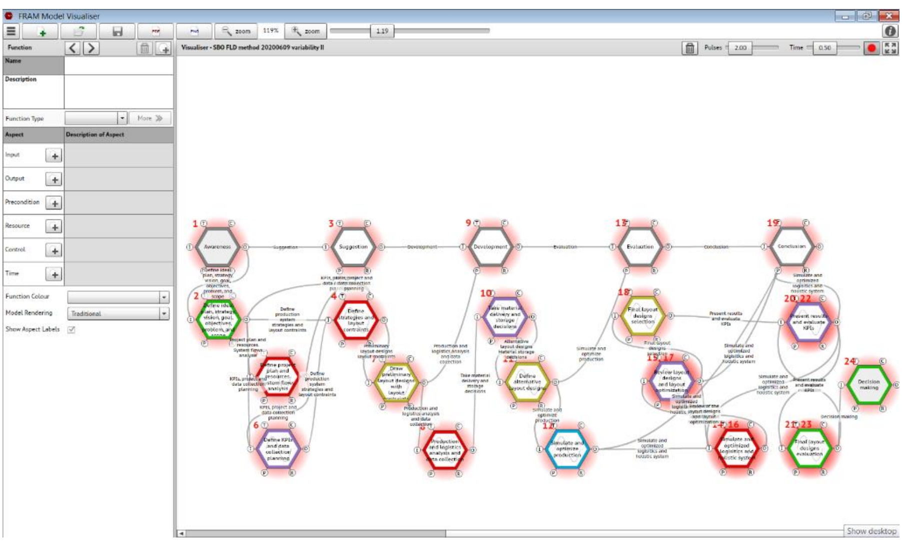

Figure 21. Critical activities functional resonance analysis model.

The activities highlighted in red in the figure represent those activities with a higher variability, with a high frequency and high amplitude of variation. Those activities trigger unwanted variability in downstream processes, escalating the amplitude of the variability. The reason for the higher variability is human and organizational factors combined with the risk of performing the activities too early or too late or with an imprecise outcome. These activities represent the project plan and all that it contains: project resources, analysis of the system flows, definition of strategies, layout constraints and requirements, the data collection, and the simulation and optimization of the logistics and holistic systems. These activities reveal all the sources of risk. These include management underestimating the time required for the allocation of resources, not meeting the requirements related to the production strategies and constraints, unclear aims and objectives, strategy, not planning long-term, and incomplete data collection. A continuing holistic view of the processes involved in the layout and its verification and validation approach is required to avoid deficiencies.

For more complex models, automatic variability analysis would be very useful to analyze the outcome variability of the system. However, this is not possible in the development stage of FRAM. The implementation of the FRAM approach for more complex methodologies and systems would improve considerably if automatic variability analysis could be integrated into FRAM together with statistical distributions. The statistical distributions could quantify the outcome of the different activities and their connections taking into account the variability of each activity.

The FLD methodology has the potential to be significantly useful to managers and stakeholders in complex and midsize and large manufacturing systems. It can save time and resources for engineering teams and avoid undesirable changes in layout designs. A summary of the results will be presented in the next chapter, including the answers to the proposed RQs and a summary of the main industrial application studies performed during this research.

SUMMARY OF RESULTS

CHAPTER 4
SUMMARY OF RESULTS

The outcome of this research is summarized in the form of a methodology addressing the improvement and design of production and logistics systems taking the configuration of the facility layout into account. This methodology uses DES and SBO techniques. It was validated by case studies analyzing its implementation in industrial environments. It was also validated by using the FRAM approach for the variability analysis and implementation order of the methodology steps. It is based on the appended paper 7, *Simulation-based Optimization Methodology for Production System Layout Design in Manufacturing*. The outcome of the implementation is beneficial for the main research partner as well as for similar medium-size and large manufacturing industries. Besides accomplishing the aim of this thesis, the presented RQs are also addressed in the outcome of this research project.

4.1 ANSWERS TO RESEARCH QUESTIONS

Regarding the aim of this thesis and the proposed RQs, the relationship between the research strategies and appended publications was established for the proper development of the thesis. This is summarized in Figure 22:

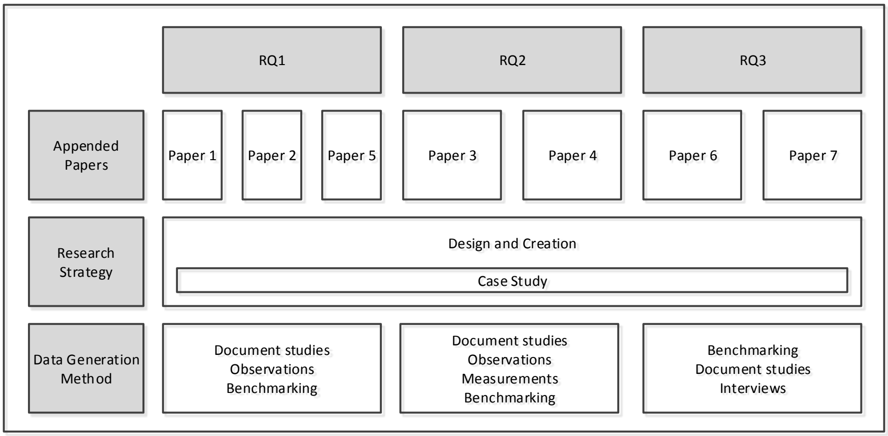

Figure 22. Relationship between RQs, research strategies, and data generation methods.

The top part of this figure presents the RQs to indicate the connection with the appended papers, the research strategies, and how the data were obtained. The research strategy was based on the design and creation strategy. However, as this is industrial research, case study research was used to integrate the industrial case studies with the design and creation research strategy. Here are the RQs and their answers.

RQ1. What are the challenges for the design and improvement of facility layouts taking into account process, flow, and logistics requirements?

An initial step to answering this question is the clarification of the problem description and the literature review of FLD. Industrial case studies with SBO related to the optimization of processes, flows, and logistics in manufacturing were presented in appended paper 1, *Production Logistics Design and Development Support: A Simulation-Based Optimization Case Study*, and in paper 2, *Integrating Simulation-Based Optimization, Lean, and the Concepts of Industry 4.0*. The complexity of these systems is increased by stochasticity, as well as by the number of variables and parameters necessary to design optimized facility layouts. Industry 4.0 plays an important role due to the potential contribution to SBO of digitalization, data collection, and information management allowing a wider and more effective use of simulation and optimization in manufacturing today.

