Analysis of the Behaviour of Flexibility Parameters in Intralogistics Systems

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Declaration

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Abstract

Today's logistics systems are characterised by uncertainty and constantly changing requirements. Rising demand for customised products, short product lifecycles, and a large number of variants enormously increase the complexity of these systems. In particular, intralogistics material flow systems must be able to adapt to changing conditions at short notice, with little effort and at low cost. To fulfil these requirements, the material flow system must be flexible in three important dimensions, namely layout, throughput, and product. Whilst the scope of the flexibility parameters is described in literature, the respective effects on an intralogistics material flow system and the influencing factors are mostly unknown. In this context, this thesis aims to analyse the behaviour of the flexibility parameters with the help of a multimethod simulation. Therefore, the definitions of the parameters found in the literature are first analysed and specified with regard to their influencing factors. Subsequently, hypotheses regarding the characteristics of the flexibility parameters on the logistical throughput, the production output, and the degree of utilisation of the means of transport are formulated. To confirm the hypotheses, a simulation model based on the logistics learning factory Werk150 of the ESB Business School on the campus of Reutlingen University is developed. The intralogistics system consists of various flexible means of transport which have a defined source-sink relationship. Within the scope of the simulation, these static structures are incrementally transformed into more flexible ones and examined with regard to their behaviour. The model as well as the obtained results are ultimately verified and validated using common techniques in production and logistics systems simulation. The work shows that with an increasing flexibilization of the intralogistics material flow system, the performance can significantly increase. Furthermore, the analysis provides information on where the system-specific potentials of flexibility as well as the limits to changeability lie.

Opsomming

Hedendaagse logistieke stelsels word gekenmerk deur onsekerheid en voortdurend veranderende vereistes. Die toenemende aanvraag na doelgemaakte produkte, produkte met kort lewensiklusse en 'n groot aantal variante verhoog die kompleksiteit van hierdie stelsels. Intralogistieke materiaalvloeistelsels moet veral op kort kennisgewing, met min moeite en teen lae koste kan aanpas by veranderende omstandighede. Om aan hierdie vereistes te voldoen moet die materiaalvloeistelsel buigsaam wees ten opsigte van drie belangrike dimensies, naamlik uitleg, deurvloei en produk. Alhoewel die omvang van die buigsaamheidsparameters in die literatuur beskryf word, is die onderskeie effekte daarvan op 'n intralogistieke materiaalvloeistelsel en die beïnvloedende faktore meestal onbekend. In hierdie konteks is hierdie tesis daarop gemik om die gedrag van die buigsaamheidsparameters met behulp van 'n multimetodesimulasie te analiseer. Daarom word die definisies van die parameters wat in die literatuur aangetref word, eers ontleed en gespesifiseer met betrekking tot die beïnvloedende faktore. Vervolgens word hipoteses aangaande die kenmerke van die buigsaamheidsparameters op die logistieke deurvloei, die produksie-uitset en die mate van benutting van die vervoermiddels geformuleer. Om die hipoteses te bevestig, word 'n simulasiemodel gebaseer op die logistiekleerskool Werk150 van die "ESB Business School" op die kampus van die Reutlingen Universiteit ontwikkel. Die intralogistieke stelsel bestaan uit verskillende buigsame vervoermiddels wat 'n gedefinieerde bron-sink-verhouding het. Hierdie statiese strukture word inkrementeel binne die omvang van die simulasie tot meer buigbare strukture uitgebrei en met betrekking tot hul gedrag ondersoek. Die model sowel as die behaalde resultate word uiteindelik deur middel van toepaslike verifikasie- en valideringstegnieke getoets om die geloofwaardigheid van die stelsel te bevestig. Die studie toon dat die algehele prestasie deur die toenemende buigsaamheid van die intralogistieke materiaalvloeistelsel aansienlik verbeter kan word. Verder verskaf die analise inligting oor waar die stelselspesifieke potensiaal van buigsaamheid sowel as die limiete vir veranderlikheid lê.

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The author

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List of Acronyms

AGV	Autonomous Guided Vehicle
CeMAT	Centrum für Materialflusstechnik
FIFO	First In – First Out
GUI	Graphical User Interface
KPI	Key Performance Indicator
LPI	Logistics Performance Index
OID	Order Identification Number
PRQ	Primary Research Question
RMS	Reconfigurable Manufacturing Systems
SLC	Small Load Carrier
SQL	Structured Query Language
SRQ	Secondary Research Question
TID	Transporter Identification Number
TPS	Toyota Production System
UML	Unified Modelling Language
VDMA	Verband Deutscher Maschinen- und Anlagenbau

Chapter 1
Introduction

In this chapter familiarises the reader with the research which was carried out. First, it comprehensively describes the theoretical background from which the problem definition is derived. Based on the problem statement, research questions are formulated which are to be answered within the scope of this research. In a further step, research objectives are defined to structure the study. Subsequently, the research design and the methodology used are described. Finally, the chapter concludes by presenting the thesis outline.

1.1 Background and Relation of Research

Nothing is as constant as change.

—Heraclitus of Ephesus, 520–460 BC

Heraclitus's statement is an accurate characterisation of the current challenges which manufacturing companies face. Uncertainty and constant changes affect both production and logistics. Increasing demands for customised products, short product lifecycles, and a large number of variants are just several examples of these challenges (Jain et al. 2013, p. 5946; Brauer et al. 2010, p. 51). This phenomenon is particularly evident in the automotive industry, with its complex products and the number of models and vehicle feature variants, which has exploded in recent years (Göpfert et al. 2019, pp. 177–178).

Comparing model types of Daimler AG in 2000 and today, the number has risen from nine to over 33 different types (Daimler Chrysler AG 2000, p. 33; Daimler AG 2020). This general increase in available vehicle models is not only seen at Daimler AG (see Figure 1-1). In the years 1998 to 2008, a tripling of the number of derivatives at European original equipment manufacturers (OEMs) can be observed (Berret 2007, pp. 69–70). In addition to the growth in model types, the OEMs are also offering a high degree of individualisation of their products, for example, through motorisation, paintwork, rims, multimedia systems, and the like. Consequently, production and logistics systems must map all of these configuration options. According to Mößmer et al. (2007, p. 4), the number of available vehicle feature variants per derivate in the BMW Group is 10^{31}. However, these developments are not confined to the premium segment, as the following numbers of variants of high-volume models demonstrate:

- Volkswagen Golf, number of variants: 10^{23}.
- Opel Astra, number of variants: 10^{17}.
- Ford Focus, number of variants: 10^{16}.

These effects are ultimately amplified by the reduction of the product lifecycles, which, on average, currently lie between five and six years (Ihme 2006, p. 10). In concrete terms, this means that the highly automated and highly specialised manufacturing systems developed for certain derivates often cannot be reused (Heinecker 2006, p. 47).

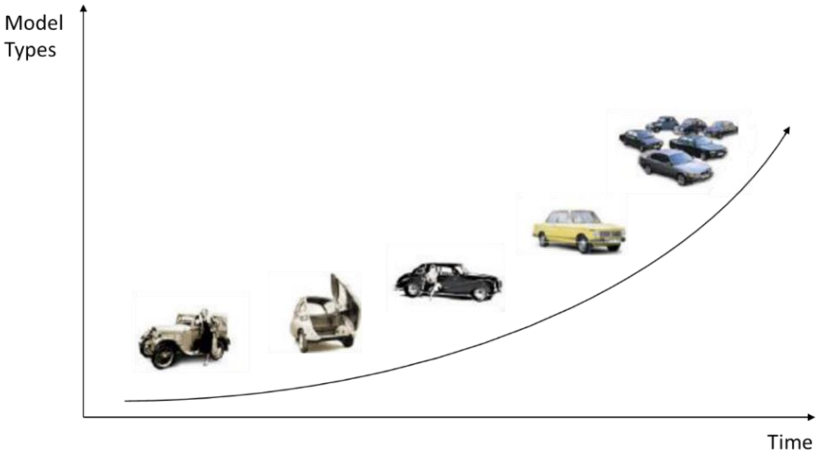

Figure 1-1: Development of available vehicle types of the BMW Group according to Mößmer et al. (2007, p. 4)

These outlined aspects are the cause of increasing dynamics in logistic flows, which ultimately require long-term changes to the network structure in addition to short-term adjustments to network capacity (Brauer et al. 2010, p. 51). To be successful as a company, therefore, change must be continuously shaped and controlled (Handrich 2001, p. 1). Key concepts in this context are flexibility and versatility (Spath et al. 2008, p. 11; Pfohl 2016, p. 291). Whilst flexibility describes the ability of a system to adapt to changes within a defined area, versatility refers to a system's ability to make rapid and sustainable structural changes (Mößmer et al. 2007, p. 5). In particular, intralogistics transport systems must be able to adapt to changing conditions at short notice, with little effort and at low cost (Günthner et al. 2014, p. 299). This is due to the fact that material flows link production systems and must therefore meet their requirements. Whereas in the past, the transport task consisted of bulk and uncoordinated transports, the current demand for transports which are organisationally coordinated with the production process is omnipresent. The material flow system therefore has a direct effect on the production structure and thus determines it. The main requirement for such systems is adaptivity to changes in structure, quantity, and product. However, material flow systems often fail to meet this requirement because adaptation to the production system is usually accompanied by a high level of modification expenses (Handrich 2001, p. 3).

Nonetheless, to ensure a sustainable and future-oriented intralogistics material flow system, a certain degree of flexibility with regard to changes in structure, quantities, and products is required. This is also referred to as layout flexibility, throughput flexibility, and product flexibility (Günthner et al. 2002, p. 8).

1.2 Research Problem and Questions

The planning and quantitative evaluation of flexibility in terms of changes in structure, volume, and product are highly complex (Roscher 2008, p. 32). In fact, no planning method which comprehensively considers all three flexibility parameters can be found in the literature (see Appendix A). Solely remarks regarding the consideration of any fluctuations which may occur (e.g. in throughput) can be identified. Furthermore, only a single method can be found in the area of evaluation methods which explicitly considers layout, throughput, and product flexibility. However, the informative value for planners and system operators is very low, and no practical added value of this evaluation can be identified in terms of planning such a system (see section 2.4). In order to adequately plan or evaluate the required sustainable and future-oriented intralogistics material flow systems described in section 1.1, the behaviour of the flexibility parameters must first be analysed.

Due to the specific and heterogeneous system requirements, the behaviour of the parameters is highly dependent on the respective material flow system and must therefore be analysed for each individually (Krenn 2008, p. 1). As a consequence of the complexity of logistics systems and the interdependencies, the use of a simulation is predestined for the investigation of the behaviour (Eley 2012, pp. 3–5). With the knowledge gained from the simulation about the current existing capacities and the possible activatable flexibility potentials, companies can make their intralogistics more economically efficient, since flexibility potentials can be activated as needed. Furthermore, the information contributes to an improved decision-making process for strategic topics that have a direct influence on the intralogistics material flow system. For example, new sales programmes can be evaluated for feasibility. Ultimately, efficient and continuous adaptation to new market requirements is possible.

This research work therefore proposes the topic of analysing the behaviour of an intralogistics material flow system with regard to these flexibility parameters by means of a simulation model to draw system-specific conclusions. These conclusions can not only be used to assess the actual situation in the existing intralogistics system but also to reveal which flexibility potentials are present, when they need to be activated, and where changeability lies. To address the abovementioned issues, the following primary research question (PRQ) and secondary research questions (SRQs) are formulated:

PRQ	How does the level of layout flexibility, throughput flexibility, and product flexibility affect an intralogistics system in terms of its logistical throughput, production output, and degree of utilisation regarding the means of transport?

In the context of the PRQ, the behaviour of an intralogistics system is examined with respect to changes in the three flexibilities using a simulation model. Thereby, the system's behaviour is represented by the logistical throughput, the production output, and the degree of utilisation of the means of transport as these figures are one of the most important ones in material flow planning (Noche and Druyen 2018, pp. 243–244).

SRQ1	How are the flexibility parameters for layout, throughput, and product defined in terms of their influencing factors?

Before the analysis of the behaviour of flexibility parameters in intralogistics systems can be conducted, the question of how the three flexibility parameters are defined must first be answered. Hereby, special attention is paid to the individual influencing factors of the respective parameter as these ultimately determine the behaviour of the system. As there is no uniform definition of these flexibility parameters in the literature, the author's own definition is developed and taken as a basis within this research work (Günthner et al. 2002, p. 8; Handrich 2001, pp. 23–25; Heinecker 2006, pp. 68–71; Wilke 2006, pp. 21–22).

SRQ2	How must a simulation model be structured to analyse the material flow system-specific potentials of the three flexibility parameters regarding layout, throughput, and product?

The second SRQ addresses the structure of the simulation model to be developed. As the system behaviour is always very specific, no quantifiable conclusions from this study can be transferred to any other intralogistics systems. Therefore, in the course of this research work, it shall be determined how a simulation model must be structured to analyse a system in terms of its layout, throughput, and product flexibility.

1.3 Research Objectives

To achieve the aim of this work, a total of eight research objectives were developed (see Table 1-1). These goals represent the main structure of the study and serve to guide the research in the intended direction:

Table 1-1: Research objectives of this thesis

No.	Research Objective	Chapter
1	Critical review of the definitions for intralogistics, material flow systems	2.1 – 2.2
2	Examination of different flexibility parameter definitions for intralogistics material flow systems	2.3.1
3	Distinction amongst the terms flexibility, reactability, changeability, and versatility	2.3.1 – 2.3.3
4	Development of a new generic definition for the three flexibility dimensions for layout, throughput, and product as well as specification of the respective influencing factors	3.1 – 3.3
5	Derivation of hypotheses regarding the possible impact of these parameters on intralogistics systems	3.4
6	Development of a simulation model of the logistics learning factory Werk150 of ESB Business School and simulation of the flexibility parameters	4.4
7	Validation and verification of the developed simulation model	5.2 – 5.3
8	Comparison of the derived hypotheses with the simulation results	6.1 – 6.3

1.4 Research Design and Methodology

In the last decades of the still relatively young scientific discipline of logistics, the demand for stronger and more solid theories has intensified (Arlbjørn and Halldorsson 2002, p. 22). Thereby, using a deductive approach, a positivist paradigm has emerged as dominant research philosophy (Arlbjørn and Halldorsson 2002, p. 22; Mentzer and Kahn 1995, p. 232; Näslund 2002, p. 322; Kovács and Spens 2005, p. 133). The findings of Craighead et al. (2007, pp. 34–35), who analysed the trends in logistics research, have underlined this predominant paradigm. According to Mentzer and Kahn (1995, p. 232), the main reason for the dominant positivism paradigm is that logistics research is influenced by two factors: economics and behaviour. Both factors have their origin in the scientific approach of positivism. Whilst the economic aspect focusses on cost minimisation and profit maximisation using methods like cost analysis, mathematical modelling, or simulation, the behaviour factor focusses on psychological and sociological aspects primarily obtained through questionnaires, interviews, or case studies.

The fundamental aim of positivism is to explain and predict reality. In contrast to people, who are considered deterministic and reactive, reality is viewed as objective, tangible, and fragmentable (Mentzer and Kahn 1995, p. 232). The results of the research conducted are considered to be truly objective and thus value free, time free, and context independent, and causal relationships can be discovered (Hirschman 1986, 239; Peter and Olson 1983, pp. 118–119; Mentzer and Kahn 1995,

p. 232). Mentzer and Kahn state, that ‘positivist researchers consider themselves separate from research setting and at a privileged point of observation’ (Mentzer and Kahn 1995, p. 232).

In combination with the positivist research philosophy, a deductive approach is dominant in logistics research. Thereby, the research occurs in a conscious direction, namely from a general law to a specific case (Kovács and Spens 2005, p. 133; Hyde 2000, p. 83). The starting point is a theory or generalisation (e.g. through literature research) from which hypotheses and propositions are first derived (Woiceshyn and Daellenbach 2018, p. 185; Kovács and Spens 2005, p. 137). In this process, there are no particular guidelines as to how a hypothesis must be developed (Locke 2007, p. 869). After successfully formulating hypotheses, these must then be tested in an empirical environment. In the end, the findings are summarised, and the theories are confirmed or rejected (Woiceshyn and Daellenbach 2018, p. 185; Kovács and Spens 2005, p. 137).

This study also adopts the positivistic research philosophy and follows a deductive approach. Within the scope of this research, the theory behind flexibility in intralogistics systems and the functioning of material flow systems is first described in detail. Subsequently, according to the deductive approach, hypotheses and propositions are developed, which are then empirically investigated in a further step. The study concludes with general findings from the investigation of the behaviour of flexibility parameters in intralogistics systems. Throughout the entire research, the highest priority is given to validity, reliability, and precision. These aspects are fundamental elements to ensure that the study results are accepted by the research community (Mentzer and Kahn 1995, pp. 237–240).

With regard to the research design, the study can be divided into two parts. At the beginning, a literature research is conducted, which includes the state of the art of logistics, material flow systems, flexibility and the logistics learning factory Werk150. Historical and present research results are used to create a basis for the development of hypotheses and propositions. In addition to the results of the literature review, logical thinking and physical relationships are used to further specify the hypotheses. In the second part of the study, the propositions and hypotheses are empirically examined using a simulation model. The logistics learning factory Werk150, located on the campus of the ESB Business School at Reutlingen University, serves as a reference model. The simulation model itself is examined using various verification and validation methods to ensure validity, reliability, and precision. This also includes practical experiments within the logistics learning factory.

1.4.1 Literature Review

A literature search is a necessary and valid approach to structure a research field or topic (Seuring et al. 2005, p. 93). It is therefore an integral part of the research to be conducted (Mentzer and Kahn 1995, 233 ff.). In this study, a traditional narrative literature search was carried out as there is no particular research question to be answered (Montori et al. 2003, p. 44). The results serve solely to reflect the current state of the art of logistics/intralogistics, material flow systems, flexibility, and versatility. Based on these results, hypotheses were then developed regarding the behaviour of flexibility parameters in intralogistics systems.

To reduce effects such as the personal selection of materials based on the assumption of important contributions of the author, the narrative approach is supplemented by systematic aspects. Thus, central elements in this study which result from the literature research are confirmed by numerous authors. By using this snowballing approach, one-sided or biased arguments can be prevented (Jesson et al. 2011, p. 15). Moreover, with this approach, a reflective description of scientific findings is achieved by critically considering the individual results.