An analysis of the major theoretical challenges of working with FLD taking into account production and logistics requirements and constraints is presented in paper 5, *Challenges of Simulation-Based Optimization in Facility Layout Design of Production Systems*, and Table 3 and Table 4. The following challenges were highlighted as affecting FLD: complexity, dynamicity, randomness, and simultaneity. Cost, integration, process, and safety effects are challenges to the resources required for FLD. An analysis of empirical challenges was also performed in Paper 5, and shown in Table 9. One of the major challenges in facility layout is an overall or holistic manufacturing system approach. The need for a holistic approach is usually not appreciated. Generally the problem of FLD is isolated from internal logistics systems including material handling and storage, as well as the flows of materials, staff, and products. Another major challenge is the need to provide for adaptability in current manufacturing to adapt to the trend toward mass customization rather than mass production.

A flexible and adaptable layout is a requirement to be able to handle several flows of products with fluctuating demand. Tools to analyze, visualize and control these flows and layout adaptations are a necessity today. Simulation has significant potential for analyzing and evaluating different configurations without the need to interrupt production. However, there are also other challenges such as a lack of competence and expertise in manufacturing companies around the world, especially related to layout design. Furthermore, it is still unclear how to work with these questions and SBO. Relevant literature can be found about production, logistics, and layout separately. However, there is no methodology available to guide the use of simulation and optimization in the design of facility layouts.

RQ2. How can SBO address these challenges to support FLD in manufacturing systems taking into account process, flow, and logistics requirements?

Simulation and optimization were integrated into the methodology to address the challenges for the design of facility layout taking into account production and logistics requirements. The main reasons are the stochasticity of the parameters of the manufacturing system and the related activities taking place on the facility layout. Paper 3, *Improving the Material Flow of a Manufacturing Company via Lean, Simulation and Optimization*, highlighted the benefits of Lean, especially for process and flow optimization and its contribution to project planning when combined with simulation and optimization. Reducing uncertainty is important when developing new facility layouts, as presented in paper 4, *Simulation-Based Optimization for Facility Layout Design in Conditions of High Uncertainty*. This paper identifies the need to use SBO at specific stages of the FLD process, and its contribution to reducing uncertainty in the specific stages of conceptual layout, detail layout, and evaluation or test.

The first step in addressing the challenges in layout design is increasing the competence and expertise in simulation and optimization in manufacturing companies. At least one expert in simulation should be involved if a company wants to stay ahead of competitors and new factories in terms of innovation and flexibility requirements. The use of simulation can then be expanded to other problems and departments. Universities and research centers regularly offer skill development courses for companies; companies and organizations should make use of the opportunity to increase their employees' knowledge and expertise not just in simulation, but also in optimization and topics like Lean, system improvement, data collection techniques, and project management.

Once the required competence is available in the project team, the proposed methodology is a guide to designing flexible and optimized facility layouts. This methodology is the answer to the main research question of this industrial thesis.

RQ3. How can a methodology based on SBO be developed for FLD in manufacturing taking into account process, flow, and logistics requirements?

To facilitate the use of SBO in the design of facility layouts the FLD methodology with SBO is proposed. This methodology is presented in paper 6, *Holistic Simulation-Based Optimization Methodology for Facility Layout Design with Consideration to Production and Logistics Constraints*, and detailed and evaluated in paper 7, *Simulation-based Optimization Methodology for Production System Layout Design in Manufacturing*.

The main contribution of the methodology is the definition of the major stages, generic steps, and detailed specific steps for developing facility layouts taking production and logistics requirements into account, and supported by simulation and optimization. It can be used as a guideline by managers, stakeholders, and engineers for the development of this kind of FLD project. It can also be used in a generic way as a draft guideline for different layout projects in small companies, or in other sectors outside manufacturing.

The answers to the RQs and the published papers demonstrate that the integration of DES and SBO in the design of facility layouts, under the umbrella of the design and creation research strategy and supported by different case studies, can be a useful approach to increase the capacity and use of manufacturing production systems, internal logistics systems, and facility layouts. The trial and validation of potential improvements in the system can be performed using the implementation guideline without interrupting production. The validation was performed using the FRAM method, interviews, and in-depth case studies.

A number of case studies were analyzed implementing DES and SBO for the improvement and design of different layout systems. Some case studies were performed with the main industrial partner, where simulation and optimization were combined to improve the performance of an assembly line, working with the number of resources, and the size of the buffers. Related case studies with this partner were performed to design optimized internal logistics systems minimizing the required conveyor lengths used as buffers and the number of required transports. Some other studies used SBO to design different possible layout scenarios taking into account the possibility of merging existing assembly lines. In some of the presented papers, Industry 4.0 and Lean were used to support the simulation methodology by establishing a base of digitalization and connectivity, and system improvement approaches, respectively.

The research in these case studies was used as the base to answer the proposed RQs. The SBO case studies were developed in a common format, working with simulation and optimization for system improvement in production systems, focusing on production, internal logistics, and facility layout. The following subsection presents a summary of some of the most relevant case studies in this research using the proposed methodology.

4.2 INDUSTRIAL APPLICATION STUDIES

The main industrial case study during this research was with the industrial partner Xylem Water Solutions, an American corporation present in more than 150 countries. Its largest factory is in Emmaboda, in southern Sweden. Xylem Water Solutions Manufacturing AB primarily produces a large range of water pumps (Figure 23). The Emmaboda factory makes pumps and mixers in sizes from 0.5 kW up to 700 kW and employs about 1200 people. It is the main arena for the development of this research.

A case study involves studying or analyzing a unique phenomenon in its natural environment in a detailed manner so as to generate meaningful and relevant theory and archive good knowledge of actual conditions [5]. Case studies are usually suitable for developing theory as well as for testing or refining theories [5]. A case study can be approached as either a single-case design, or as a multiple-case design, or multiple-case study. The inclusion of the term “holistic” in the proposed methodology refers to the involvement of one unit of analysis, FLD, with multiple-case designs drawing on SBO in production and internal logistics systems related to the layout. Production and logistics requirements were included to obtain a deep understanding in FLD with SBO. The large family of products (Figure 23) increases the complexity of the main industrial partner considerably.