In this thesis, the literature research is based on German and English sources, including books, edited volumes, journal papers, and norms. The main sources for this research were the Reutlingen Library, Stellenbosch Library, Datenbank-Infosystem Hochschule Reutlingen (EDDI), elektronische

Zeitschriften Bibliothek, Perinorm, Elsevier (ScienceDirect), Emerald Insight, IEEE, Sage, and Google Scholar. Furthermore, the references in the publications used were also checked.

1.4.2 Simulation

The term simulation is widely used and often refers to 'computer supported calculations to project past and future outcomes' (Happach and Tilebein 2015, p. 243). With simulation models, various real-world processes (e.g. of a manufacturing system or a supply chain) can be imitated or simulated. Thereby, the processes of interest are usually called a system, whereas the assumptions taken from mathematical or logical relationships represent the model. The model is then used to gain an understanding of how the system behaves (Law 2015, pp. 1–2). In general, a simulation model is used when it is impossible or inconvenient to solve the research problem in a different way because of costs or risks involved (Pidd 2004, p. 3; Größler and Schieritz 2005, p. 447). This mostly applies in real-world systems with a high mathematical complexity as there is no analytical solution (Happach and Tilebein 2015, p. 243). To cope with the inherent complexity of reality, Happach and Tilebein (2015, pp. 239–240) have recommended using idealised models which create the necessary simplification.

1.4.2.1 Simulation Process

To analyse the cause-effect relationships of flexibility parameters in intralogistics systems, the present work uses the process model based on Rabe et al. (2008, p. 5) as it puts special emphasis on verification and validation of the model and data (see Figure 1-2) (Gutenschwager et al. 2017, p. 142). As mentioned, the simulation model should reflect the intralogistics system of the logistics learning factory Werk150 located on the campus of the ESB Business School at Reutlingen University.

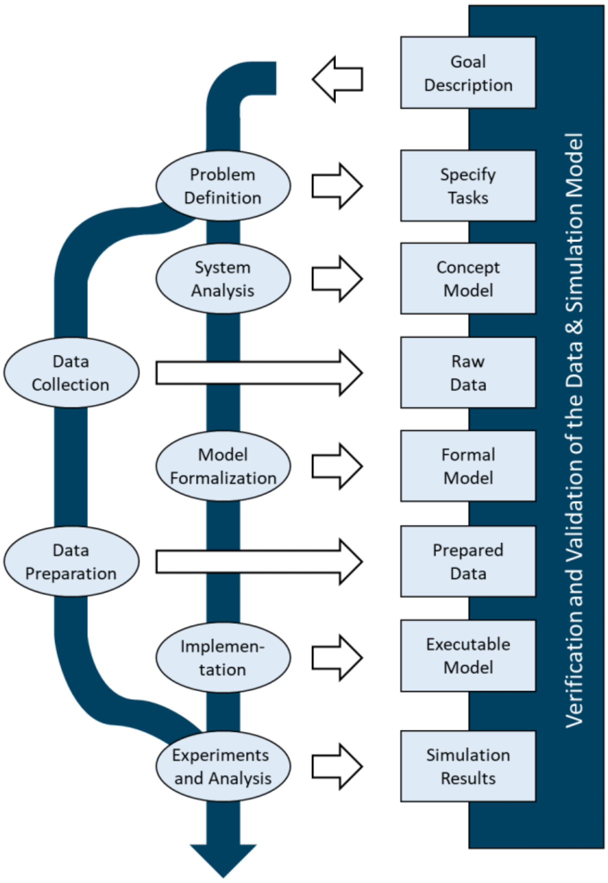

Figure 1-2: Process model of simulation according to Rabe et al. (2008, p. 5)

The following description of the process model is a summary of the detailed explanation according to Gutenschwager et al. (2017, pp. 144–145). The process model is generally divided into seven phases: problem definition, system analysis, data collection, model formalisation, data preparation, implementation, and experiments and analysis. Each phase has a corresponding result, which can be either models or documents (see grey rectangle in Figure 1-2). The goal description at the top of the process model, however, is not a phase result but the starting point of the simulation study. It describes the problem to be solved. Following that is the problem definition phase, in which the goal description is complemented and specified. The result of this phase is the specified task, which creates a common understanding of the objective and possible solutions. In the second phase, the system to be simulated is analysed with regard to the technical system; its boundaries, input, and output variables; and the degree of detail to be depicted. The degree of detail for the simulation model on the one hand should be as accurate as necessary, it should also be as abstract as possible on the other as abstraction leads to a better understanding of the system as well as less effort in terms of data collection, modelling, runtime and storage (VDI 3633:2018-05). Resulting from this analysis is the concept model, which is further elaborated in the model formalisation. During formalisation, the real or imaginary system is transformed into a conceptual, not yet experimental model. The transfer of the conceptual model to an experimental, executable, and replicable one is done in the fourth phase–the implementation–by using simulation software with its corresponding language.

In parallel to these four phases, which can be summarised by the term model development, the data collection and data preparation are conducted. These phases are separate from the main development process as they can be completed independently of the modelling. During data collection, required information regarding the system is aggregated. The type and scope of the gathered data depend on task specification and the concept model. In a subsequent step, in the data preparation phase, the gathered raw data is prepared so that the executable model can properly use the provided information. This is achieved, for example, by filtering or structuring the data.

The last phase of the process model according to Rabe et al. covers the experiments and analysis of the simulation model. Therein, the prepared data and the executable model are merged to execute the experiments. During the experiments, quantitative data is collected, which must, in turn, be analysed to derive a conclusion for the real system. The findings of this final phase are the simulation results, which summarise the underlying data as well as their analysis.

1.4.2.2 Delimitations and Limitations

As part of the system analysis phase, this section serves to demarcate the simulation model to be developed using assumptions to idealise and, for example, ignore less important aspects of the real intralogistics system.

Manufacturing System: The underlying manufacturing system corresponds to the logistics learning factory Werk150 of the ESB Business School of Reutlingen University. The system has a fixed production sequence for assembling a city scooter, which cannot be changed. Furthermore, each workstation can only process one order at a time. Other events such as machine breakdowns, external supply bottlenecks of required components, working hours of employees, or other factors affecting production are not considered. The system is therefore represented in an ideal state.

Production Programme: Throughout the simulation, the production programme is unknown, and thus the assumption is made that the system works at full capacity. This means that the first two stations in the assembly process are always supplied with picking orders if one of the subsequent workstations is not occupied.[1] Therefore, the measured actual throughput always represents the maximum of the

[1] A detailed description of the production process can be found in Section 2.5.1.

system. Furthermore, the corresponding process and setup times of the two product variants represent the actual values in the original system. As no product change is planned, these are fixed within the scope of this study. In principle, however, the process times can be adjusted to make investigations regarding the maximum theoretical possible throughput.

Transport Control System: In the context of this study, only the means of transport between the goods receipt and goods issue storage are considered and simulated. The allocation of the transport orders to the means of transport is done analogous to the real system. If changes are made, for example, regarding the prioritisation, these are explicitly described in the respective section.

Means of Transport: The means of transport considered in this thesis are the same as in Werk150. In the simulation model, the parameters for speed, acceleration, curve radius, type of navigation, load carrier capacity, and total cargo load, as well as the dimensions, are considered. Furthermore, reference values for the loading and unloading times are accounted for. All other factors such as machine failures, battery charge status, motivation, or stress are not included.

1.5 Thesis Outline

This thesis is organised into seven chapters. After this introduction to the problem definition, research question, research design, and methodology, chapter 2 follows with the state of the art, in which the topics of logistics and intralogistics systems are introduced. This is followed by an overview of material flow systems. In particular, planning is addressed as well as the most common types of load carriers. Subsequently, an overview of existing flexibility taxonomies in relation to material flow systems is given, as well as the distinction amongst reactability, changeability, and versatility. Furthermore, it describes how flexibility and versatility can be evaluated. The chapter concludes with an in-depth description of the flexible manufacturing system of Werk150 at Reutlingen University, which serves as a reference model for this study.

Chapter 3 analyses the different flexibility taxonomies from the previous chapter to develop news definition for layout flexibility, throughput flexibility, and product flexibility. Furthermore, this chapter describes the respective influencing factors and proposes hypotheses regarding their behaviour in intralogistics systems, which are investigated in the simulation study.

Chapter 4 discusses the formalisation of the model as well as the implementation in the simulation software. It describes in detail how the model is structured, which functions are elementary for the analysis of the behaviour, and how the individual control mechanisms ultimately function.

In chapter 5, detailed verification and validation of the created simulation model is examined. Amongst other methods, practical validation in the logistics learning factory Werk150 was conducted to ensure that the model adequately reflects reality and that the results can be accepted by the research community.

Chapter 6 then presents the simulation results from the individual simulation runs. The findings regarding the influencing factors of the flexibility parameters are analysed with regard to their causal relationships. In addition, the influencing factors are graphically displayed in relation to throughput, production output, and the degree of system utilisation.

Chapter 7 contains a summary and conclusion of the most important results in this research. In addition, it provides an outlook on further research topics in the field of flexibility and versatility of intralogistics systems.

Chapter 2
State of the Art and Research

This chapter provides definitions for the terminology used in this thesis. Furthermore, it presents a detailed introduction to material flow systems regarding their planning and commonly used standard load carrier types. The topics of flexibility and versatility, as well as their evaluation in material flow systems, are also discussed. In this context, the terms flexibility, reactability, changeability, and versatility are distinguished. Lastly, the intralogistics system of the logistics learning factory Werk150 is described in detail.

2.1 Logistics and Logistics Systems

The term logistics dates back to the 19th century, originating from a military background (Pfohl 2010, p. 11). Since 1950 in the United States and the 1970s in Germany, logistics can be found in the literature experiencing a rapid growth in importance all around the world with several thousand members in industry and science (Arnold et al. 2008, p. 3). Examining its overall turnover and growth over the last several years demonstrates the impact and importance of this sector (Table 2-1).

Table 2-1: Turnover and growth of the logistics sector in Germany and South Africa in 2016 (Bundesvereinigung Logistik and Fraunhofer SCS 2018; Statistics South Africa 2016, p. 3)

Country	**Turnover in million [€ / R]** [2]		**Growth since 2010**
Germany	258,000 Euro	4,754,091 Rand	22.86%
South Africa	27,387 Euro	504,668 Rand	73.64%

As stated by Bundesvereinigung Logistik (2018), logistics is the third largest industry sector in Germany. With over 25% market share in Europe alone, Germany demonstrates its relevance and quality regarding highly efficient logistics. Additionally, The World Bank (2018) conducted a study to measure the logistics performance of 167 countries by introducing a logistics performance index (LPI). On a scale from 1 to 5, with 5 being the best, they rated each country in the following categories: customs, infrastructure, international shipment, logistics competence, tracking and tracing, and timeliness. In their latest dataset from 2018, Germany was ranked first with an LPI of 4.19. In comparison, South Africa was ranked 29th with an LPI of 3.51. Nevertheless, with only two places apart from China (27th place, LPI of 3.60), South Africa's logistical performance is more than acceptable and remarkable when considering its location, infrastructure imbalances, and other domestic political challenges (Bundeszentrale für politische Bildung 2009; Auswärtiges Amt 2019; German Trade & Invest 2018).

2.1.1 Definition of Logistics

The main operative task of logistics, also known as the four rights of logistics, is providing the right product/quantities of goods, within the right timeframe, at the right place, in the right order (Gudehus

[2] Exchange rate: 1 Euro = 18,43 Rand (13. December 2020)

and Kotzab 2012, p. 3; Pfohl 2010, p. 12). In the literature, the four rights are extended by adding in the right costs and the right quality (Jünemann 1989, p. 18; Martin 2014, p. 2). The main focus does not lie solely in minimising costs (e.g. an individual transportation process) but much rather in 'holistic planning, control and monitoring of systems in order to optimize them' (Jünemann 1989, p. 18).

Even though these rights are an accurate description of the requirements or tasks of logistics, they do not comprise a sufficient definition (Muchna et al. 2018, p. 8). In the literature, several definitions of logistics can be found (Pfohl 2010, p. 12). For instance, according to Arnold et al. (2008, p. 3), it can be broadly described as the 'design of logistic systems and the control of the logistic processes within them'. However, to precisely define the term, Table 2-2 provides an overview of common definitions.

Table 2-2: Definitions of logistics in the literature

Author	**Definition**
(Pfohl 2010, p. 12)	'Logistics includes all activities through which the transformation of goods over time and space and the associated transformations with regards to the quantities and types of goods, the goods handling characteristics and the logistical determinacy of the goods are planned, controlled, realized or controlled. Through the interaction of these activities, a flow of goods takes place that connects a delivery point with a receiving point as efficiently as possible'.
(Schulte 2016, p. 26)	'[...] market-oriented, integrated planning, design, development and control of the entire flow of materials and related information between a company and its suppliers, within a company and between a company and its customers'.
(Ten Hompel and Heidenblut 2011, p. 185)	'[Logistics] is the scientific teaching of the planning, control and optimisation of material-, person-, energy- and information flows in systems, networks and processes'.
(Bundesvereinigung Logistik 2019)	'Logistics is a system that means an optimal supply of materials, information, parts and modules for production—initially within the company, but also across companies with suppliers and customers—and on the other hand, of course, of the markets'.

The examined and abovementioned definitions share the following characteristics:

- Transformation of goods over time and space with regard to the amount and types of goods.
- Having holistic, integrated planning, design, control, and monitoring.
- The handled goods—logistical objects—can be either material (modules, parts, persons, etc.) or immaterial (information, energy, etc.).
- The scope reach from the market/customer to the company itself and strive for efficiency.
- With respect to its scope, logistics is market-/customer-oriented.

In this thesis, the term logistics is defined as follows by adding the abovementioned characteristics to Ten Hompel and Heidenblut (2011, p. 185):

> *Logistics is an interdisciplinary science for a market-oriented, integrated planning, design, development, and control of all logistical goods flows over the entire supply chain with maximum efficiency, starting from the supplier to (and within) the company itself and continuing to the customers.*

2.1.2 Definition of Logistics Systems

The previous, rather holistic definition of logistics covers different logistics systems and therefore needs further differentiation in terms of its logistics task (Pfohl 2010, p. 14). Generally, a logistics system can be described as the interaction of transportation and storage processes of the abovementioned logistical objects. These systems can be visualised as a network with knots and edges. Knots represent (temporary) storages for the objects; edges represent the possible routes each object can take between knots (Pfohl 2010, p. 5; Arnold et al. 2008, p. 18). Figure 2-1 shows the possible fundamental direct and indirect single-/multistage logistics systems structures. For further reference, the supplying point for logistical objects in logistics systems is defined as the source, and the receiving point is defined as the sink.

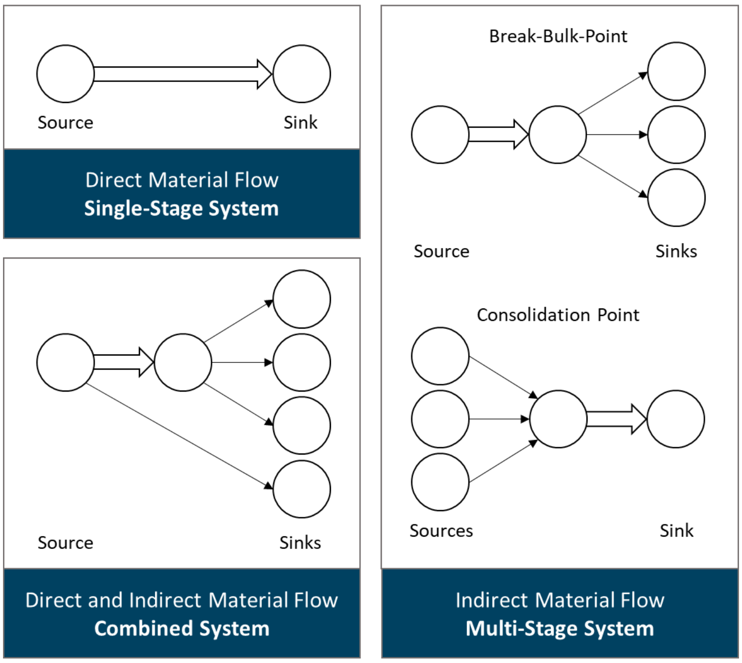

Figure 2-1: Fundamental structures of logistics systems according to Pfohl (2010, p. 6)

Logistics systems in this research work are defined as follows by Dürrschmidt (2001, p. 10):

> *'A logistics system is an open, dynamic system that consists of a set of objects that are related to each other. An object is a distinguishable unit that is described by characteristic values. The objects of a system can be of a material or immaterial nature. It is an open system because its objects are related to the system environment. As a result, the objects are subject to a change over time, causing logistics systems to be dynamic systems.'*

To further categorise logistics systems, Pfohl (2010, p. 14) has recognised two different types: institutional and functional differentiation of logistics systems.

In the institutional differentiation of logistics, three levels of aggregation can be found, analogous to the principles of economics: macro, micro, and meta logistics (see Figure 2-2).

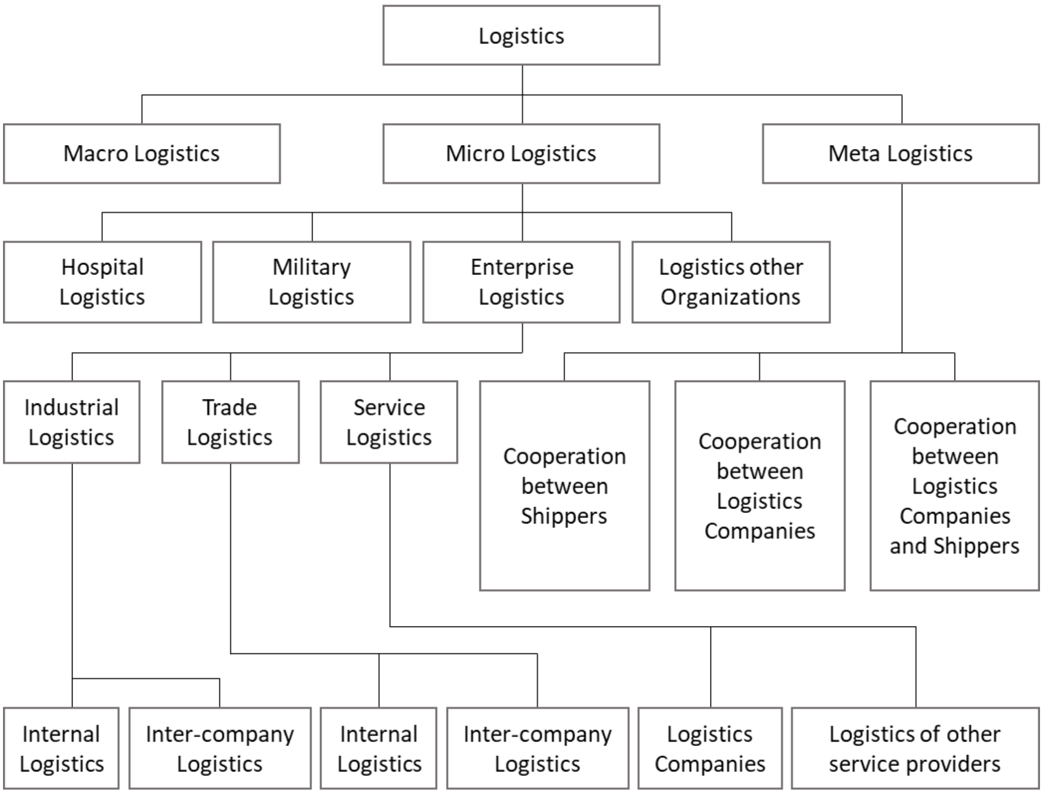

Figure 2-2: Institutional differentiation of logistics systems according to Pfohl (2010, p. 15)

The first aggregation, macro logistics systems, is macroeconomic in nature and describes the transportation system of a region, an economy, or the world. It consists of land (road and rail), air-, and waterways as well as public and individual freight and passenger transport processes (Klaus et al. 2012, p. 417; Pfohl 2010, p. 14).

Micro logistics systems are microeconomic in nature and describe the logistics systems of public and private organisations. Furthermore, they include all transportation processes to, within, and from a company as well as storage and transloading processes (Arnold et al. 2008, p. 4; Pfohl 2010, p. 14; Klaus et al. 2012, p. 436). The main focus of this thesis is on the enterprise logistics as part of micro logistics. Within this category, depending on the business purpose of a company, further differentiations can be made into industrial, trade, and service logistics. With respect to the problem statement defined in section 1.2, only the internal logistics of industrial and trade logistics are considered. Service logistics can be excluded per the definition since its main focus on an institutional understanding lies in the logistics of service providers such as banks or insurance companies (Wannenwetsch 2008, p. 127). In the subsequent chapter, further specifications of internal logistics are provided.

The last aggregation level, meta logistics, is, according to Pfohl (2010, pp. 14–15), in between macro and micro logistics. As an example, he states that meta logistics systems do not cover all freight transports in an economy nor the freight transports of a single company. It rather covers the freight transports of organisations working together in a certain distribution channel.

The second category for logistics systems stated by Pfohl derives from the differentiation based on their functions. By analysing different phases of a material flow, starting from the supplier market up to the sales market or supplier market, phase-specific logistics subsystems can be defined (see Figure 2-3) (Pfohl 2010, pp. 16–19). Although splitting enterprise logistics into individual subsystems contradicts the desired holistic view of logistics, it is nonetheless useful for analysing and planning logistics systems (Arnold et al. 2008, p. 5). For a better understanding of the figure provided, a short explanation is given below:

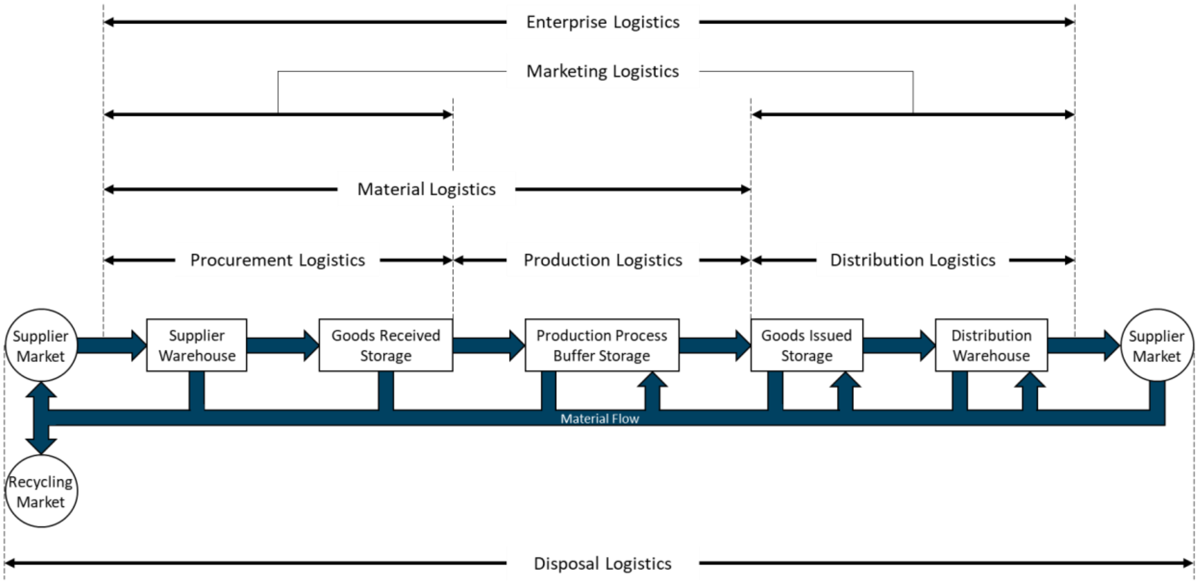

Figure 2-3: Functional differentiation of logistics systems according to Pfohl (2010, p. 19)

Physical objects are procured from the supplier market and might be stored in a supplier warehouse to consolidate or sort them. A direct material flow from the supplier market to the goods received storage is also possible. This scope of logistical tasks is defined as procurement logistics (Ten Hompel and Heidenblut 2011, p. 31; Lasch and Janker 2007, p. 3; Westkämper 2006, p. 226). In the next step, the object enters the production process to manufacture the final product. In addition to the production process, the object can be stored in so-called buffer storages. The overarching terms for these logistical processes are production logistics or internal logistics, respectively, and they are discussed in depth in section 2.1.3 (Ten Hompel and Heidenblut 2011, p. 238; Lasch and Janker 2007, p. 63; Westkämper 2006, p. 227). According to Tempelmeier (2006, p. 1), procurement logistics and production logistics can be grouped into material logistics.

After leaving the production process, the final product enters the goods issued storage. From here, products are either sent to a distribution warehouse for consolidating/sorting or directly to the customer in the sales market or supplier market. These processes are defined as distribution logistics (Ten Hompel and Heidenblut 2011, p. 65; Lasch and Janker 2007, p. 125; Westkämper 2006, p. 227). Furthermore, procurement and distribution logistics can be summarised as marketing logistics since they directly interact with the markets. The penultimate logistical scope, disposal logistics, addresses a reverse material flow of residues, which can be split up into secondary raw materials and waste (Ten Hompel and Heidenblut 2011, p. 86). Whereas waste should be disposed of, secondary raw material is brought back to the recycling market. Lastly, all of the aforementioned logistics scopes fall under the term enterprise logistics. The main objective is to align material, information, and value streams according to the business goals (Ten Hompel and Heidenblut 2011, p. 321).

For this thesis, a functional differentiation is taken as the basis for a better understanding of the logistical scope. When applying the problem statement to this differentiation type, this thesis focusses on production logistics—more precisely, on intralogistics. An exact definition of the term and its scope is provided in the subsequent section2.1.3

2.1.3 Definition of Intralogistics

In the literature, the terms internal logistics, production logistics, and intralogistics are often used synonymously (Arnold et al. 2008, p. 18; Martin 2014, p. 9; Pfohl 2010, p. 130; Martin 2014, 4). However, there is a slight difference for companies with several production plants. Whilst the scope of production logistics considers all plants of a company, the other terms, including intralogistics, focus on one plant (Muchna et al. 2018, p. 29). The tasks associated with terms applied to one plant can be described as follow:

- Connecting the goods received storage with the internal sinks and sources as well as the goods issued storage on the same site (Gudehus and Kotzab 2012, p. 6).
- Material provision and disposal of machines and manual workstations between the goods received storage and the goods issued storage (Arnold et al. 2008, p. 19).
- Transloading, storing, transporting, commissioning, and packaging (placing parts onto machines is not a task of internal logistics) (Martin 2014, p. 9).

For a better understanding, the term intralogistics was introduced in 2005 at the logistics fair Centrum für Materialflusstechnik (CeMAT) by the Verband Deutscher Maschinen- und Anlagenbau (VDMA) (VDMA 2003). Their definition is used in this research:

> *'Intralogistics comprises the organization, control, implementation and optimization of internal material flows, information flows and goods handling in industry, trade and public institutions.'*

As the definition states, intralogistics is an interdisciplinary science in which the planning processes, according to Koch (2009), occur on three levels: management, information flow, and material flow. A material flow is not possible without the associated flow of information, as can be seen in Figure 2-4.

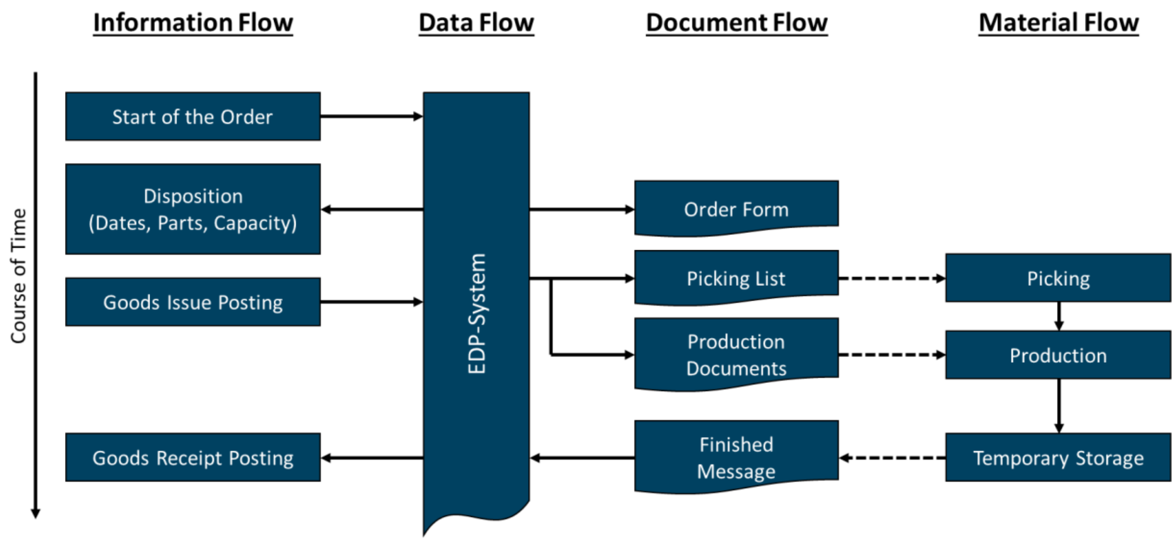

Figure 2-4: Interlinking of information flow and material flow according to Martin (2014, p. 25)

According to Wiendahl (2019, p. 246), the overall goal of production logistics or intralogistics is economic efficiency in consideration of the dependencies logistics costs and logistics performance (see Figure 2-5). He has stated that the logistics performance as perceived by the market should generally be as high as possible, determined by the delivery time and reliability. To achieve short delivery times, the production requires short throughput times. For a high level of delivery reliability, a high level of punctuality in order processing is required. In terms of logistics costs–which comprises of capital commitment costs and process costs–Wiendahl has claimed that these should be as low as possible from the company's point of view. Low capital commitment costs are achieved with low inventories and low process costs with a high degree of utilisation.

Since the focus is on high economic efficiency, which is expressed in low manufacturing costs, an internal goal conflict results due to the different interests of the customers and the company. The interests of the customers are short lead times and high punctuality to obtain the ordered product as quickly as possible within the agreed delivery time. From the perspective of a business, capacities should be high and evenly utilised to avoid downtime costs. This conflicts with the goal of keeping inventory levels as low as possible to minimise interest costs and logistical costs. This is also referred to as the dilemma of production control.

Whilst in the past, a high degree of utilisation of operating equipment was the main goal, delivery reliability and delivery time are the primary target figures today. However, stocks in warehouses and production should not be neglected (Wiendahl 2019, p. 246). One aspect of addressing this goal conflict is flexibilisation, which enables synchronisation of customer demand and production output (Haseloh 2013, p. 138).

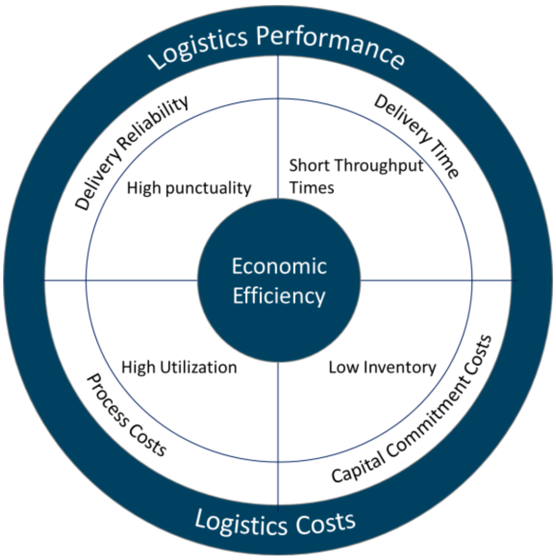

Figure 2-5: Target system of production logistics according to Wiendahl (2019, p. 247)

2.2 Fundamentals of Material Flow Systems

A material flow represents the technical view of logistics. It is comprised of all processes involved in the extraction, processing, and distribution of goods. A material flow system is therefore aggregated from several individual material flows (Ten Hompel et al. 2018, p. 2). The economic and information technological view of logistics includes information, data, and document flows (see Figure 2-4). In the following, the basics of material flow systems are explained, which are relevant for this research.

2.2.1 Definition of Material Flow Systems

As mentioned, a material flow can be best described as the 'interlinking of all processes in the extraction, processing and distribution of goods within defined areas' (VDI 2411; DIN 30781-1). The transformation processes refer to discrete objects (piece goods) which are changed in regular or irregular time intervals in terms of time, place, amount, composition, and quality (Arnold and Furmans 2005, p. 1; Pfohl 2010, p. 4). According to several authors, the scope of material flow functions includes processing, checking, handling, conveying, storing, and staying (Martin 2014, p. 26; Jünemann 1989, p. 16; VDI 2411). Currently, assembly, commissioning, palletising and packing, buffering, separating, and merging are also included (Handrich 2001, p. 9; Günthner and Severin 2005, U70).

In terms of structuring a material flow system, a system-oriented and hierarchical approach can be found in the literature. Bullinger and Lung (1994, p. 5), similarly to Martin (2014, pp. 23–24), have named four levels to delimitate material flows which originate from production planning (see Figure 2-6). The first level covers all transportation processes between different production sites of the company or between the company and its suppliers or customers. On the second level, all transports within a factory site between different areas or factory buildings are included. Building internal transports form the third level and represent all transports within a factory building between departments or machine/workplace groups of different areas and transports between individual equipment or workplaces. The last level of material flows covers the supply and handling at the workplace. This research focusses on the third level, building internal transports.

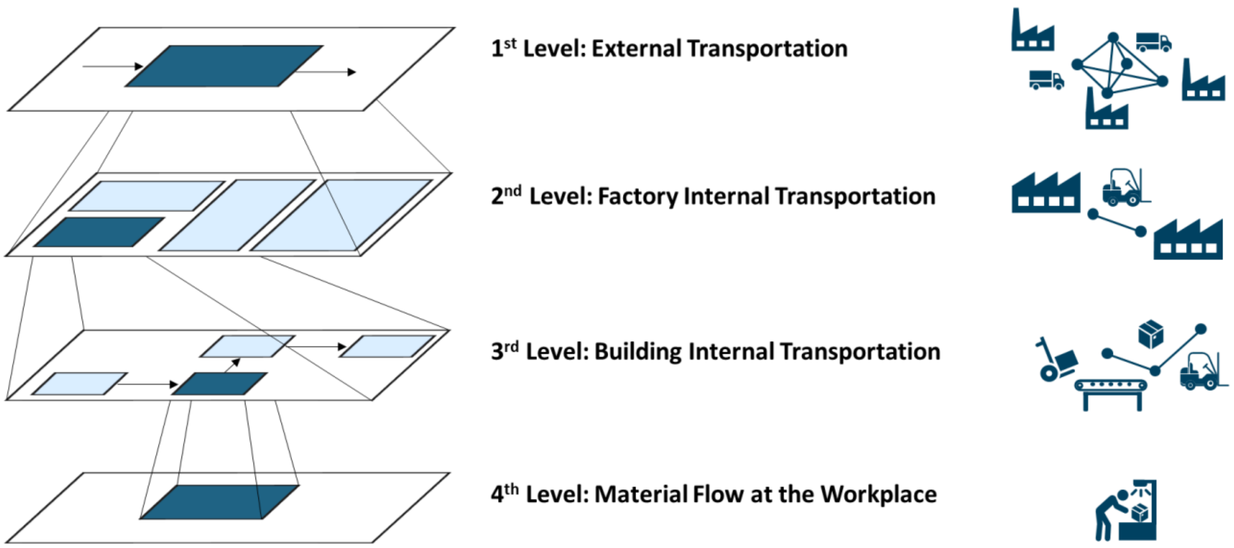

Figure 2-6: Hierarchical levels of material flows according to Bullinger and Lung (1994, p. 5)

To control a material flow, two general principles can be applied. In the so-called push principle, material is brought from the goods receiving or production warehouse to the place of consumption by transport workers and/or means of transport according to demand. The second is the pull principle, in which the workers themselves retrieve the required materials from the warehouse according to consumption. Within the pull principle, a differentiation is made between the one-bin and the two-bin systems. In the one-bin system, also known as the Kanban system, each bin has a material card assigned to it which serves as a request or order card when the bin is empty. In the two-bin system, two bins are placed at the place of consumption. If the first bin is empty, another bin is ordered. The place of consumption can continue to work without interruption due to the second bin (Martin 2014, p. 23).