Figure 23. Example of different product families of a water-pump manufacturer.

The production manager at Xylem explained, “The challenge is that we have a complex product mix and a lack of space on our shop floor. The focus for us at Xylem has been optimization of logistic flows in manufacturing, especially in the production areas where we have the highest volume of products and material flows.”

The case studies developed with this partner are summarized here. Some of these projects were developed as part of engineering theses with the engineering team of the organization. The main layout project developed for this thesis was the development of a new facility layout for the main building of the factory. It involves up to two-thirds of the total production of the factory. Several subprojects are also included in the development of the methodology presented in this thesis.

This project aimed to modify and improve the layout including the flows of products and materials. A review of Lean procedures to minimize waste was considered, looking for increased productivity and adaptability. The goals of the project were to increase productivity in terms of products per person and shift, reduce lead times and stock levels, and facilitate adaptability and increase the product mix. The overall project length was established to be five years.

The desired outcome was a new adaptive layout design capable of handling higher production volumes taking into consideration normal seasonal variations for the next ten years after its design. The new layout should be able to cope with an expected increase in volume in ten years and future expansion after that. The key considerations of this project included simulation modeling of the family of products manufactured in different machining areas and assembly lines, redefinition of transport containers, introduction of kitting procedures, redefinition of internal transports including minimizing numbers and increasing safety, minimization of storage requirements, the use of a pull Kanban system, redistribution of departments on the shop floor, integration of new procedures for the next generation of products, the study of new a location for the incoming goods, and the redefinition of how products are transferred from the assembly lines to a newly designed painting line. Many of these tasks were performed as subprojects. Some results are not included here due to confidentiality. The different projects documenting this outcome are defined below:

- Bottleneck analysis and capacity analysis regarding transports, operators, and processes of a new automation-adapted assembly line with kitting. This study was included in appended paper 1, *Production Logistics Design and Development Support: A Simulation-Based Optimization Case Study*, and determined the optimal number of buffers, their capacity, and the number of operators for the different processes on the assembly line.
- A conceptual robust design of an assembly line with a high product mix supported by Lean and SBO. This case study was included in paper 4,

Simulation-Based Optimization for Facility Layout Design in Conditions of High Uncertainty, as case study C. The main result was the redesign of one of the assembly lines implementing Kanban, reducing waste, and using optimization to analyze the impact of standardizing processes and the number of operators in the production capacity.

- Increasing the material flow efficiency in a manufacturing company, as presented in paper 3, *Improving the Material Flow of a Manufacturing Company via Lean, Simulation and Optimization*. This resulted in an optimized solution for the transport of materials from an input hub to different machining areas, significantly reducing lead times, minimizing the number of transports and storage capacity required.
- Analysis and simulation of production flows at a manufacturing company with simulation and optimization combined with Lean. This resulted in the design of a pull system and transport system and the relocation of some machining processes, reducing waste and increasing capacity considerably.
- System analysis, improvement, and visualization of a manufacturing workflow using DES. A complete analysis of parts and products on the facility layout was performed for a bottleneck analysis, identifying some critical sub-assembly processes and proposing an automated solution.
- Analysis, design, and evaluation of a material flow transportation system with SBO. This resulted in an improved transportation system by redefining the material flows on the facility layout and the transportation method, minimizing lead time and work-in-progress by at least 20%.
- Design and analysis of a material handling system with SBO. Several material delivery solutions were proposed and analyzed for the relocation of a painting line fed by eight different assembly lines. The number of transports and required buffer capacity were minimized and lead times were significantly reduced. The proposed alternatives included roller conveyors, tow trains, AGVs, and overhead conveyors.
- An SBO approach for automated vehicle scheduling on assembly lines. This combined Lean and simulation, analyzing the problem of feeding rearranged assembly lines, minimizing the number of transports, lead times, and work-in-progress. Optimizing the location of supermarket storage was presented as part of the explanation of the methodology in appended paper 7, *Simulation-based Optimization Methodology for Production System Layout Design in Manufacturing*.

These industrial or application case studies contributed significantly to developing the contribution of the industrial thesis as well as to the development of the main research partner. The new facility layout contributes significantly to the visibility and control of material flows, reduces waste, lead times, and work-in-progress. It also increases safety and adaptability for new products and accommodates future layout redistribution.

CONCLUSIONS AND FUTURE WORK

CHAPTER 5
CONCLUSIONS AND FUTURE WORK

This chapter presents a summary of this thesis and the conclusions reached. The contributions to knowledge and practice are summarized, and potential future research is highlighted.

5.1 SUMMARY AND CONCLUSIONS

The fierce competition manufacturing companies are facing and the need for mass customization make adaptation and flexibility crucial issues in manufacturing systems. In order to achieve adaptable and flexible production, it is essential to have optimized flows of materials and products in facility layouts. However, many factories have non-optimized facility flows and layouts. In many cases, this is the result of successive redesign of their production and logistics systems over many years without an overall strategy. The shortened product life cycle, the requirements of just-in-time production, and the numerous global suppliers and production sites greatly increase the complexity of manufacturing systems.

The following are some of the major challenges of FLD identified in this thesis:

- The intrinsic complexity of manufacturing systems due to the high number of entities involved and their interrelations.
- The dynamicity of manufacturing systems due to the number of entities and products and changes in demand.
- The difficulty inherent in attempting to address all the problems related to layout simultaneously rather than sequentially.
- The uncertainty of the return on the high cost of designing new facility layouts.
- The lack of information and the need to integrate information from different sources to design and evaluate different layout designs.
- The reliance on individuals rather than standardized processes.
- The lack of focus on human and safety factors due to the almost exclusive focus in operational performance.

This thesis recommends using DES and SBO to support the optimization of facility layouts and their production and logistics requirements. It investigated how the combination of simulation and optimization can support the redesign and improvement process while taking into account the production and logistics flows involved in existing facility layouts. The application of SBO offers significant benefits to companies when used to optimize their facility layouts and related production and logistics flows requirements and constraints. Using digitalization and the concepts of Industry 4.0 to access, collect, and manage data can considerably enhance the FLD process in manufacturing companies.