2.2.2 Planning of Material Flow Systems

To explain the complexity of material flow systems, a generic planning approach by Allgayer (1999, p. 24) is presented. Other planning procedures aggregated using the semi-systematic literature review differ only in certain structural aspects.[3]

In general, there are four consecutive planning phases: preparation, rough planning, detailed planning, and realisation (see Figure 2-7). Before planning a new material flow system, an analysis of weak points and their causes must be performed. Allgayer has argued that data about, for example, assortment, transported and stored goods, operating equipment, and the building, hall, and property must be collected. This process requires a significant amount of time, but it is necessary to not only evaluate the current situation but also build the foundation of every material flow plan.

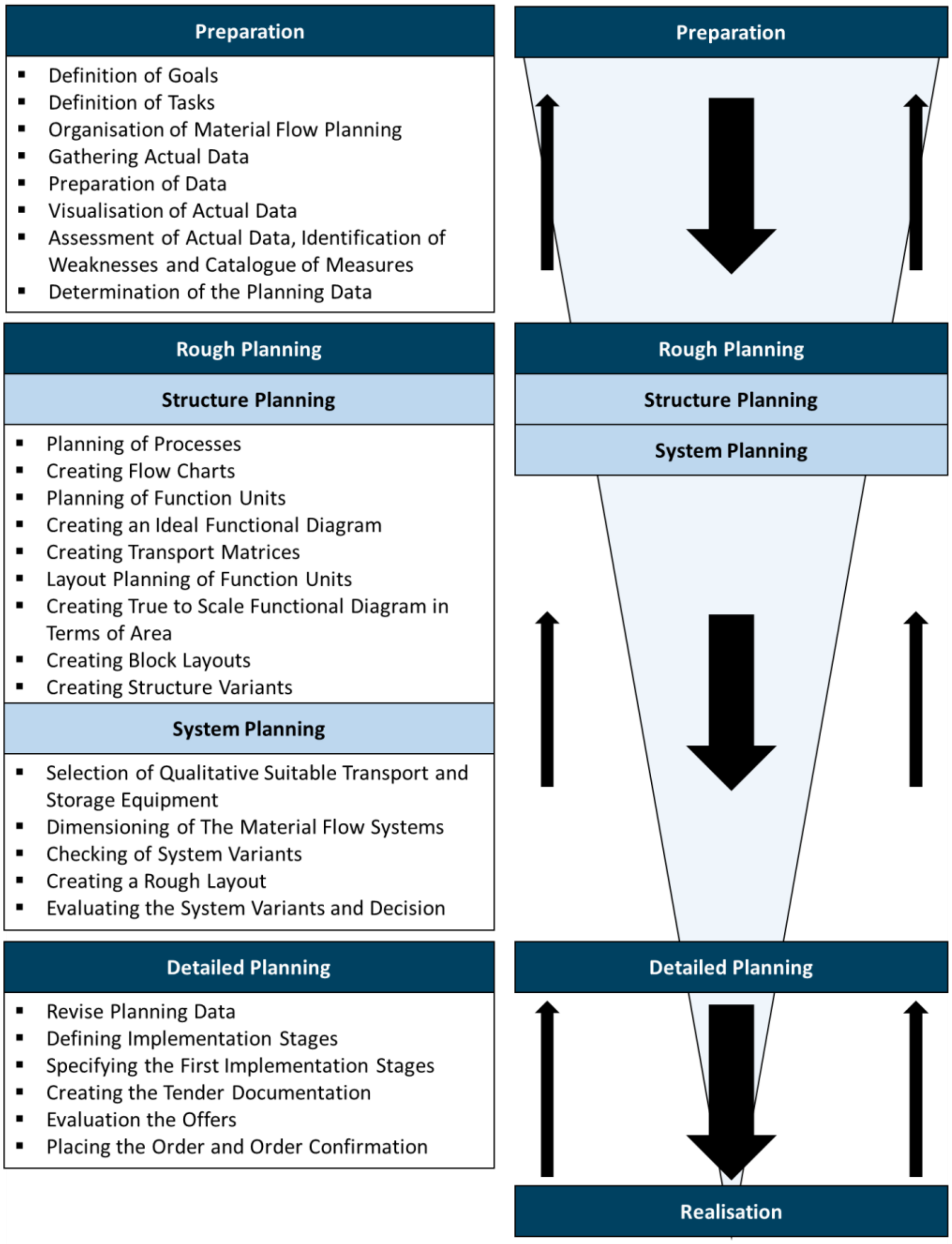

Figure 2-7: Planning approach for material flow systems by Allgayer (1999, p. 26)

[3] See Appendix A

After a first analysis, the preparation phase starts by defining the goals to evaluate the success of the planning afterwards. Such a goal could be reducing lead time, improving bottlenecks, or improving the degree of area utilisation. This goal, in turn, is also a first draft of the subsequent step: defining the tasks. In this step, a detailed version of the goal is created using subtasks to ensure a successful realisation. To do so, a rough study must be conducted whereby relevant actions, figures, requirements, and decision-making criteria are analysed. Special attention should be paid to the boundary conditions which are already defined by external factors and to those which must still be defined. Having highly detailed and formulated tasks leads to a better estimation of workload, time, and costs. This information is used to decide whether a project should be realised or not. Lastly, if the planning should be realised, the tasks serve as binding bases for the analysis, execution, and billing of the project.

The third step of the preparation phase is the organisation of the material flow planning, in which all relevant points for carrying out the planning are defined. These points are determining a project leader and members, delimiting the scope of planning, defining the procedure, creating a timetable, and defining the method, accuracy, and duration of gathering data. A plan in graphical or tabular form will result, which defines the approach for realising the project.

Next, the actual data—for example, quantity structure, plant structures, processes, or requirements—must be gathered, prepared, and visualised. For gathering, the planner has several tools like checklists and questionnaires. Martin (2014, p. 464) has defined methods for direct and indirect data collection, as can be seen in Figure 2-8. After gathering all relevant data, they must be prepared in terms of plausibility, relevance, and completeness. In particular, data which have been collected directly must be compared with target and plan data. If there are major deviations, both the actual data collected and the target data must be checked again for errors. When all the relevant actual data are collected and validated, they can be visualised by using, for example, flow charts, Sankey diagrams, technical drawings, petri nets, photos, matrices, or numeric models.

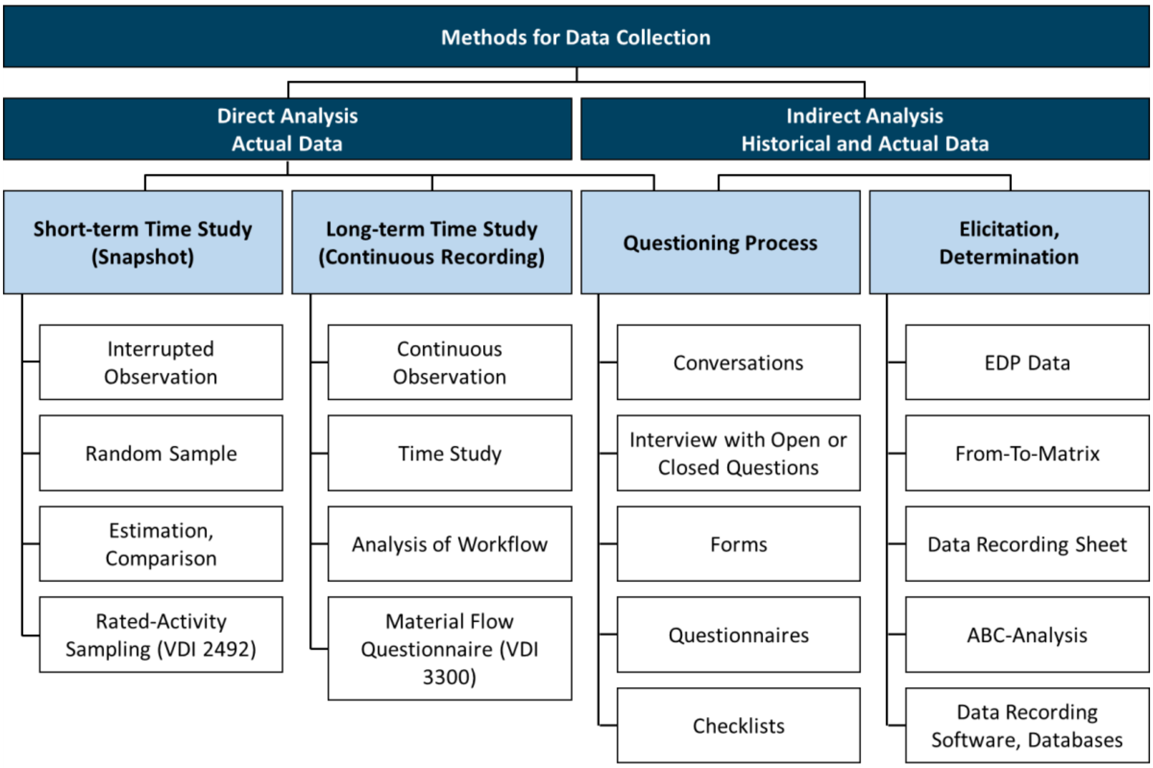

Figure 2-8: Methods for directly and indirectly gathering data according to Martin (2014, p. 464)

The next-to-last step in the preparation phase for planning material flow systems, according to Allgayer, is the assessment of the actual data, identification of weaknesses, and the development of a catalogue of measures. The actual state is assessed with checklists, key performance indicators (KPIs), and fundamental material flow principles such as:

- Linear and process-efficient material flow design.
- Only one-way transportation routes without cross-sections.
- Manufacturing unit = transport unit = storage unit = packaging and shipping unit.

After this evaluation, the weaknesses of the system are identified, and a catalogue of corrective measures is developed. With regard to the implementation of the measures, these will be carried out in phase II.

To end the preparation phase, the planning or target data must be determined based on actual data using trend calculations and forecasts. Thereby, target data can also be determined by specifications from the management. Allgayer has mentioned four categories based on Aggteleky (1990):

- analytical forecasting methods (extrapolation).
- mathematical models (operations research).
- formalistic methods (time series).
- intuitive forecasting methods (Delphi method).

The resulting target data from these methods finally form the binding basis of the material flow planning.

The second phase of the material flow planning method is the most important and creative task. The goal is to develop a technically functional, economically feasible, and organisationally simple solution. The rough planning is characterised by its stepwise iterative procedure in which variants are developed, evaluated, and selected. As can be seen in Figure 2-7, the phase is split into structure and system planning. Although the figure shows a strict sequence of actions, it should be mentioned that the individual steps overlap considerably and should therefore be thought through and worked on simultaneously. During the structure planning, different concepts with varying processes, material flow operations, or transportation processes are developed and enhanced with layout planning. Thus, several structure variants result, which form the foundation of the subsequent system planning.

In system planning, a qualitative evaluation of material flow equipment for the previously planned processes occurs. Since processes can be summarised or combined differently, several system variants (technical solutions) for a single structure variant result. These variants must then be properly dimensioned and evaluated to select an optimal solution for the detailed planning and realisation.

The task of structured planning is process planning by using the target data and existing boundary conditions. All operations and process which together solve the material flow task are defined and graphically displayed in a flow chart. Based on the defined organisation forms (e.g. workshop production, assembly-line production, man to goods or goods to man) resulting from the manufacturing, assembly, and storage principles or strategies, the material flow operations are summarised into functional units. Again, a flow chart is used to display the workflow of the (ideal) functional units. The connection between each unit represents a transport process from which the transport volume can be calculated from the target data. The transport volume[4] can be further aggregated to transport units per time unit, providing the planner the possibility to design true-to-scale Sankey diagrams or transport matrices.

[4] Units are usually: number of pieces per time unit, weight per time unit, or volume per time unit

When planning the layout of functional units, the main goal is to reduce transportation effort and costs by placing functional units with high transportation volumes next to each other. To optimise the transport efforts, Allgayer has referred to Arnold and Furmans's (2005, p. 285) classification of layout planning methods (see Figure 2-9). In the classification, heuristic and exact methods can be found. The selection of an adequate method depends on the optimisation problem as well as on the available computing power and storage space. The next step of layout planning is the development of a true-to-scale function unit layout by deriving the target areas from the actual data or other KPIs. This ideal layout of the functional units should then be converted into a block layout by merging the functional units with the floor plan, taking the previously identified dependencies into account. Several solutions may result, which are called structure variants. Allgayer has further stated that it is important to consider the expandability of the individual functional units in this planning step. The development of all structure variants concludes the structure planning.

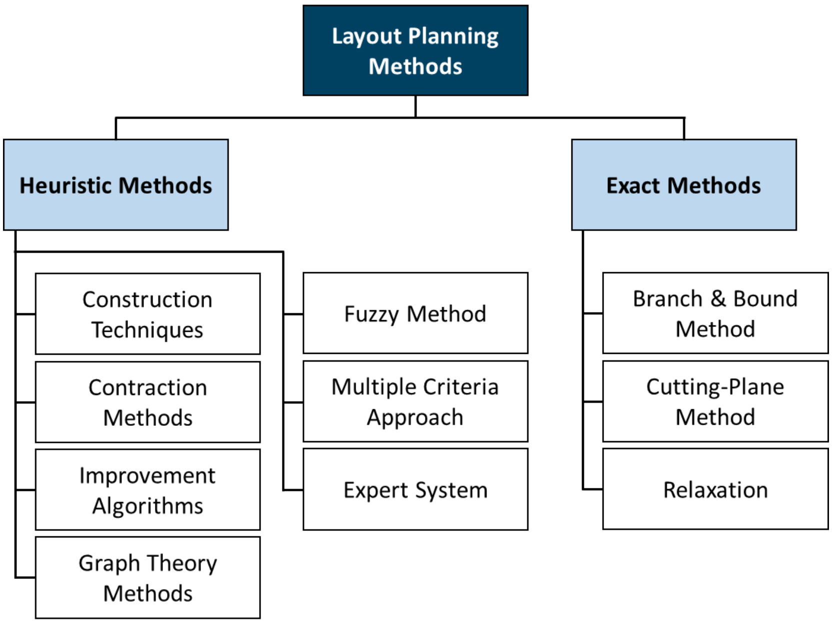

Figure 2-9: Classification of layout planning methods by Arnold and Furmans (2005, p. 285)

Subsequent to structural planning is system planning, which begins with the selection of qualitative means of transport and storage for each structure variant. The central point in this step is the definition of characteristics of the material flow operations such as properties of the transported goods, properties of the transportation routes and storages, and properties of the transport and logistics processes in terms of throughput, functions, and performance. These characteristics should be additionally summarised in the specification sheet. For the selection of suitable material flow equipment, a morphological analysis must be conducted. In terms of means of transport and storage, attention should be paid to the following points:

- Manufacturing unit = transport unit = storage unit = packaging and shipping unit.
- Standardised handling and transport aids.
- Amount of different handling and transport aids should be kept to a minimum.

In a second step, the system variants resulting from the previous step must be quantitatively dimensioned. There are two types of variables for this: time-independent (e.g. geometrical dimensions) and time-dependent (e.g. velocities). The time-dependent variables can be determined by the number of transports required per time and the distance covered. If the system should be dimensioned dynamically, simulations are required which consider transportation and storage strategies. Thus, the higher the accuracy of the results, the higher the effort. At the end of each dimensioned system variant, an evaluation should occur to verify its functionality. Only functioning and appropriate system variants will be considered for developing a rough layout. A rough layout comprises, for example, the floor plan, location and dimensions of departments, machines, doors, transportation routes, and storage systems. The last step in the system planning, and therefore the rough planning, phase is the evaluation of all variants as well as the final selection. To evaluate a system, Allgayer has stated three criteria: profitability, quantitative, (e.g. performance, uptime) and qualitative (e.g. safety, expandability). Qualitative criteria must especially be evaluated objectively by applying a cost-benefit analysis and a two-step point evaluation. For evaluating the profitability, Allgayer has recommended static and dynamic calculation methods (see Table 2-3):

Table 2-3: Static and dynamic profitability calculation methods based on Allgayer (1999, p. 48)

Static Calculation Methods	**Dynamic Calculation Methods**
Cost comparison calculation	Net present value
Profit comparison calculation	Internal rate of return
Profitability comparison calculation	Equivalent annual cost
Amortisation calculation	Amortisation calculation

After each variant has been evaluated using the abovementioned methods, the 'point of no return' is reached. The system planning step, and therefore rough planning step, ends with the decision of management whether one of the system variants should continue to be planned in detail and implemented or whether the planning process should be stopped.

If a system variant is chosen, the third step of planning material flow systems follows. In the detailed planning phase, existing planning data are checked and updated if necessary. In a subsequent step, realisation stages are developed depending on the financial situation. The first implementation stage is subjected to a more precise structure and system planning as well as dimensioning. This is also where the control and organisation of the material flow system is specified. Finally, tender documents are prepared, incoming offers are evaluated, and finally the order is placed and confirmed.

The realisation phase ends the planning process. All work is carried out by the contracted companies and coordinated and monitored by a project manager. Allgayer has stated that this phase is not a planning phase as such but has a coordinating, monitoring, and testing function. The planning project is completed with a final inspection test.

2.2.3 Standard Types of Load Carriers

In a material flow system, the logistical object is a piece good, as stated in the definition in section 2.2.1. In reference to DIN 30781-1 and Ten Hompel et al. (2018, p. 10), piece goods can also be formed from bulk materials, gases, or liquids by using packaging materials and packaging aids. To transport a piece good in a material flow system, a load unit must be aggregated. This is achieved by using load carriers (loading aids). The selection of an appropriate load carrier is crucial for the entire material flow process as it has a significant impact on all subprocesses. In general, load carriers can be split up into three categories (Ten Hompel et al. 2018, 24 ff.).

The first category covers the carrying loading aids. These could be, for example, a European flat pallet, a Düsseldorf pallet, a stacking pallet, or even product fixtures. The most common type in Germany is the European flat pallet, which has the following dimensions: 800 mm x 1200 mm. Its maximum load capacity is 1,500 kg. The pallet's specifications are standardised according to DIN EN 13382 and DIN EN 13698-1.