In the thesis a holistic and generic methodology based on SBO that considers production and logistics is proposed for the design of facility layouts. The methodology is intended to contribute to increase productivity and efficiency, helping companies to survive in a competitive market. The theory developed and the methodology were tested in several industrial case studies as well as by benchmarking and application of the functional resonance analysis method. This method allows testing, adapting, and improving of the proposed methodology to predict future outcomes of its implementation. Once the outcome has been analyzed and approved, the FLD methodology with SBO is considered to be valid for that application in manufacturing.

This methodology can support decision-makers, managers, and stakeholders in improving their production and logistics systems as well as the facility layout in order to meet the company's mid- and long-term goals. A further benefit of the methodology is that it minimizes disruption of production in the design and implementation phases and avoids trial and error approaches. The methodology has been evaluated and shown to be a useful decision support system for manufacturing companies. The methodology can optimize production, increasing flow efficiency and resource utilization, maximizing the utilization of the layout, and facilitating its design. Addressing these issues can help manufacturing industries to increase their flexibility, adaptability, competitiveness, and growth.

5.2 CONTRIBUTION TO KNOWLEDGE

The literature review undertaken for this thesis identified the lack of any holistic methodology for FLD including process, flow, and logistics optimization that could be applied generically in manufacturing companies. The contribution of the first RQ was to identify the challenges of FLD with SBO in manufacturing. Many of these challenges are still present in traditional manufacturing companies, mainly due to the simultaneity and stochasticity of the processes and systems related to layouts that have been adapted over time.

The contribution of RQ2 was to show how SBO can be used to address the challenges identified in RQ1 by using a combination of DES and SBO to handle stochasticity in complex manufacturing systems, helping to manage the very large amounts of data that define the performance of the system.

This thesis's main contribution to knowledge is the proposed methodology, which was addressed under RQ3, for using SBO to design optimized layouts taking into account process, flow, and logistics requirements. Using this methodology the design phase of facility layouts can be performed without disturbing the production or logistics systems. The power of simulation allows verification and validation, modeling of what-if scenarios, and optimization to be conducted without the need to interrupt or disturb the real system. Guidelines for a structured and logical process for implementing production and logistics changes in manufacturing systems are also part of the methodology.

This methodology has been constructed as a generic way to support the process of designing facility layouts in manufacturing companies. Its holistic approach also supports the optimization of different processes, production and logistics flows in the facility layout, including transports, storage facilities, and labor.

The design of optimized facility layouts with SBO was identified as the area of study. The challenges, key variables, and relationships when working in this area were also identified. The main challenges are as follows:

- The complexity of the simulation models, with a high risk of models incorporating too much detail, with the result that the FLD process becomes tedious and time-consuming. On the other hand, in some cases a model may be unusable due to too many simplifications.
- Noise, that is, dealing with imperfect estimates in stochastic simulation.
- Evaluation, as it may be hard to recognize optimal solutions.
- Lack of understanding or technical competence in SBO in manufacturing companies.
- Deficiencies in routines and processes related to SBO.
- Technology barriers due to skepticism and doubts related to the use of new technologies such SBO.

The set of activities and procedures defined in the stages and steps of the proposed methodology can make a significant contribution to overcoming these challenges. The activities and procedures can also advance research by establishing a base for a more complete, structured, and comprehensive way of working with FLD problems.

5.3 CONTRIBUTION TO PRACTICE

The research conducted for this thesis focused on process, flow, and logistics optimization in a holistic way for the redesign of facility layouts. By modeling different types of production systems such as production lines and machining areas, as well as their flows of materials and products and related logistic systems, the design and improvement of the facility layouts can be optimized with SBO. The transports, flows of materials and products, labor, production processes, and the distribution of the layout were considered. This methodology can be used to evaluate different scenarios, helping to fulfill companies' visions, strategies, and ideal plans for their facility layout while reducing the risk and uncertainty usually associated with this kind of change. A set of logical steps was identified to provide a clearer process in the search for optimized facility layout designs taking into account process, flow, and logistics requirements.

The implementation of the methodology proposed in this thesis contributed positively to modifying and optimizing the facility layout of the main industrial partner in cases where there was high initial uncertainty. The implementation of the methodology with SBO significantly contributed to reducing this uncertainty. The optimization included several flows of materials and products, stores, logistics systems, and assembly and painting lines. The results enabled the company to increase capacity and productivity while reducing lead times and storage requirements. This facilitated the integration of new products and their related material and logistics flows, as well as the design of a robust facility layout able to cope with future adaptations and volume increases.

The presented methodology is intended to increase the productivity and service levels of similar manufacturing systems. Additionally, it can serve as a guideline to related production systems. The resultant increase in productivity and service levels can help manufacturing companies with very old factories compete with new factories built from scratch. The results can provide information to managers, stakeholders, and decision-makers to support the implementation of changes and major redesigns in their manufacturing systems.

In various industrial case studies, this methodology has been shown to be useful in practice for improving facility layouts and providing a decision support system. Ola Gustavsson, the production manager at Xylem has this to say: “Through thesis projects we have had several subprocesses analyzed with the combined toolboxes of simulation and Lean. Something that we could not have done ourselves, the results of these analyses have helped us get a good basis when making investment decisions to improve our productivity in logistics and machine cells.” The work presented in this thesis has thus positively impacted the manufacturing development of the main industrial partner as well as expanding our knowledge.

5.4 FUTURE WORK

This research establishes a base for the design of optimized facility layouts taking into account production and logistics systems and constraints. Future work should analyze the implementation of the methodology in different kinds of manufacturing systems, including small manufacturing companies. Other possible research includes extrapolating the proposed methodology to domains outside manufacturing; for example, studying its implementation for the redesign of layouts in healthcare systems such as hospitals, emergency departments, and operating theaters. The generalization of the proposed methodology and its application to other domains are the strongest potential of this thesis.

In addition, adapting FLD to the Industry 4.0 paradigm may offer advantages, for example, by designing a holistic virtual copy or digital twin of the system, connected with the enterprise resource planning system of the factory in real time. This methodology could become a vital tool in the future for the analysis, control, and redesign of flexible and adaptable manufacturing systems and facility layouts, aiming to optimize in real time the high number of processes, flows, and layouts for different products and variants in the era of mass customization.

The work done in this thesis could be extended to provide guidelines for the design of facility layouts from scratch. However, such an extension would require thoughtful consideration of architectural and construction perspectives and characteristics, close collaboration with the architect and engineering teams, as well as the design of the required technical installations.

REFERENCES

REFERENCES

1. Slack, N., A. Brandon-Jones and R. Johnston, *Operations management*. Pitman Publishing, 2013.
2. Roser, C., M. Nakano and M. Tanaka, *Holistic Manufacturing System Analysis*. Presented at the International Conference on Advanced Mechatronics, 2004, Simulation 4, M4.
3. Walter, E., *Cambridge advanced learner's dictionary*. Cambridge university press, 2008.
4. Banks, J., *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*. John Wiley & Sons, Inc., 1998.
5. Säfsten, K. and M. Gustavsson, *Forskningsmetodik: för ingenjörer och andra problemlösare*. Studentlitteratur AB, 2019.
6. Dhéret, C. and M. Morosi, *Towards a New Industrial Policy for Europe. EPC Issue Paper No. 78,* 2014.
7. Jovane, F., E. Westkämper and D. Williams, *The ManuFuture Road to High-Adding-Value Competitive Sustainable Manufacturing*. In *The ManuFuture Road*, 2008, pp. 149-163.
8. Robinson, S., *Discrete-Event Simulation: From the Pioneers to the Present, What Next?* In *The Journal of the Operational Research Society*, 2005. 56(6): pp. 619-629.
9. Tate, W.L. and L. Bals, *Outsourcing/offshoring insights: going beyond reshoring to rightshoring*. In *International Journal of Physical Distribution & Logistics Management*, 2017, 47(2/3), pp. 106-113.
10. Kulkarni, M., S. Bhatwadekar, and H. Thakur, *A literature review of facility planning and plant layouts*. In *International Journal of Engineering Sciences & Research Technology*, 2015, 4(3), pp. 35–42.
11. Pourhassan, M. R. and S. Raissi, *An integrated simulation-based optimization technique for multi-objective dynamic facility layout problem*. In *Journal of Industrial Information Integration*, 2017, 8, pp. 49-58.
12. Macías, E. J. and M. P. de la Parte, *Simulation and optimization of logistic and production systems using discrete and continuous Petri nets*. In Simulation, 2004, 80(3), pp. 143-152.
13. Dawson, C., *For Toyota, Patriotism and Profits May not Mix*. In *The Wall Street Journal*, 2011, pp. A1-A6.
14. Zha, S., Y. Guo, S. Huang, Q. Wu and P. Tang, *A hybrid optimization approach for unequal-sized dynamic facility layout problems under fuzzy random demands*. In Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2020, 234(3), 382-399.
15. Drira, A., H. Pierreval and S. Hajri-Gabouj, *Facility layout problems: A survey*. In *Annual Reviews in Control*, 2007, 31(2): p. 255-267.

16. Robinson, S., *Conceptual modelling for simulation Part II: a framework for conceptual modelling*. In *Journal of the Operational Research Society*, 2008, 59(3), pp. 291-304.
17. Jalonen, H. and A. Lehtonen, *Uncertainty in the innovation process*. Presented at the *European Conference on Innovation and Entrepreneurship*, 2011.
18. Comstock, M., K. Johansen and M. Winroth, *From mass production to mass customization: enabling perspectives from the Swedish mobile telephone industry*. In *Production Planning & Control*, 2004, 15(4), pp. 362-372.
19. Tompkins, J. A., J. A. White, Y. A. Bozer and J. M. A. Tanchoco, *Facilities planning*. John Wiley & Sons, 2010.
20. Zhang, Z., X. Wang, X. Wang, F. Cui and H. Cheng, *A simulation-based approach for plant layout design and production planning.* In *Journal of Ambient Intelligence and Humanized Computing*, 2019, 10(3), pp. 1217-1230.
21. Shrouf, F., J. Ordieres and G. Miragliotta. *Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm*. Presented at *IEEE International Conference on Industrial Engineering and Engineering Management*, 2014, pp. 697-701.
22. Karabegović, I., A. Kovacevic, L. Banjanovic-Mehmedovic and P. Dašić, *Handbook of Research on Integrated Industry 4.0 in Business and Manufacturing*. IGI Global, 2020.
23. Sisodia, R. and D. Villegas Forero, *Quality 4.0–How to Handle Quality in the Industry 4.0 Revolution*. Master's thesis, Chalmers University of Technology, 2019.
24. Flores-Garcia, E., M. Wiktorsson, M. Jackson and J. Bruch, *Simulation in the production system design process of assembly systems*. Presented at *Winter Simulation Conference 2015, pp. 2124-2135.*
25. Flores-García, E., *Decision Making in Production System Design–Approaches and Challenges.* In *International Journal of Production Research*, 2017.
26. Juneja, P., *Facility layout objectives, design and factors affecting the layout.* Management Student Guide, 2015. https://www.managementstudyguide.com/facility-layout.htm
27. Krishnan, K.K., S.H. Cheraghi and C.N. Nayak, *Dynamic From-Between Chart: a new tool for solving dynamic facility layout problems.* In *International Journal of Industrial and Systems Engineering*, 2006, 1(1-2), pp. 182-200.
28. Moslemipour, G., T.S. Lee and D. Rilling, *A review of intelligent approaches for designing dynamic and robust layouts in flexible manufacturing systems.* In *The International Journal of Advanced Manufacturing Technology*, 2012, 60(1-4), pp. 11-27.
29. Sanli, H.E. and F. Eldemir, *Spiral facility Layout Generation and Improvement Algorithm*. In *Progress in Material Handling Research*, 2010, paper 5.
30. Muther, R., *Systematic Layout Planning*. Management & Industrríal, 1973.
31. Yang, T. and C.-C. Hung, *Multiple-attribute decision making methods for plant layout design problem*. In *Robotics and Computer-Integrated Manufacturing*, 2007, 23(1), pp. 126-137.
32. Smutkupt, U. and S. Wimonkasame. *Plant layout design with simulation*. Presented at *Proceedings of the International MultiConference of Engineers and Computer Scientists,* 2009. Vol. 2, pp. 18-20.
33. Farahani, R. Z., M. SteadieSeifi and N. Asgari, *Multiple criteria facility location problems: A survey*. In *Applied Mathematical Modelling*, 2010, 34(7), pp. 1689-1709.
34. Gould, O., A. Simeone, J. Colwill, E. Woolley, R. Willey and S. Rahimifardal, *Optimized assembly design for resource efficient production in a multiproduct manufacturing system*. In *Procedia CIRP*, 2017. 62, pp. 523-528.