The enclosed loading aids form the second category, which consists, for instance, of small load carriers (SLC), wire mesh box pallets, or flat pallets with a foldable stacking frame. These load carrier types enclose their load and are often used for smaller, non-stackable piece goods. Modular load carriers such as the abovementioned SLCs play an especially important role in intralogistics systems for manual and automatic handling (Ten Hompel et al. 2018, p. 29). Their dimensions, load capacities, and materials are defined in several norms such as VDA 4500 and DIN EN 13199-1. The three most common types of SLCs in terms of their length and width are:

- SLC 6040 (600 mm x 400 mm, maximum load capacity 600 kg).
- SLC 4030 (400 mm x 300 mm, maximum load capacity 600 kg).
- SLC 3020 (200 mm x 300 mm, maximum load capacity 400 kg).

The last category constitutes the closed loading aids, which enable a closed transport of piece goods (e.g. overseas using an ISO container). In addition to ISO containers, there are also semi-trailers, box trailers, swap bodies, or unit load device (ULD) containers. However, the most universal container is the ISO (Ten Hompel et al. 2018, p. 31). Its dimensions and load capacity are normed in ISO 668. They are eight feet wide and 10, 20, 30, 40, or 45 feet long and can carry up to 25 tonnes of goods.

2.3 Flexibility and Versatility

Current logistics and production systems face a highly volatile and turbulent environment with constantly changing requirements. To fulfil these requirements, these systems should be flexible and versatile. The following sections introduce the topics of flexibility and versatility with special emphasis on material flow systems. The different views and definitions in the literature are shown and summarised. This also encompasses the concept of reactability and changeability.

2.3.1 Flexibility

In the context of manufacturing systems, the term flexibility has replaced elasticity since the 1950s.[5] Especially with rising competition from the Asian market in the 1970s, the term has become increasingly important (Heinecker 2006, pp. 46–47). During this time, Toyota's multidimensional integrated production concept, developed over decades, has served as a role model and has been the subject of numerous studies (Zanker and Reisen 2016, p. 13). Its general consensus is to avoid waste (Japanese *muda*) and thus increase the stability of a production system. Stability refers to the efficiency and effectiveness of the system and therefore to costs, product quality, and process quality (Zanker and Reisen 2016, p. 14). According to Ohno (2013, p. 78), stability plays an important role in the standardisation of processes, methods, and tools. Intra- and intercompany process costs (e.g. for tools, transport, or supply) can thereby be reduced. Companies which adopted Toyota’s production system (TPS) could therefore react successfully to the dramatically risen costs and customer requirements. However, a maximum of stability can only be achieved within a constant environment. Changes in the production process are solely reactive; proactive changes and flexibility aspects are not considered at all (Zanker and Reisen 2016, p. 14). However, as indicated, the environment of logistics and production systems has changed drastically and thus requires the systems to be flexible and versatile.

The term flexibility is described in the *Cambridge Dictionary* (2020) as ‘the ability to change or be changed easily according to the situation’. In the context of organisations, the adaption to changing environmental conditions is meant (Zanker and Reisen 2016, p. 14). Pfohl (2016, p. 291) has stated that flexibility in an organisation is an essential perquisite for meeting the constantly changing

[5] For further information and discussion see Grob 1986, p. 24.

requirements in a turbulent environment. In contrast to the abovementioned TPS and its reactive adaptions to changing environmental conditions, flexibility enables a proactive adaption of the system in a planned scope. Tempelmeier and Kuhn (1993, p. 18) have defined flexibility as the existing of degrees of freedom in a decision-making process. In comparison, Westkämper et al. (2000, p. 24) have specifically addressed the process of reversibility. Their definition is used as a basis for this research:

> *'A system is described as flexible if it is reversibly adaptable to changing circumstances within the framework of a principally planned scope of attributes and their characteristics'.*

This definition states that a system can handle changing circumstances within a defined scope. In the relevant literature, authors have therefore referred to a so-called flexibility corridor which defines an upper and a lower boundary (Bullinger et al. 2009, p. 15; Wiendahl 2002, p. 124; Spath et al. 2008, p. 12). Generally, a certain degree of flexibility is immanent in manufacturing systems with a low degree of automation. The predominantly manual work leads to a more environmentally focussed production and fast reactions. In the case of highly automated systems, the area in which economic production is possible is very limited. One of the reasons for this is the high investment costs, which can only be compensated if the planned system is used over its entire planned lifespan without any changes. However, a reuse of the system is often not possible due to its strong specialisation (Heinecker 2006, p. 47). When planning a new highly automated system, special emphasis should therefore be paid to its flexibility and respective corridor width[6] (Heinecker 2006, p. 49). However, having a high flexibility reserve in the system is very expensive (Spath et al. 2008, p. 11).

Thus, Heinecker (2006, pp. 49–50) has developed a concept in which the total degree of flexibility is differentiated over time, and therefore a planned activation of flexibility in response to planned events/turbulences occurs. In his differentiation, he introduces two types of flexibility: base and enhanced. Base flexibility considers all environmental turbulences which can happen during operation. However, if the introduction of a new product is planned which requires an expansion of the system, investments as well as the activation of additional flexibility potentials are made at a later point in time (see Figure 2-10). The flexibility potential for such pre-planned events is defined in the enhanced flexibility. The main advantage of splitting the total flexibility potential of a system into basic and enhanced flexibility is that the timeframe of the individual investments is different, thus reducing fixed costs to a minimum.

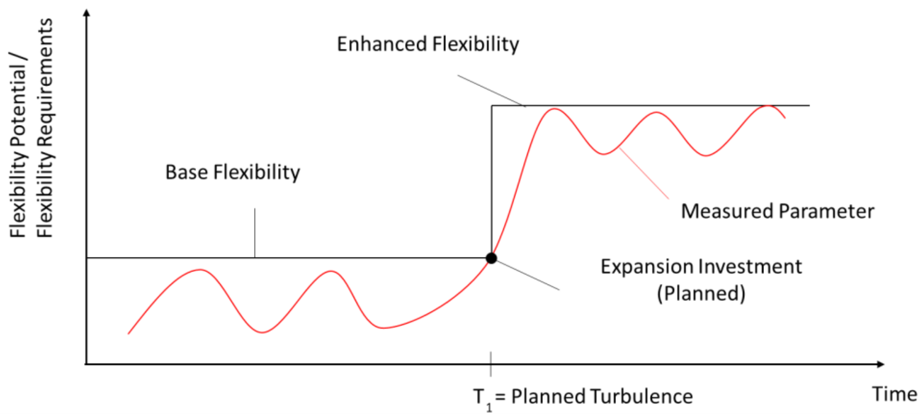

Figure 2-10: Connection between base flexibility and enhanced flexibility according to Heinecker (2006, p. 50)

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[6] A semi-systematic literature review was conducted as part of this research, which showed that the existing methods and procedures for material flow systems do not cover all facets of flexibility (see Appendix A).

To further adequately plan a system's flexibility, a classification into independent parameters is useful (Heinecker 2006, p. 61). In the literature, several flexibility parameters can be found, all of them having a non-uniform definition in terms of their scopes and names.

2.3.1.1 Flexibility Taxonomy according to Browne et al.

Browne et al. (1984, pp. 114–115) have defined eight classes of flexibility parameters (see Table 2-4). Although the focus during development of the taxonomy was on flexible manufacturing systems, aspects influencing the respective material flow systems can be found (e.g. routing, volume, or expansion flexibility affect the transport system). The individual parameters are outlined in the following:

Table 2-4: Flexibility taxonomy according to Browne et al. (1984, pp. 114–115)

Parameter	Description
Machine Flexibility	This parameter describes the ability of a machine or production system to perform a number of different manufacturing operations such as drilling, milling, or turning.
Process Flexibility	The number of producing different workpieces in a production system without reconfiguration or reconstruction measures is described by the process flexibility.
Product Flexibility	With product flexibility, the ability of a production system to manufacture different products or products in different combinations is meant. The switch is economical and fast.
Routing Flexibility	This describes the ability of the system to produce a product on different material routes through the system in case of breakdowns. Browne et al. have further stated that alternative routes can also be used for optimising the degree of utilisation of a production system even without an existing breakdown.
Volume Flexibility	Volume flexibility describes the ability of a production system to produce economically at different output levels within the technical capabilities.
Expansion Flexibility	Whilst volume flexibility describes fluctuations within the capabilities of the system, expansion flexibility describes the ability to expand as needed, easily and modularly.
Operation Flexibility	Flexibility in operation is given when a product can be processed in different technological sequences, and the system is variable in choosing the next machine.
Production Flexibility	It represents all products the system can produce and is attained by increasing the system's level of technology and versatility whilst requiring all capabilities of the previous flexibility parameters.

2.3.1.2 Flexibility Taxonomy according to REFA

Similar to Browne et al., REFA (1990, p. 47) has developed five flexibility parameters for production systems (see Table 2-5). Moreover, a distinction is made between short- and long-term flexibility parameters. The short-term parameters include product flexibility, manufacturing redundancy, and volume flexibility. Adaptation flexibility and expansion flexibility are long-term parameters.

Table 2-5: Flexibility taxonomy according to REFA (1990, p. 47)

Parameter	Description
Product Flexibility	This parameter describes the number of different products and their degrees of freedom for assignment to different machines.
Manufacturing Redundancy	Manufacturing redundancy represents the number of alternatively usable pieces of operating equipment.
Volume Flexibility	The economic limits for additional shifts or short-time work, as well as having additional operating resources available, lie within the scope of volume flexibility.
Adaption Flexibility	This describes the complexity/expenditure of reconstructing the system.
Expansion Flexibility	Expansion flexibility describes the effort required for a future expansion of the system.

2.3.1.3 Flexibility Taxonomy according to Tempelmeier and Kuhn

Tempelmeier and Kuhn (1993, p. 19) have listed eight flexibility parameters assigned to one of the four following categories: machine, material flow technology, product, or system (see Table 2-6). These categories represent the scope of the individual parameter. Machine flexibility is assigned to the category of machine and material flow flexibility to material flow technology. The product category consists only of the working plan flexibility. All other parameters such as the system change flexibility, product mix change and product mix flexibility, manufacturing process flexibility, and product quantity flexibility belong to the system category.

Table 2-6: Flexibility taxonomy according to Tempelmeier and Kuhn (1993, p. 19)

Parameter	Description
Machine Flexibility	Machine flexibility describes the ease of switching the system to a new work task.
Material Flow Flexibility	With the material flow flexibility, different products can be transported on any route in the system.
Working Plan Flexibility	The possibility of having alternative working plans is described in the working plan flexibility.
System Change Flexibility	In the system change flexibility, the change in the number of resources is described.
Product Mix Change Flexibility	This describes the handling of different products without external changes to the system but with setup processes.
Product Mix Flexibility	Similar to the product mix change flexibility, the product mix flexibility describes the handling of different products without setup processes.
Manufacturing Process Flexibility	Manufacturing process flexibility means the possibility of routing products on different paths and machines through the system.
Product Quantity Flexibility	Product quantity flexibility refers to the ability to produce economically with different throughputs.

2.3.1.4 Flexibility Taxonomy according to Handrich

In a study conducted by Handrich (2001, pp. 6–26) covering the flexibility requirements of intralogistical material flow systems in a (small) series production with autonomous, decentralised units, six flexibility parameters were identified (see Table 2-7). The parameters used in the taxonomy are similar to those of the authors mentioned above but have a different scope of definition. Whilst Handrich shares the same scope for the product mix flexibility with Tempelmeier and Kuhn and REFA’s and Browne et al.’s product flexibility, the expandability is defined much more precisely. In addition, Handrich has introduced the parameter 'flexibility of the degree of automation' due to its thematic focus on autonomous and decentralised units. The degree of automation of a system is directly related to its cost and flexibility (Handrich 2001, p. 21). The fulfilment of a high degree of automation and high flexibility quickly drives costs into uneconomical levels. For this reason, manual or semi-automated material flow systems are predominantly used where high flexibility is required.

Table 2-7: Flexibility taxonomy according to Handrich (2001, pp. 23–25)

Parameter	Description
Product Mix Flexibility	The product mix flexibility, also referred to as conveyed material flexibility, describes the ability of flexible material flow systems to convey different products.
Layout Flexibility	Layout-flexible material flow systems can transport goods to different sources and sinks within the working area using different routes.
Expandability	This describes the ability to handle new sources and sinks, resulting from an expansion of the production hall/production system.
Throughput Flexibility	A throughput-flexible system can cope with fluctuations in the production output.
Integrability	The ability not only describes the integration of material flow systems into control systems or production planning and control systems but also into other material flow systems.
Flexibility of the Degree of Automation	To operate the system at the optimum operating point in terms of flexibility requirements, costs, and level of automation, the system should be able to adopt different degrees of automation at both the operational and planning levels.

2.3.1.5 Further Flexibility Taxonomies

Based on Handrich’s parameters for material flow systems, Günthner et al. (2002, p. 8) have introduced a differentiation into flexibility parameters and changeability parameters. The term changeability is introduced at a later point (see section 2.3.3). As flexibility parameters, Günthner et al. have defined the product mix flexibility, layout flexibility, and throughput flexibility. In terms of changeability parameters, Günthner et al. have named ‘expandability, integrability, and flexibility of the degree of automation.

Another taxonomy comes from Heinecker (2006, pp. 68–71). In his research, he only uses five of the six parameters from Handrich and Günthner et al.: conveyed goods flexibility, layout flexibility, throughput flexibility, expandability, and integrability. The flexibility of the degree of automation is not considered. Furthermore, he has categorised, according to Günthner et al., conveyed goods flexibility, layout flexibility, and throughput flexibility as flexibility parameters and expandability and integrability as changeability enablers. Heinecker (2006, p. 66) has further stated in his research that all other flexibility parameters in the literature are either used synonymously or can be represented through a combination of the abovementioned three. In his definition of conveyed goods flexibility, he has highlighted that predefined product spectrums or variations of it must be able to be transported. As a main factor influencing this parameter, he has mentioned the dimensions and weight of the products. With regard to the layout flexibility, Heinecker has referred to the fact that every location in the hall must be kept operating should pre-planned changes occur and that the material flow system must be able to adapt to changed material flows. For the last flexibility parameter, throughput flexibility, he has stipulated that the throughput should be adjust to predefined fluctuations in production output.

In a similar way to Heinecker, Wilke (2006, pp. 21–22) has also defined three flexibility parameters, the scope and definition of which are analogous to Heinecker; however, factors influencing the layout flexibility and throughput flexibility are different. For the layout flexibility, Wilke has placed greater emphasis on the transport route (e.g. in terms of its length). For the throughput flexibility, he has mentioned the number of load carriers transported per means of transport.

2.3.2 Reactability

Reactability and flexibility are closely related. As the previous sections have shown, flexibility describes how to address turbulences which occur during operation. The system can respond to the turbulences to a certain, predefined degree. The reactability goes beyond this point. It refers to the ability of a system to react to unpredictable, sudden events where the pre-planned dimensions or corridors of flexibility are not sufficient (see Figure 2-11). In the literature, this characteristic is often referred to as the creativity and problem-solving ability of a factory planner. Flexibility, on the other hand, is described as routine (Blessing 1999, p. 19; Dürrschmidt 2001, p. 14; Reinhart 2000, pp. 24–25; Reinhart et al. 2002, p. 19; Wiendahl 2002, p. 124). According to Reinhart (2000, p. 25), the reactability potential can be described as the sum of known and unknown parameters in a system to meet the newly changed conditions. It is also important to note that the flexibility potential increases as soon as parameters are found which meet the new requirements. The reason for this is that a reoccurrence of the same known turbulence can be solved routinely and flexibly.

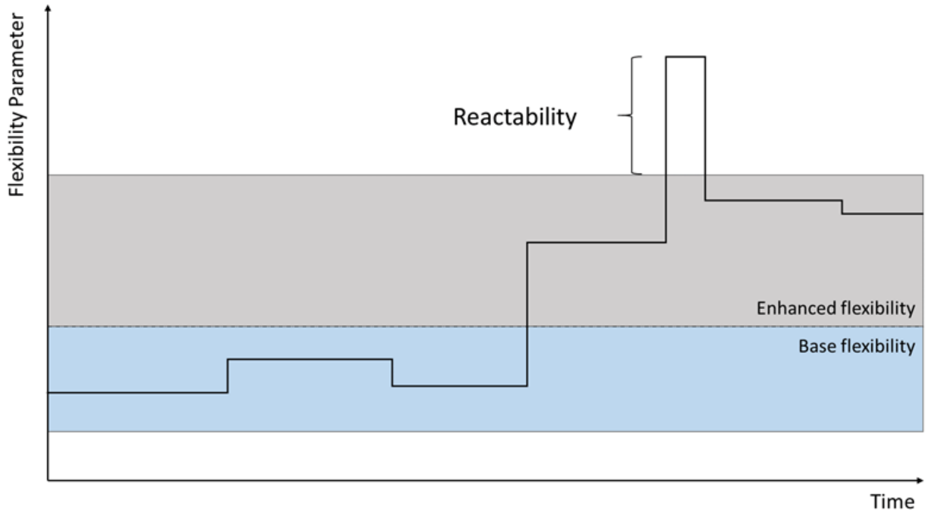


Figure 2-11: Reactability and flexibility based on Zanker and Reisen (2016, p. 21)

Dürrschmidt (2001, p. 15) has provided a sound definition of the term reactability. The main aspect of the definition is, as described above, the ability to react to unplanned, sudden events in a non-predefined manner. Thus, its potential is undirected. Only through the realisation of the solution, resulting from the reactability, is a dimension-oriented flexibility potential generated:

> *Reactability describes the potential of a system to react to unforeseen events that have already happened and to be able to adapt to new situations. As a potential, the ability to react is therefore undirected. In contrast, the conversion of the potential is shown by the realisation of a target vector in a specific realized environmental situation.*

2.3.3 Versatility and Changeability

The versatility of a system describes the ability to operate beyond planned flexibility corridors (Küber 2017, p. 20). To be more specific, this means the adaptation of the system to new boundary conditions and requirements in accordance with the changed environment (Wemhöner 2006, p. 30). The planned flexibility potentials are shifted accordingly. For the term versatility, there are numerous definitions in the literature (Reinhart 2000, p. 25; Blessing 1999, p. 19; Schenk et al. 2014, pp. 39–40; Wiendahl et al. 2005, p. 13; Westkämper et al. 2000, p. 25). For instance, Reinhart has defined versatility as the combination of flexibility and reactability, whereas Blessing has described the term as an ability of a company to change according to unplanned and unforeseen events. The dimension of the change does not need be known beforehand. According to Schenk et al., versatility is possible when the ability to adapt and develop goes beyond the phases of the factory lifecycle. In contrast, Wiendahl et al. have stated that versatility is granted when internal and external factors enable a factory to actively change its structure at all levels with little effort. Westkämper et al. have defined versatility below:

> *A system is described as versatile if it has process and structural variability as well as behavioural variability that can be used in a targeted manner. Versatile systems are able to make both reactive and anticipatory adjustments. These adjustments can work towards system changes as well as changes in the environment.*

Based on this definition, a system can therefore react to future requirements, even though these were not yet known at the time of planning. To ensure that the system responds appropriately to drivers of change, it must have characteristics which enable it to change. In the literature, a large number of so-called transformation enablers can be identified, which can be divided into primary and secondary enablers (Heinen et al. 2008, p. 26). In this thesis, however, only five primary transformation enablers, according to Nyhuis et al. (2007, p. 290), are explained in more detail as secondary enablers do not add any new aspects (see Table 2-8); they only serve to supplement and detail the existing ones (Heinen et al. 2008, p. 27).

Table 2-8: Transformation enablers for versatile systems according to Nyhuis et al. (2007, p. 290)

Transformation Enabler	Description
Universality	Universality describes the dimensioning and designing of an object for various requirements regarding product, function, or technology (e.g. training for employees).
Mobility	This refers to the unrestrained mobility of objects (e.g. machines on wheels).
Scalability	It describes the ability to expand and contract technically and spatially as well as in terms of personnel (e.g. working time model to adjust the available capacity).
Modularity	The modularity describes standardised, technical functional units or elements (e.g. modular exchangeable arm of an industrial robot).
Compatibility	This represents the networking capability with regard to material, information, media, and energy (e.g. uniform software interface for linking control systems).

Concluding from the definition and the transformation enablers, it can be seen that versatility refers to the entire company. According to Westkämper et al. (2000, p. 25), this is also referred to as socio-technical systems as creativity and human intelligence are taken into account. However, if the change of a system only affects the technical side, Westkämper et al. (2000, p. 24) speak of changeability (see Figure 2-12).

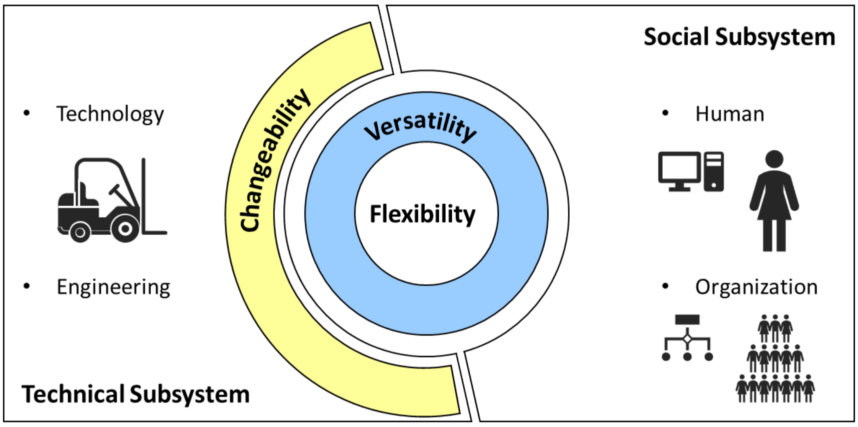


Figure 2-12: The relationship amongst flexibility, changeability, and versatility according to Westkämper et al. (2000, p. 25)

In contrast to flexibility, changeability also accounts for changes in spatial arrangement. Furthermore, the system must be able to adapt to future requirements—similar to versatility—which were not known at the time of planning. Accordingly, the restriction on the reversibility of flexibility must be dropped. The definition of changeability, according to Westkämper et al. (2000, p. 24), is as follows:

> *A system is described as changeable if its physical structure as well as its behavioural spectrum can be changed by adapting its scope to characteristics and values, even if the circumstances are initially unknown.*

With respect to the works of Günthner et al. (2002, p. 8) and Heinecker (2006, pp. 68–71), a system is changeable if the conveyed goods flexibility, layout flexibility, and throughput flexibility are 100% fulfilled.[7] However, as mentioned in section 2.3.1, having a high flexibility reserve in the system is very expensive. Therefore, both authors have demanded the addition of expandability and integrability for an economical operation of the system. Günthner et al. have extended this by further including the flexibility of the degree of automation. The authors have stated that, depending on the material flow task, an approximation to the optimum operating point should be made with regard to changeability requirements, costs, and degree of automation.

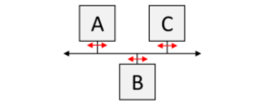
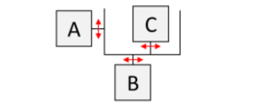
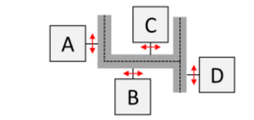
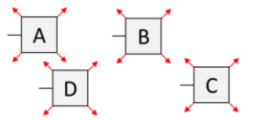
2.4 Evaluating Flexibility and Changeability

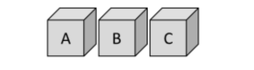
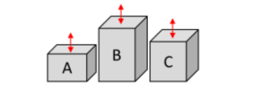
In the literature, several approaches can be found to quantify flexibility and versatility (Haller 1999; Bai and Sarkis 2013; Nopper and Ten Hompel 2010; Roscher 2008). The individual methods all refer to different areas and aspects of logistics. However, if the scope is limited to material flow systems and the respective flexibility parameters to layout, throughput, and product, only one method can be found. This approach was developed by Heinecker (2006, pp. 73–91) but only exemplarily shows the application on the material flow function conveyed. To be more precise, Heinecker has stated that a holistic description of all material flow functions is not possible. His method, which is explained in the following sections, focusses on a flexibility-oriented selection of means of transport. Furthermore, he has stated that the evaluation of versatility or changeability is not possible. Thus, he has implemented another parameter, the changeability potential. Based on this parameter, Heinecker has provided the planner with a tool which determines the potential for meeting new requirements.

2.4.1 Layout Flexibility

To determine the layout flexibility, Heinecker (2006, pp. 73–76) has placed special emphasis on the transfer points of each source-sink relationship. These represent the interface amongst manufacturing, production, workstations, and other material flow systems. The connection of the transfer point is assessed by its horizontal and vertical dimensions (see Figure 2-13). In the horizontal dimension, the relationships to each other are evaluated (in other words, if there is a fixed connection or free configuration). In the vertical dimension, only a differentiation between a fixed and variable height of the transfer point is made. Based on the selected values in both tables, Heinecker has established a matrix which defines the corresponding means of transport with regard to the respective criteria.

[7] Conveyed Goods Flexibility and Product Mix Flexibility have the same scope and definition.

Value	Description	Configuration
1	Fixed connection and spatial fixation of transfer points	
2	Transfer points are variable within a straight line	
3	Transfer points are variable within an arbitrary line: - Variable within a fixed predefined line	
4	Transfer points are variable within an arbitrary line: - Variable within variable transportation routes	
5	Transfer points are independent from the layout	

Value	Description	Configuration
1	Transfer points fixed in height	
2	Transfer points variable in height	

Vertical \ Horizontal	1	2	3	4	5
1	Suspension chain conveyor, Belt/Roller conveyor (automatic)	Traverse shuttle, Belt/Roller conveyor (manual)	AGV (without lifting platform)	Tugger, pallet truck	
2	Vertical floor conveyor, S-conveyor, Telescopic belt conveyor	Storage and retrieval machine	Electrified monorail system, AGV (with lifting platform)	Fork lift truck, Articulated robot	Bridge crane, Portal crane

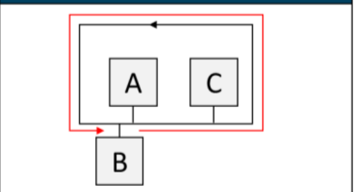
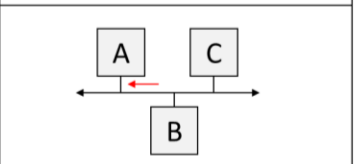
Figure 2-13: Criteria for evaluating layout flexibility according to Heinecker (2006, pp. 74–76)

2.4.2 Throughput Flexibility

With regard to throughput flexibility, Heinecker (2006, pp. 76–80) has states two methods. The first calculates the throughput flexibility based on the maximum throughput of the material flow system (see Formula 2.1). As a unit, he uses an equivalent to the utilisation level transport units (TU) per time unit. Furthermore, he has mentioned that the throughput cannot arbitrarily be increased to have a high throughput flexibility. Otherwise, an efficient and economically feasible operation would not be possible.

$$Throughput = \frac{Actual\ Throughput\ (TU/h)}{Maximum\ Throughput\ (TU/h)} \tag{2.1}$$

Figure 2-14 shows the second method for evaluating the material flow system in terms of its directions. A distinction is made between whether a TU can only be transported in one direction within the material flow system or if a direction-independent transport is possible. According to Heinecker, a direction-independent transport can be an advantage if the process steps vary greatly depending on the order. This ensures that the shortest conveying distance can always be selected.

Value	Description	Configuration
1	Material flow in one direction	
2	Material flow independent of direction	

Value	Means of Transportation
1	▪ Roller conveyor ▪ Belt Conveyor ▪ …
2	▪ Traverse shuttle ▪ Fork lift truck ▪ Bridge crane ▪ …

Figure 2-14: Criteria for evaluating throughput flexibility according to Heinecker (2006, pp. 76–77)

2.4.3 Product Flexibility

The third and last flexibility parameter is product flexibility. Heinecker (2006, pp. 80–83) has set two criteria to evaluate it: usage of standardised load carrier and the flexibility of the gripping pattern for load-handling attachments (see Figure 2-15). Due to the use of standardised loading equipment, a flexible transport of the goods within the given dimensions and weight is ensured. The flexibility refers to the goods to be transported. The material flow system is flexible within the limits of the selected load carriers. Furthermore, the standardisation of the load carriers also ensures flexibility within the goods transported. According to Heinecker, due to the different load carriers in the material flow system, an evaluation of the gripping pattern for load-handling attachments is also useful. This way, several container sizes can be handled with one load carrier.

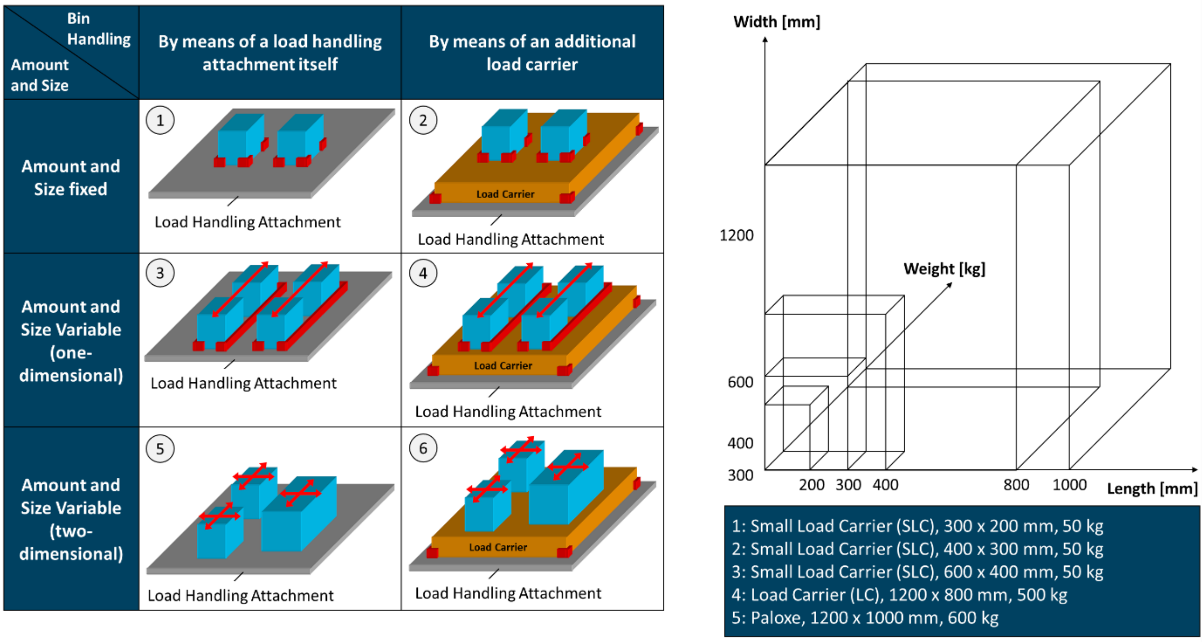


Figure 2-15: Criteria for evaluating product flexibility according to Heinecker (2006, pp. 81–82)

2.4.4 Changeability Potential

The last method which Heinecker (2006, pp. 84–91) has presented addresses the topic of changeability potential. Due to unpredictable turbulences, a quantitative evaluation—similar to flexibility—is not possible for changeability. The author has therefore chosen the path of a potential analysis to classify and evaluate material flow systems nonetheless. The result of the method represents the effort to adapt the flexibilities to new requirements and thus estimates the changeability potential of a system. The determination is done in four steps (see Figure 2-16).

At the beginning, the planner defines a catalogue of measures for changeable material flow systems with which the system can react to the new requirements. These criteria are directly related to the flexibility criteria. In a next step, these criteria are evaluated according to their influence on layout, throughput, and product flexibility. The value 0 represents no influence, 1 an indirect, and 2 a direct influence. In the third step, the assessment of the changeability potential of the material flow system is then carried out. The measures are evaluated on a scale from 0 to 5 according to their degree of fulfilment and technical feasibility. The evaluation method concludes with the calculation of the potential values for each flexibility parameter. The influencing values of the measures are multiplied by the evaluation of the degree of fulfilment/technical feasibility and summed up line by line. This results in a potential value for each flexibility parameter with which individual material flow systems can be compared.

According to Heinecker, the method for determining the changeability potential can also be used as a weak-point analysis. Thus, it is possible to check the material flow system for its reactability in relation to the three flexibility parameters to derive specific optimisation potential.

Measures 1		Flexibility / Value 3	Layout Flexibility	Throughput Flexibility	Product Flexibility
Transport Equipment	Increasing the Amount	(0...5)	0	2	1
	Increasing the Speed	(0...5)	0	2	0
Transport Process	Changes in the Transportation Routes	(0...5)	2	1	0
	Adding new Transfer Points	(0...5)	2	2	2
Transport Unit	Variants of Amount and Type of Transport Units	(0...5)	0	2	2
	Exchange of Load Handling Attachment	(0...5)	0	2	2
Changeability Potential 4			X	Y	Z

Figure 2-16: Method for evaluating the changeability potential according to Heinecker (2006, pp. 85–86)

2.5 Learning Factory Werk150 of the ESB Business School

The logistics learning factory Werk150, a realistic production and logistics environment of the ESB Business School on the Reutlingen University campus, was founded in 2014. As an authentic learning, development, and research environment with a cutting-edge infrastructure, the facility is used for developing and testing current issues of applied research. The main focus areas are, for example, new methods and tools, or control methods for logistics systems (Hummel 2020). With the available infrastructure of the learning factory, it is possible to assemble, store, and ship multivariant city scooters. The main reason for choosing the city scooter as a product is its high levels of modularity, variance, and reusability. The Werk150 is equipped with various lightweight robot systems, different autonomous guided vehicles (AGV), latest communication and information technology, and additive manufacturing technology (Hummel et al. 2019, p. 351). For this research study, Werk150 serves as a template for the simulation study on flexibility parameters.

2.5.1 Production Environment

In this section, the production environment of Werk150—to be more precise, the system, its individual workstations, their tasks, and their relationships—is described. Figure 2-17 shows the layout of the learning factory. Its main structures are a goods receipt, a supermarket, two order-picking stations, six workstations, and a goods issue.

In the goods receipt, which is marked as the green area in the layout, all A-parts required to produce a city scooter are stored. A-parts are components, which have a low-quantity but have a high value share. Next to the goods receipt is a supermarket for the collaborative tugger train, which is marked as the brown area. Within the supermarket, all C-parts required to assemble a scooter are stored. C-parts are those with a low-value share and a high-quantity share. Furthermore, every order-picking station and workstation in the production line has its own gravity flow rack. These racks, which assure the first in–first out (FIFO) principle, are marked with light grey in the layout. Once the city scooters are assembled, they are stored in the blue-marked goods issue until shipping to the final customer.

The production process for a city scooter is as follows. The incoming customer order is divided into two modules: stem and base. The reason for this is the fact that both modules are processed separately in the production process until final assembly. Whilst order-picking station 1 (OP1) picks the items for the stem, order-picking station 2 (OP2) picks the items for the base. In both cases, all required A-parts for the production are placed in a product fixture. During both order-picking processes, the worker is assisted by a robot.

After completion of the picking, the product fixtures for the base are transported to workstation WS1.1 or WS1.2, depending on their occupancy. The product fixtures for the stem are transported to either workstation WS2.1 or WS2.2, depending on their occupancy. The required C-parts for both modules are provided with the help of the collaborative tugger train, also called KollRo. Its route is fixed to one direction. The red-marked areas are the stops of the KollRo at the individual workstations. The purple-marked areas refer to the stops of the AGVs and handcart. In section 2.5.4, the considered means of transport are described in more detail.

After assembling the stem and base, both product fixtures are transported to workstation WS3.1 or WS3.2, depending on the occupancy. At this workstation, the final assembly of the city scooter takes place. Furthermore, the scooter is packed and waits for its transport to the goods issue. Both product fixtures from the stem and base are transported back to the two order-picking stations.