35. Wanniarachchi, W., R. Gopura and H. Punchihewa, *Development of a layout model suitable for the food processing industry*. In *Journal of Industrial Engineering*, 2016, pp. 1-8.

36. Kia, R., A. Baboli, N. Javadian, R. Tavakkoli-Moghaddam, M. Kazemi and J. Khorrami, *Solving a group layout design model of a dynamic cellular manufacturing system with alternative process routings, lot splitting and flexible reconfiguration by simulated annealing*. In *Computers & Operations Research*, 2012, 39(11), pp. 2642-2658.

37. Kia, R., F. Khaksar-Haghani, N. Javadian and R. Tavakkoli-Moghaddamal, *Solving a multi-floor layout design model of a dynamic cellular manufacturing system by an efficient genetic algorithm*. In *Journal of Manufacturing Systems*, 2014. 33(1), pp. 218-232.

38. Azadeh, A., R. Heydari, R. Yazdanparast and A. Keramati, *An integrated fuzzy simulation-mathematical programming approach for layout optimization by considering resilience engineering factors: a gas transmission unit*. In *World Journal of Engineering*, 2016, 13(6), pp. 547-559.

39. Zhang, G., T. Nishi, S. D. Turner, K. Oga and X. Li, *An integrated strategy for a production planning and warehouse layout problem: Modeling and solution approaches*. In *Omega*, 2017, 68, pp. 85-94.

40. Derhami, S., J.S. Smith and K.R. Gue, *A simulation-based optimization approach to design optimal layouts for block stacking warehouses*. In *International Journal of Production Economics*, 2019, 223, 107525.

41. Wangta, P. and P. Pongcharoen, *Designing machine layout using tabu search and simulated annealing*. In *Naresuan University Journal: Science and Technology*, 2013, 18(3), pp. 1-8.

42. Önüt, S., U.R. Tuzkaya and B. Doğaç, *A particle swarm optimization algorithm for the multiple-level warehouse layout design problem*. In *Computers & Industrial Engineering*, 2008, 54(4), pp. 783-799.

43. McKendall Jr, A.R. and W. Liu, *New Tabu search heuristics for the dynamic facility layout problem*. In *International Journal of Production Research*, 2012. 50(3), pp. 867-878.

44. Zha, S., Y. Guo, S. Huang and S. Wang, *A Hybrid MCDM Method Using Combination Weight for the Selection of Facility Layout in the Manufacturing System: A Case Study*. In *Mathematical Problems in Engineering*, 2020, 234 (3), pp. 382-399.

45. Jithavech, I. and K. K. Krishnan, *A simulation-based approach for risk assessment of facility layout designs under stochastic product demands*. In *The International Journal of Advanced Manufacturing Technology*, 2010, 49(1-4), pp. 27-40.

46. Tam, K. Y., *Genetic algorithms, function optimization, and facility layout design*. In *European Journal of Operational Research*, 1992, 63(2), pp. 322-346.

47. Shah, D., K. Krishnan and M. Dhuttargaon, *Dynamic facility planning under production and material handling capacity constraints*. In *Journal of Supply Chain and Operations Management*, 2015, 15(1), pp. 78-107.

48. Balamurugan, K., V. Selladurai and B. Ilamathi, *Design and optimization of manufacturing facilities layouts*. In *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2006, 220(8), pp. 1249-1257.

49. Jiang, S. and A. Nee, *A novel facility layout planning and optimization methodology*. In *CIRP Annals*, 2013, 62(1), pp. 483-486.

50. Prajapat, N., T. Waller, J. Young and A. Tiwari, *Layout optimization of a repair facility using discrete event simulation*. In *Procedia CIRP*, 2016, 56, pp. 574-579.

51. Ng, A., J. Svensson and M. Urenda, *Introducing Simulation-based Optimization for Production Systems. Design to Industry: the FACTS Game*. Presented at

International Conference on Flexible Automation and Intelligent Manufacturing, 2008, pp. 1359-1372.

52. Tempelmeiera, H., *Practical considerations in the optimization of flow production systems*. In *International Journal of Production Research*, 2003, pp. 149-170.

53. Banks, J., J. S. CARSON II and L. Barry, *Discrete-Event System Simulation*. Pearson Prentice, 2005.

54. Law, A. M. and W. D. Kelton, *Simulation Modeling and Analysis*. The McGraw-Hill Companies, 2000.

55. Korde, M. R., D. A. Sahu and A. Shahare, *Design and development of simulation model for plant layout*. In *International Journal of Science Technology & Engineering*, 2017, 3(9), pp. 446–449.

56. Dotoli, M., M.P. Fanti, C. Meloni and M. Zhou, *A decision support system for the supply chain configuration*. Presented at *IEEE International Conference on Systems, Man and Cybernetics, 2003, pp. 2667-2672.*

57. Javahernia, A. and F. Sunmola, *A simulation approach to innovation deployment readiness assessment in manufacturing*. In *Production & Manufacturing Research*, 2017, 5(1), pp. 81-89.

58. Sengupta, R.N., A. Gupta and J. Dutta, *Decision sciences: theory and practice*. Crc Press, 2016.

59. Figueira, G. and B. Almada-Lobo, *Hybrid simulation–optimization methods: A taxonomy and discussion*. In *Simulation Modelling Practice and Theory*, 2014, 46, pp. 118-134.

60. Ng, A.H., J. Bernedixen and P. Leif, *What Does Multi-Objective Optimization Have to Do with Bottleneck Improvement of Production Systems?* Presented at *International Swedish Production Symposium 2014.*

61. Ng, A.H., J. Bernedixen, M Urenda and M. Jägstam, *Factory flow design and analysis using internet-enabled simulation-based optimization and automatic model generation*. Presented at the IEEE *Winter Simulation Conference,* 2011, pp. 2176-2188.