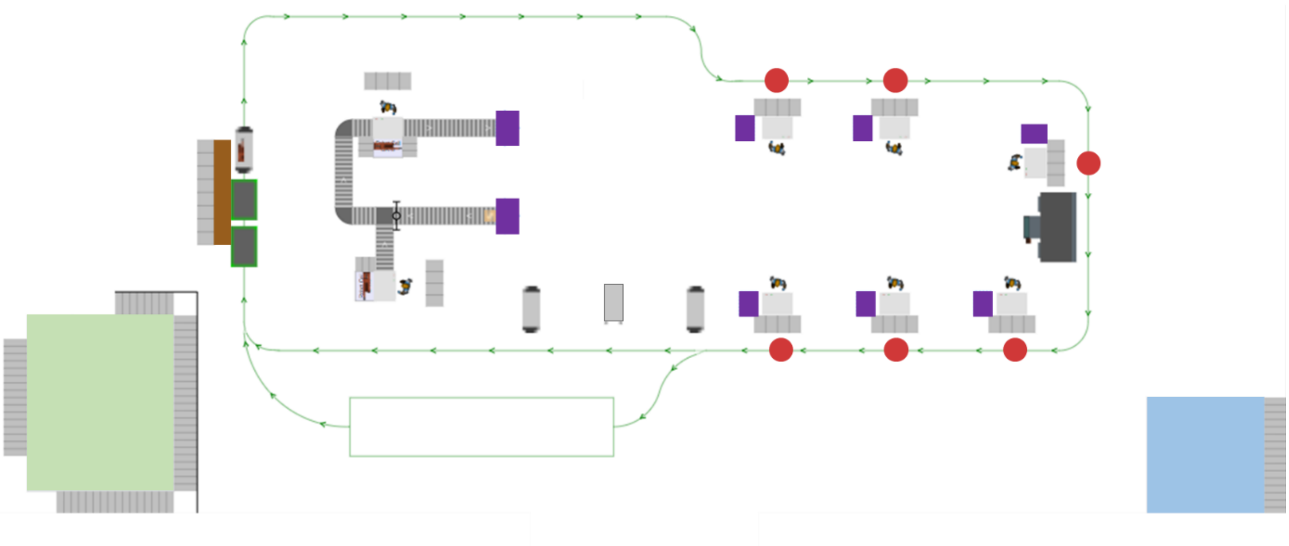


Figure 2-17: Layout of the Werk150 city scooter production

2.5.2 Products of Werk150

As stated in the description of the production environment of Werk150, the system is able to produce multivariant city scooters. However, for this thesis, only the FlexBlue and FlexAir city scooters are considered. In principle, both products are the same in terms of their production process except that the FlexBlue requires an additional splash guard. In Figure 2-18, an assembly plan shows the individual components at each station as well as their assembly time. In this research, the assembly order at the individual workstations is not considered.

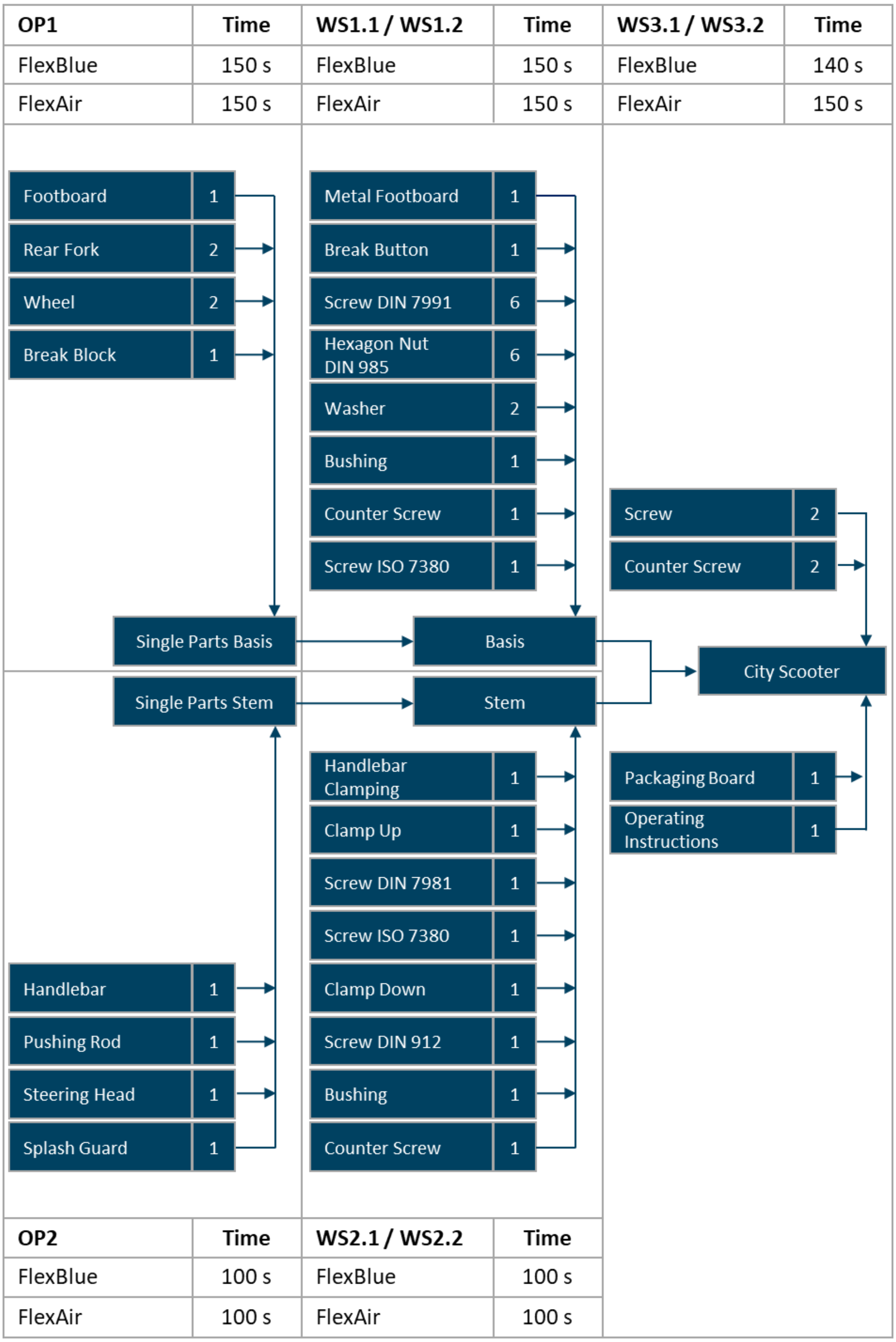


Figure 2-18: Assembly plan of the two city scooters according to Große Erdmann (2020, p. 37)

2.5.3 List of Components of a Scooter

To produce either one of the two city scooters, 23 or 24 different components are required, depending on the variant. As stated, the FlexBlue requires an additional splash guard. Whereas all C-parts are the same for both variants, the A-parts further differ in terms of their colour. Table 2-9 provides an overview of the individual components and their item type as well as their standard load carrier with which they come.

Table 2-9: Overview of the city scooter components and load carriers

Component	Type	SLC Type	Quantity	Weight [kg]	Component	Type	SLC Type	Quantity	Weight [kg]
Handlebar	A	4030	8	3.2	Clamp Down	C	3020	20	2.8
Pushing Rod	A	4030	6	3.6	Screw DIN 912	C	3020	100	1.5
Steering Head	A	4030	6	5.4	Bushing	C	3020	40	1.4
Splash Guard	A	4030	10	4.9	Counter Screw	C	3020	60	1.2
Footboard	A	4030	6	4.6	Metal Footboard	C	3020	15	3.7
Rear Fork	A	4030	4	4.4	Break Button	C	3020	10	1.8
Wheel	A	4030	6	3.2	Screw DIN 7991	C	3020	80	1.2
Break Block	A	4030	4	4.0	Hexagon Nut DIN 985	C	3020	120	0.9
Handlebar Clamping	C	3020	20	3.1	Washer	C	3020	150	0.9
Clamp Up	C	3020	20	3.0	Screw	C	3020	80	1.1
Screw DIN 7981	C	3020	100	1.2	Packaging Board	C	3020	10	6.3
Screw ISO 7380	C	3020	100	1.3	Operating Instructions	C	3020	20	1.8

2.5.4 Considered Means of Transport

In this section, the used means of transport in Werk150, and those considered in this research, are explained in more detail. In general, there are three AGVs and one handcart which are used for transporting the standard load carriers as well as the product fixtures. The AGVs are divided as follows: one is used for the collaborative tugger train KollRo, another is used in combination with a mobile robot platform, and the last AGV is just a regular one.

2.5.4.1 Collaborative Tugger Train KollRo 4.0

The KollRo is an autonomously operating towing vehicle which includes a manipulator and gripper system for handling standardised SLCs (Echelmeyer et al. 2020). Its basis consists of a Neobotix MPO-700 autonomous guided vehicle which can normally guide itself freely through the production plant. However, in the use case of the KollRo, the AGV can only drive on a predefined one-way route through the production area. In addition to the MPO-700, there is an UR10e from Universal Robots mounted. The specifications for the AGV and robot are shown in Table 2-10. Attached to the driving unit are trailers which contain all the required C-parts for the assembly of the city scooters. In total, the KollRo can carry two SLC 4030 load carriers of each C-part.

Table 2-10: Technical specifications of the KollRo (Neobotix 2020b; Universal Robots 2020)

MPO-700		UR10e	
Load capacity	400 kg	Load capacity	10 kg
Speed	< 0.9 m/s	Speed	1 m/s

In summary, the KollRo can only transport C-parts as A-parts are not assigned to it. It can only drive on a predefined route and stops at all four assembly, as well as the two final assembly, workstations. Per tour, the KollRo can carry two load carriers of each C-part in an SLC 4030.

2.5.4.2 Neobotix AGV MPO-700 NeoKu

The second AGV is used in combination with a mobile robot platform. This vehicle is also called NeoKu. It consists of a Neobotix MPO-700 used as a mobile platform and a human-robot-collaboration capable lightweight KUKA LBR iiwa robot. Due to the MPO-700, the NeoKu can guide itself freely through the production plant. The main task of the NeoKu is to support the other AGV and handcart in supplying the production with A-parts. However, it can only transport a single A-part load carrier (SLC 4030) at a time. Its technical properties are shown in Table 2-11.

Table 2-11: Technical specifications of the NeoKu (Neobotix 2020b; KUKA 2020)

KUKA LBR iiwa	
Load capacity	14 kg
Speed	< 0.9 m/s

The NeoKu can only transport a single A-part load carrier of type SLC4030 but not the product fixture or complete city scooter. Moreover, the NeoKu is not rail bound and can move freely through the production plant.

2.5.4.3 Neobotix AGV MP-400

The last AGV in Werk150 is also from Neobotix. Unlike the other two AGVs, this one is an MP-400. Similar to the MPO-700, this model can guide itself freely through the production plant. The technical properties of the Neobotix MP-400 are described in Table 2-12. The MP-400 is used for supplying the two order-picking stations with A-parts, transporting the product fixtures, and transporting the complete city scooter from the two final assembly stations to the goods issue. In addition to the product fixtures and city scooter, it can carry either one SLC 6040, two SLC 4030s, or four SLC 3020s.

Table 2-12: Technical specifications of the MP-400 (Neobotix 2020a)

MP-400	
Load capacity	100 kg
Speed	< 1.5 m/s

To conclude, the MP-400 handles all A-part transports to the order-picking stations, the transportation of the product fixtures, and the transportation of the complete city scooter to the goods issue. It is not rail bound and can move freely through the production. The capacity of the MP-400 is either one product fixture, one complete city scooter, one SLC 6040, two SLC 4030s, or four SLC 3020s.

2.5.4.4 Handcart

The fourth and last means of transport is a standard handcart, which is operated by a human. Just like the MP-400, the worker can navigate the handcart freely through the production hall. The main task of the handcart is to support the MP-400 in supplying the order-picking stations with A-parts and to transport the product fixtures as well as the complete city scooter. Due to its dimensions, the handcart can only carry one product fixture, one complete city scooter, one SLC 640, two SLC 4030s, or four SLC 3020s. The technical specifications of the handcart as well as the properties of the worker (derived from literature) are described in Table 2-13. Hettinger (1982, p. 96) has developed the so-called Hettinger table, which is used to determine the suggested load handling of a worker. For this research, a maximum of 10 kg is assumed. In terms of speed, the handcart is bound to the worker's pace. According to the standard DIN EN ISO 13855, humans can reach a speed of 1.6 to 2 meters per second (DIN EN ISO 13855, p. 15). For the sake of simplicity, an average of 1.8 meters per second is considered.

Table 2-13: Technical specifications of the handcart and worker

Handcart		Worker	
Load capacity	200 kg	Load capacity	10 kg
Speed	-	Speed	< 1.8 m/s

The human with a handcart can transport all A-parts to their respective order-picking stations, the product fixture to the workstations, and the completely assembled city scooter to the goods issue. In terms of capacity, the handcart can transport one product fixture, one complete city scooter, one SLC 640, two SLC 4030s, or four SLC 3020s. It is not rail bound, thus allowing it to move freely through the production hall.

After this system analysis of the Werk150 and the broad theoretical basis, a uniform definition for the three flexibility parameters can be developed. This in turn allows hypotheses to be formulated which will be investigated subsequently.

Chapter 3
Definition of Flexibility Parameters for Material Flow Systems

This chapter provides an analysis of the presented flexibility taxonomies to develop a new generic definition for flexibility parameters of material flow systems. In addition, the influencing factors of each parameter are examined. Based on these results, hypotheses regarding the behaviour of the flexibility parameter in intralogistics systems are then established. In the previous chapter, section 2.3.1 presents different flexibility taxonomies. In this context, a study by Heinecker on flexibility parameters for material flow systems found that there are three parameters in total: layout flexibility, throughput flexibility, and product flexibility. All other parameters are either used synonymously or can be formed by combining these three parameters. This result can be shown exemplarily by the throughput flexibility and by the product quantity flexibility, according to Tempelmeier and Kuhn. The same example also applies to the expandability or adaptability of the system to new requirements. Manufacturing process flexibility, on the other hand, can be represented by a combination of layout flexibility and product mix flexibility. For the material flow system, only the transport route (source-sink relationship) and, if relevant, the product dimension change. However, as can be seen from the respective definitions of Handrich, Günthner et al., Heinecker, or Wilke, for these three parameters, no generic definition exists. This is developed in the context of this chapter and supplemented by factors which influence the respective parameter. In addition, these factors represent the aspects to be simulated on a logistics system. Furthermore, possible assumed effects are first theoretically discussed. Aspects like expandability and integrability are not considered in this research. They are seen, analogous to the definition by Günthner et al., as a prerequisite for the changeability of a system. The same applies to the flexibility of the degree of automation by Handrich.

3.1 Layout Flexibility

Based on the different definitions in section 2.3.1 regarding layout flexibility—also referred to as routing flexibility or material flow flexibility—its main aspects are listed below. In a second step, these characteristics are used to develop a new generic definition. In detail, these aspects are:

- Using different material routes through the system in case of breakdowns.
- Using alternative routes to optimise the degree of utilisation.
- Taking any route in the system.
- Transporting goods from different sources to different sinks within the working area.
- Enabling every location in the factory to be operated.
- Considering only pre-planned changes of the sources and sinks locations.
- Adapting changed material flow paths quickly.

One crucial aspect of layout flexibility is its scope. Most of the abovementioned authors have stated that this parameter affects the whole system. Handrich, however, has argued that the scope of layout flexibility is only within a defined working area. In the definition developed herein, the scope is set to the corresponding material flow system; thus, the term ‘system’ is used. Furthermore, all authors have mentioned that layout-flexible material flow systems can transport goods from any source to any sink within the defined system. The condition of Heinecker that only pre-planned changes of the sources and sinks locations are considered refers to the dimensioning or planning aspect of the flexibility parameter. The new definition, on the other hand, defines a fully layout-flexible system.

Therefore, the aspect of pre-planned location changes is not mentioned. In addition to the characteristics already elaborated, Browne et al. have supplemented the system's ability to select different transport routes either due to machine breakdowns or to optimise the degree of utilisation. Lastly, Wilke has specified that material flow paths can be quickly changed; this aspect is also considered. In conclusion, the following generic definition for layout flexibility is derived:

> *A layout-flexible material flow system can use any route in the system to transport goods from different sources to different sinks to keep the corresponding machines operating as required.*

To design a material flow system which is 100% layout-flexible, a wide range of influencing factors and requirements must be considered. Decisive factors in this study are the respective transport system and the material flow route. According to Gleißner and Femerling (2008, p. 40), a transport system consists of three components: transport object, means of transport, and transport process. The transport object is subject to product flexibility and is therefore not elaborated further in this section. Similarly, the means of transport and their respective parameters such as velocity or capacity are subject to throughput flexibility. The means of transport's specific reachability of certain sinks and sources is an aspect of the transport process as it describes the control and sequence of operations which are responsible for dynamically guiding the respective means of transport, with the associated transport object, through the system. Thus, the transport process and particularly the reachability of sources and sinks are especially important for determining layout flexibility. As an example, Handrich (2001, pp. 29–32) has stated that a continuous conveyor has considerably less layout flexibility compared to an AGV as the ability of reaching new sources and sinks is coupled with an immense reconstruction process. Along with the transport process, layout flexibility is also limited by the loaded means of transport and the material flow route. To ensure that any route can be used in a system, it is necessary that restrictions such as width or height of the transport route, the load-bearing capacity of the floor or ceiling, and the like are considered.

In the context of this work, two factors are analysed using the simulation model. The first is the effect of the means of transport-specific reachability on the logistics system. In this case, the presented means of transport in section 2.5.4 are compared to each other with different degrees of reaching all sources and sinks in the system. The second factor analysed is the effect of the length of a material flow route network on a logistics system. The means of transport can dynamically select any route depending on their network and technical conditions such as free navigation. All other factors—for example, the load-bearing capacity of the floor or ceiling or the width and height of the individual material flow routes—can be calculated statically and are therefore not part of the simulation.

3.2 Throughput Flexibility

Similar to layout flexibility, the main aspects of throughput flexibility are determined and listed below. These aspects are then used to develop a generic definition of throughput flexibility.

- Having additional operating resources available within economical limits.
- Enabling economical production with different throughputs.
- Coping with fluctuations in the production output.
- Adapting to changes in production output by taking appropriate measures.
- Adjusting the throughput to the required, predefined production output.