62. Persson, A., M. Andersson, H. Grimm and A. Ng, *Metamodel-Assisted Simulation-Based Optimization of a Real-World Manufacturing Problem*. Presented at International Conference on Flexible Automation and Intelligent Manufacturing, 2007, pp. 950-956.

63. Yang, T., Y. Kuo, C. Su and C. Ho, *Lean production system design for fishing net manufacturing using lean principles and simulation optimization*. In *Journal of Manufacturing Systems*, 2015, 34, pp. 66-73.

64. Zhenyuan, J., L. U. Xiaohong, W. Wei, J. Defeng and W. Lijun, *Design and implementation of lean facility layout system of a production line*. In *International Journal of Industrial Engineering*, 2011, 18(5), pp. 260-269.

65. Goienetxea Uriarte, A., A. Ng, E. Ruiz Zúñiga and M. Urenda, *Improving the material flow of a manufacturing company via lean, simulation and optimization*. Presented at *IEEE International Conference on Industrial Engineering and Engineering Management,* 2017. pp. 1245-1250.

66. Hu, X., H. Xu, J. Xu, S. Tong, Y. Yu and H. Wei, *A Novel Workshop Layout Optimization Algorithm Based on SA-PSO*. Presented at *IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference,* 2018, pp. 2431-2435.

67. Golz, J., R. Gujjula, H. Günther, S. Rinderer and M. Ziegler, *Part feeding at high-variant mixed-model assembly lines*. In *Flexible Services and Manufacturing Journal*, 2012, 24(2), pp. 119-141.

68. Wenping, L. and H. Yuming, *Car sequencing in mixed-model assembly lines from the perspective of logistics optimisation*. Presented at *IEEE International Conference on Automation and Logistics*, 2008, pp. 952-957.

69. Battini, D., M. Faccio, A. Persona and F. Sgarbossa, *Design of the optimal feeding policy in an assembly system*. In *International Journal of Production Economics*, 2009, 121(1), pp. 233-254.
70. Boysen, N., S. Emde, M. Hoeck, and M. Kauderer, *Part logistics in the automotive industry: Decision problems, literature review and research agenda.* In *European Journal of Operational Research*, 2015, 242(1), pp. 107-120.
71. Boysen, N., M. Fliedner and A. Scholl, *Sequencing mixed-model assembly lines to minimize part inventory cost.* In *Or Spectrum*, 2008, 30(3), pp. 611-633.
72. Ziarnetzky, T., L. Mönch and A. Biele, *Simulation of low-volume mixed model assembly lines: modeling aspects and case study*. Presented at IEEE *Winter Simulation Conference 2014*, pp. 2101-2112.
73. Emde, S. and N. Boysen, *Optimally locating in-house logistics areas to facilitate JIT-supply of mixed-model assembly lines.* In *International Journal of Production Economics*, 2012, 135(1), pp. 393-402.
74. Faccio, M., M. Gamberi, A. Persona, A. Regattieri and F. Sgarbossa, *Design and simulation of assembly line feeding systems in the automotive sector using supermarket, kanbans and tow trains: a general framework.* In *Journal of Management Control*, 2013. 24(2), pp. 187-208.
75. Emde, S., M. Fliedner and N. Boysen, *Optimally loading tow trains for just-in-time supply of mixed-model assembly lines.* In *Iie Transactions*, 2012. 44(2), pp. 121-135.
76. Nourmohammadi, A., H. Eskandari, M. Fathi and A. Ng, *Integrated locating in-house logistics areas and transport vehicles selection problem in assembly lines.* In *International Journal of Production Research*, 2019, pp. 1-19.
77. Piera, M. À., M. Narciso, A. Guasch and D. Rier, *Optimization of logistic and manufacturing systems through simulation: a colored Petri net-based methodology*. In *Simulation*, 2004, 80(3), pp. 121-129.
78. Heilala, J., J. Montonen, A. Salmela and P. Jarvenpaa, *Modeling and simulation for customer driven manufacturing system design and operations planning*. Presented at *IEEE Winter Simulation Conference,* 2007, pp. 1853-1862.
79. Bortolini, M., E. Ferrari, M. Gamberi, F. Pilati and M. Faccio, *Assembly system design in the Industry 4.0 era: a general framework.* In *IFAC-PapersOnLine*, 2017, 50(1), pp. 5700-5705.
80. Battini, D., M. Faccio, A. Persona and F. Sgarbossa, *Balancing–sequencing procedure for a mixed model assembly system in case of finite buffer capacity*. In *The International Journal of Advanced Manufacturing Technology*, 2009, 44(3-4), pp. 345-359.
81. Groover, M.P., *Automation, production systems, and computer-integrated manufacturing*. Pearson Education India, 2016.
82. Azadivar, F. and J. Wang, *Facility layout optimization using simulation and genetic algorithms.* In *International Journal of Production Research*, 2000, 38(17), pp. 4369-4383.
83. Liu, Y. S., L. N. Tang, Y. Z. Ma and T. Yangal, *TFT-LCD module cell layout design using simulation and fuzzy multiple attribute group decision-making approach*. In *Applied Soft Computing*, 2018, 68, pp. 873-888.
84. Kikolski, M. and C. H. Ko, *Facility layout design–review of current research directions.* In *Engineering Management in Production and Services*, 2018, 10(3), pp. 70-79.
85. Nanjing, J. and S.G. Henderson. *An introduction to simulation optimization*. Presented at IEEE *Winter Simulation Conference,* 2015, pp. 1780-1794.
86. Xu, J., E. Huang, C. H. Chen and L. H. Leeal, *Simulation Optimization: A Review and Exploration in the New Era of Cloud Computing and Big Data.* In *Asia-Pacific Journal of Operational Research*, 2015, 32(03), pp. 1–34.

87. Fu, M.C., *Optimization for simulation: Theory vs. Practice.* In *INFORMS Journal on Computing*, 2002, 14(3), pp. 192–215.
88. Gill, J. and P. Johnson, *Research methods for managers*. Sage, 2002.
89. Taşkın, Z.C., *Optimization vs. heuristics: Which is the right approach for your business?* Icron Technologies, 2018. https://icrontech.com/blog_item/optimization-vs-heuristics-which-is-the-right-approach-for-your-business/
90. Hevner, A. and S. Chatterjee, *Design science research in information systems*. In *Design Research in Information Systems*, 2010, pp. 9-22.
91. Oates, B.J., *Researching information systems and computing*. Sage, 2005.
92. Goienetxea Uriarte, A. *Bringing together lean, simulation and optimization in a framework for system design and improvement*. Presented at IEEE *Winter Simulation Conference*, 2018, pp. 4132-4133.
93. Skoogh, A. and B. Johansson. *A methodology for input data management in discrete event simulation projects*. Presented at IEEE *Winter Simulation Conference*, 2008, pp. 1727-1735.
94. Kuechler, B. and V. Vaishnavi, *On theory development in design science research: anatomy of a research project.* In *European Journal of Information Systems*, 2008, 17(5), pp. 489-504.
95. Schuh, G., R. Anderl, J. Gausemeier, M. ten Hompel, and W. Wahlster, *Industrie 4.0 maturity index. Managing the digital transformation of companies*. Herbert Utz, 2017.
96. Goienetxea Uriarte, A., *Bringing Together Lean, Simulation and Optimization: Defining a framework to support decision-making in system design and improvement*. Doctoral dissertation, University of Skövde, 2019.
97. Yin, R.K., *Case study research and applications: Design and methods*. Sage publications, 2017.
98. Ahmad, M. M. and N. Dhafr, *Establishing and improving manufacturing performance measures.* In *Robotics and Computer-Integrated Manufacturing*, 2002, 18(3-4), pp. 171-176.
99. Vollmann, T.E., W.L. Berry and D.C. Whybark, *Manufacturing planning and control systems*. Irwin, 1992.
100. Kankaanoja, S., *Implementing overall equipment effectiveness system In submarine power cable manufacturing*. Master's thesis, Aalto University, 2015.
101. Westermann, T. and R. Dumitrescu, *Maturity model-based planning of cyber-physical systems in the machinery and plant engineering industry*. Presented at *International Design Conference*, 2018, pp. 3041-3052.
102. Askar, G., T. Sillekens, L. Suhl and J. Zimmermann, *Flexibility planning in automotive plants.* In *Management logistischer Netzwerke,* 2007, pp. 235-255.
103. Guimarães, A. M. C., J. E. Leal and P. Mendes, *Discrete-event simulation software selection for manufacturing based on the maturity model.* In *Computers in Industry*, 2018, 103, pp. 14-27.
104. Mkaouer, M.W., M. Kessentini, S. Bechikh, K. Deb and M. Ó Cinnéide, *High dimensional search-based software engineering: finding tradeoffs among 15 objectives for automating software refactoring using NSGA-III.* Presented at *Annual Conference on Genetic and Evolutionary Computation*, 2014, pp. 1263-1270.
105. Deb, K., A. Pratap, S. Agarwal, and T. A. M. T. Meyarivan, *A fast and elitist multiobjective genetic algorithm: NSGA-II*. In *IEEE Transactions on Evolutionary Computation*, 2002, 6(2), pp. 182-197.
106. Rösiö, C. and J. Bruch, *Focusing early phases in production system design*. Presented at *IFIP International Conference on Advances in Production Management Systems*, 2014, pp. 100-107

107. Bo, T. and H. Jens, *Project Management-A Complete Guide*. Renate Nielsen, 2009.
108. Nourmohammadi, A., M. Fathi, M. Zandieh and M. Ghobakhloo, *A water-flow like algorithm for solving U-shaped assembly line balancing problems*. In *IEEE Access*, 2019, 7, pp. 24-33.
109. Fathi, M., A. Nourmohammadi, A. Ng, A. Syberfeldt and H. Eskandarial, *An improved genetic algorithm with variable neighborhood search to solve the assembly line balancing problem*. In *Engineering Computations*, 2019, 37 (2), 501-521.
110. Prasad, N. H., G. Rajyalakshmi and A. S. Reddy, *A Typical Manufacturing Plant Layout Design Using CRAFT Algorithm*. In *Procedia Engineering*, 2014, 97, pp. 1808-1814.
111. Liker, J.K., *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill Education, 2004.
112. Koenigsaecker, G. and H. Taha, *Leading the lean enterprise transformation*. Productivity Press, 2012.
113. Damayanti, R., A. Wijaya and B. Hartono. *Seven Management and Planning Tools in Megaproject Management: A Literature Review*. In *IOP Conference Series: Materials Science and Engineering*. 2019, 598, pp. 1-8.
114. Stumpf, P., *Best Practices-Managing Risks in Lean or Agile Projects. In Project Times,* https://www.projecttimes.com/articles/best-practices-managing-risks-in-lean-or-agile-projects/
115. Ruiz Zúñiga, E., M. Urenda Moris, and A. Syberfeldt, *Production logistics design and development support: a simulation-based optimization case study (WIP). Presented at Summer Computer Simulation Conference*, 2016, s. 56:1-56:6.
116. Fathi, M., A. Syberfeldt, M. Ghobakhloo and H. Eskandar, *An optimization model for material supply scheduling at mixed-model assembly lines*. In *Procedia CIRP*, 2018, 72, pp. 1258-1263.
117. Nourmohammadi, A., H. Eskandari and M. Fathi, *Design of stochastic assembly lines considering line balancing and part feeding with supermarkets*. In *Engineering Optimization*, 2019, 51(1), pp. 63-83.
118. Nourmohammadi, A., H. Eskandari, M. Fathi and M. Aghdasi, *A mathematical model for supermarket location problem with stochastic station demands*. In *Procedia CIRP*, 2018, 72, pp. 444-449.
119. Deshpande, V., N. D. Patil, V. Baviskar, and J. Gandhi, *Plant layout optimization using CRAFT and ALDEP methodology*. In *Productivity Journal by National Productivity Council*, 2016, 57(1), pp. 32-42.
120. Shaki, H., *Evaluating effectiveness of the application of the new perspective in safety, Safety-II: by Functional Resonance Analysis Method (FRAM) in a manufacturing environment*. East Crolina University, 2017.

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