Compared to layout flexibility, throughput flexibility is more straightforward as the term itself provides clearer understanding of the object of investigation. The main aspect of throughput-flexible material flow systems is the handling of fluctuations in throughput. Throughput in this case does not refer to the production system but to the material flow system and its output. This is also referred to as logistical throughput. According to the abovementioned aspects, a throughput-flexible system must be able to cope with these fluctuations by taking appropriate measures. According to REFA and Tempelmeier and Kuhn, all measures taken should be economical. Wilke and REFA have mentioned as examples of such measures the expansion of operational resources or increasing the capacity of means of transport. Summarising the aforementioned aspects, throughput-flexible material flow systems are defined as follows:

> *A throughput-flexible material flow system can cope with fluctuations in throughput by means of appropriate and economic measures (e.g. additional operational resources and increased transporter speed or capacities).*

According to Arnold and Furmans (2005, p. 11), it is irrelevant how the transport is conducted when considering the throughput of material flow routes. Only the speed-time behaviour is relevant. However, two modes of transportation can be identified: continuous and discontinuous conveyors. In principle, the throughput λ can be calculated by dividing the conveying speed v in meters per second with the distance s in meters between the transport objects (see Formula 3.1). Its unit is items per time unit (TU). The calculation of the throughput for discontinuous conveyors differs insofar as a constant speed cannot be assumed due to starting, braking, taking curves, and so forth. However, for a first throughput calculation and estimation, the abovementioned calculation method is sufficient (Arnold and Furmans 2005, p. 12). An exact calculation method is presented by Günthner and Severin (2005, U72).

$$\lambda = \frac{v}{s} \qquad \left[\frac{1}{TU}\right] \tag{3.1}$$

With respect to the formula, the following parameters for coping with fluctuations in throughput can be derived: the conveying speed, distance between the objects to be transported, and, in the case of discontinuous conveyors, number of vehicles or capacity of the means of transport. According to Decker and Grösel (2008, pp. 2–3), increasing the overall availability through redundancy or creating buffers can also have a positive effect on fluctuations.

In the context of this study, the flexibility of throughput is analysed by investigating how changes in speed and in capacity of the means of transport effect a logistics system. The relationship of throughput and distance between conveyed objects has already been described with fictive numbers by Arnold and Furmans (2005, p. 12) (see Figure 3-1). When considering the starting, braking, and taking curves of discontinuous conveyors, a lower average speed $\bar{v}$ in meters per second applies, as, for example, curves can't be taken at full speed.

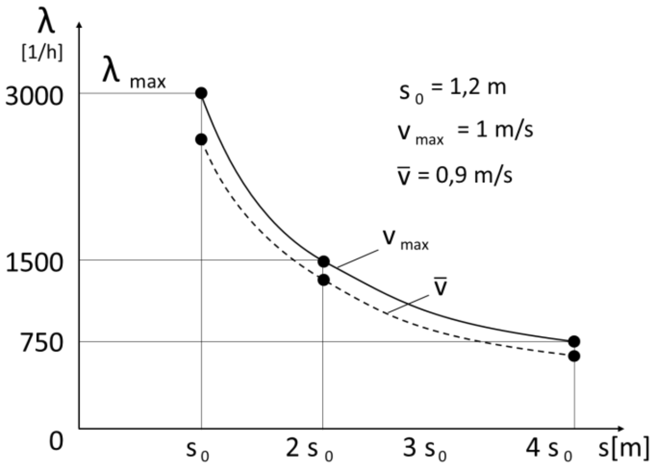


Figure 3-1: Correlation of throughput and distance on a material flow route according to Arnold and Furmans (2005, p. 12)

3.3 Product Flexibility

The last flexibility parameter to be defined is product mix flexibility, also referred to as conveyed goods flexibility or product flexibility. In the following, all characteristics associated with these parameters are referred to as product flexibility. According to the flexibility taxonomies in section 2.3.1, the main aspects of this parameter are:

- Referring generally to a number of different products in a system.
- Handling of different products without setup processes.
- Having the ability to convey different products.
- Having a predefined product spectrums and variations of it, which must be able to be transported.
- Transporting different products, regardless of their dimensions and weight.

In accordance with all the individual definitions of product flexibility, the main characteristic of a product-flexible system is handling a number of different products. In the context of material flow systems, handling refers to the transport of the products. According to Günthner et al., Heinecker, and Wilke, an important characteristic is that the products and variants can vary in their dimensions and weight. Moreover, according to Tempelmeier and Kuhn, the transport of different products must happen without setup times. Combined, this results in the following definition of product-flexible material flow systems:

> *A product-flexible material flow system can transport a range of products and variants without setup processes; the products can, furthermore, differ in terms of their dimensions and weight.*

To analyse the behaviour of logistic systems in terms of product flexibility, the impact of the dimensions and weight of load carriers is therefore examined. The simulation of different products or variants thereof is considered to be too system-specific as these can vary greatly in terms of their components, production processes, and so on.

3.4 Hypothesis on the Behaviour of Flexibility Parameters

In this section, the expected behaviour of the individual factors of layout, throughput, and product flexibility in logistics systems is described, and hypotheses are made. In total, there are six factors which influence flexibility: reachability of sources and sinks, length of the material flow routes, speed and capacity of the means of transport, dimensions of the load carrier, and the weight of the load carriers. The respective influence of these factors is described by means of throughput, production output, and degree of utilisation of the means of transport.

3.4.1 Reachability of Sources and Sinks

Within the scope of layout flexibility, the first factor to be examined is how the means of transport-specific reachability of sources and sinks affects the means of transport itself and also the logistics system. In this thesis, the reachability R of a means of transport is defined as the sum of the actual number of accessible sources and sinks divided by the total number of all sources and sinks. The reachability of the system is correspondingly determined by the overall mean of all means of transport-specific degrees of reachability. An important aspect of the hypothesis and the following analysis is the comparability of the different degrees of reachability. A decisive factor for the comparison is the logic for generating a transport order. Means of transport which were originally unable to reach certain stations were inevitably not considered for a transport order. Therefore, in this thesis, the reachability of the system is only examined in two steps. The first stage represents the initial situation, whilst the second stage considers the reachability of all vehicles and thus of the system as 100%. The generation of a transport order for the second stage is carried out based on means of transport-specific capacity. A more detailed explanation is given in section 4.4.1.3. With the two simulation results, the theoretical existing potential in the system can be calculated with regards to throughput, output and degree of utilization. Based on the existing potential, a subsequent decision-making-progress can take place, whether it is technical and economical feasible to upgrade the existing means of transport. In the scope of this thesis, only the generation of the simulation results is covered.

When observing the effects of reachability on the actual throughput of a logistics system, it is generally assumed that there will only be marginal increases. The system cannot necessarily transport more load carriers as defined by the maximum material retrieval, despite the fact that the means of transport have a larger reachability. The slight increase in throughput is the result of an optimisation of the means of transport-specific degree of utilisation. However, if one considers the theoretical throughput, it increases to a certain extent. Limiting factors can be of different natures; besides the degree of utilisation of the means of transport, the speed, material flow route length, product dimensions, loading capacity, and others play a decisive role. For a system and means of transport-specific, quantified determination of the theoretical throughput, an individual calculation must therefore be made.

Moreover, with regard to the production output, reachability only has a marginal effect. By optimising the degree of utilisation of a means of transport, as described above, several transport orders can be carried out simultaneously, which ultimately increases the total throughput time of a city roller and thus the output of the system. The limiting factor is therefore the shortest possible throughput time of a city scooter, which is the sum of all process times of the workstations.

Lastly, when considering the degree of utilisation of the system in relation to the reachability, it is assumed that with an increasing reachability, the degree of utilisation also rises to a certain extent. This slight increase reflects the higher throughput and production output.

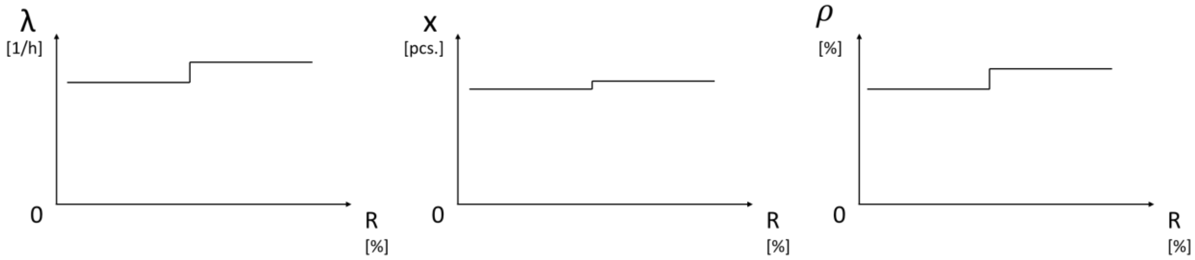


Figure 3-2: Expected behaviour of reachability

3.4.2 Material Flow Route Length

The influence of the length of a material flow route on the logistics system is examined within the scope of layout flexibility. Different lengths represent alternative routes of an available means of transport. The effects of route changes due to machine failures or optimisation measures are not part of the investigation.

With regard to the throughput of a logistics system, it is expected, similar to Figure 3-1, that it decreases with an increase in the length of the material flow routes. By observing the limits of the throughput function $\lambda\ (v, s)$, and assuming a constant average speed v with distance s not being the distance between transport objects (e.g. on a conveyer belt) but the average distances between the sources and sinks, this assumption is proven. Furthermore, by calculating the slope of the throughput function, a regressive function results. The graph, however, is assumed to limited for short material flow routes as the production system can only order material according to its maximum output. To be more precise, even though the material flow route is as short as possible, the limiting factor for a higher throughput or output is the production system itself with its process times.

$$\lim_{s \to 0^+} \lambda(s) = \infty \tag{3.2}$$

$$\lim_{s \to \infty} \lambda(s) = 0 \tag{3.3}$$

$$\frac{d}{ds}[\lambda(s)] = -\frac{v}{s^2} \tag{3.3}$$

Similar behaviour to throughput is also expected for production output x in pieces. If the system has a high throughput (i.e. the transport routes are as short as possible), it is assumed that the production output converges to its maximum output. In doing so, it is limited by the weakest element in the system, which is also called a bottleneck.[8] These elements could be, for example, storage capacities, buffers, or workstations. On the other hand, if the system has a low throughput, the production output converges to zero. It is furthermore assumed that there is no proportional relationship between the length of a material flow route and the production output.

[8] Further readings regarding bottleneck and the analysis are provided in Roser et al. 2014 or Wiendahl et al. 2003.

$$\rho = \frac{t_{operating}}{t_{total}} * 100\% \qquad [\%] \tag{3.4}$$

$$v = \frac{s}{t} \qquad \left[\frac{m}{s}\right] \tag{3.5}$$

The last factor to be analysed for changes in the length of the material flow routes is the degree of utilisation ρ of the means of transport. This percentage is determined according to Formula 3.4 by dividing the vehicle operating time $t_{operating}$ by the total time of the period under review t_{total} (e.g. a shift). Resulting from the physical relationship amongst velocity v, distance s, and time t (see Formula 3.5), and the assumption that the average vehicle speed is a constant, time must therefore change with increasing or decreasing transport route lengths. This time, on the other hand, refers to the vehicle operating times and thus increases or decreases the degree of utilisation of the means of transports accordingly. Figure 3-3 provides an overview of all expected influences on the throughput, production output, and degree of utilisation.

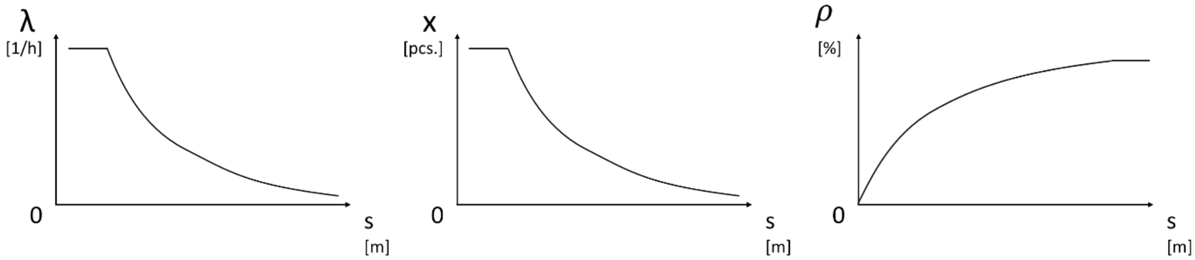


Figure 3-3: Expected behaviour of the material flow route length

3.4.3 Means of Transport Speed

The speed of the means of transport is part of the throughput flexibility. This section examines the expected influences of the speed of the means of transport on the throughput, production output, and degree of utilisation.

$$\lim_{v \to 0^+} \lambda(v) = 0 \tag{3.6}$$

$$\lim_{v \to \infty} \lambda(v) = \infty \tag{3.7}$$

$$\frac{d}{dv}[\lambda(v)] = \frac{1}{s} \tag{3.8}$$

In terms of throughput, the speed of the means of transport behaves at its limits directly opposite as the changes in the transport routes length. With the distance s being constant, the function $\lambda\,(v, s)$ behaves as follows (in Formulas 3.6 and 3.7). An increase in speed results in a higher throughput and vice versa. The calculation of the slope results in a proportional relationship between throughput and means of transport speed. However, the throughput is again limited by the maximum possible material consumption of the production system.

For the production output, again a non-proportional behaviour is assumed due to a wide variety of influences on production. However, a general relationship between a higher velocity of the means of transport and a higher production output is assumed. This increase, especially towards higher velocity, is limited by the same constraints described for the length of the material flow route.

$$\rho(v) = \frac{s}{v * t_{total}} * 100\% \tag{3.9}$$

$$\lim_{v \to 0^+} \rho(v) = \infty \tag{3.10}$$

$$\lim_{v \to \infty} \rho(v) = 0 \tag{3.11}$$

$$\frac{d}{dv}[\rho(v)] = -\frac{s}{v^2 * t_{total}} * 100\% \tag{3.12}$$

The equation for the degree of utilisation as a function of speed of the means of transport under the assumption of a constant distance s and a constant observation period t_{total} is obtained from Formulas 3.4 and 3.5 (see Formula 3.9). By observing the limits, it can be seen that the degree of utilisation declines with rising velocity. By means of the first derivative of Formula 3.9, a regressive curve of the function can be shown (see Formula 3.12). In conclusion, Figure 3-4 shows all expected effects of the speed of means of transport on throughput, production output, and degree of utilisation.

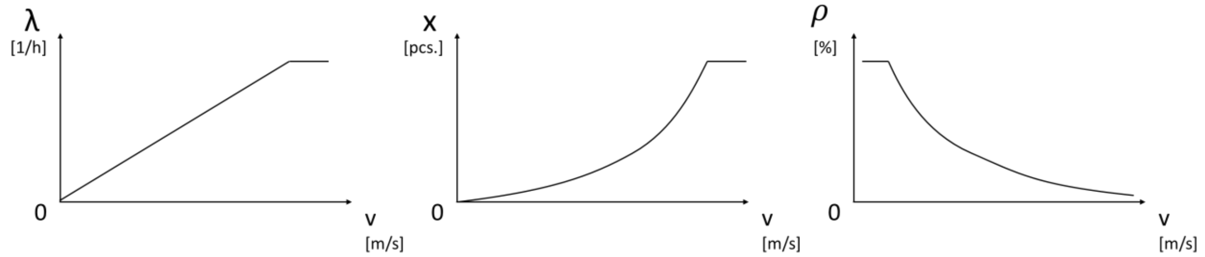


Figure 3-4: Expected behaviour of the means of transport speed

3.4.4 Means of Transport Capacity

The second effect of the throughput flexibility to be analysed is the capacity of the means of transport. In contrast to sections 3.4.2 and 3.4.3, where the length and speed of the throughput function $\lambda\ (v, s)$ are affected, the transporter capacity directly influences the throughput. In principle, the throughput has the unit 1/TU. In practical terms, this means, for example, one load carrier per second. If the capacity of the means of transport increases so that two load carriers can be transported at the same time, the throughput increases by a factor of two. Depending on the unit of the transporter capacity (e.g. volume or slots), either a proportional relationship or a step function is assumed. In the context of this research, the transporter capacity c is described by the number of SLC slots. Therefore, a step function is assumed.

When observing the limits, a differentiation between the actual and theoretical maximum throughput must be made. Whereas both throughputs have a lower limit of at least one slot, the upper limit differs. In the case of the theoretical maximum throughput, an infinite increase in theoretical throughput can be observed. However, the actual throughput is constrained by, for example, the material call-off from production. At a certain point, the transporter capacity exceeds the quantity to be transported, which is why a change in the actual throughput is no longer noticeable.

With regard to production output, it is assumed that a stepwise increase in the transporter capacity also leads to a stepwise increase in production output. Each additional slot will, however, reduce the number of additional products produced until the possible maximum production output level is reached. At this point, any extra slot no longer has an effect on the output as it is constrained by other parameters (e.g. the process time at the workstation).

In terms of the degree of utilisation, it is expected that the means of transport will operate at the highest degree of utilisation if the transporter capacity is low. This is due to the low throughput, which requires more transport runs and thus increases the operating time. A stepwise increase in transporter capacity will reduce the degree of utilisation until it converges towards the lowest possible level.

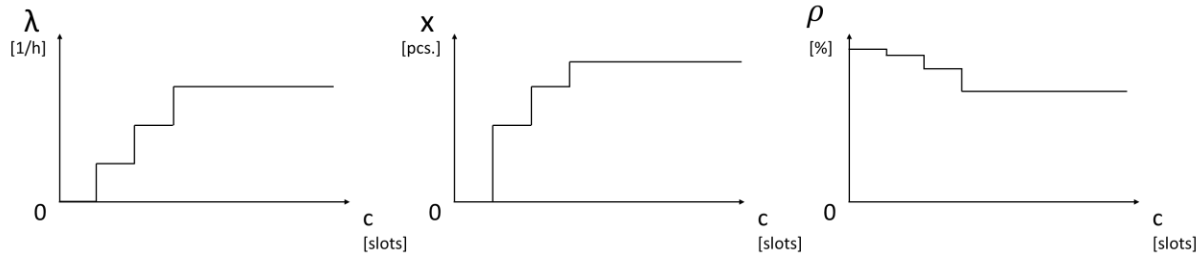


Figure 3-5: Expected behaviour of the means of transport capacity

3.4.5 Load Carrier Dimension

This section examines the expected effects of load carrier dimensions, as part of product flexibility, on throughput, production output, and degree of utilisation of the means of transport. The limits of the load carrier dimensions are defined by the standard load carriers introduced in section 2.2.3; otherwise, the means of transport are not able to transport the load carriers anymore. Thus, the unit of the load carrier dimension considered in this research is the type δ. Along with the changes of the SLC dimensions, the number of components per SLC is adjusted proportionally. This means if a load carrier is simulated twice its original size, it is also capable of transporting twice as many components.

It is expected that SLCs increase the throughput as multiple material orders can be assigned to a single means of transport. With increasing dimensions, the throughput flattens until the limits of the means of transport are reached. Beyond these limits, the throughput plunges to zero, and the production stops. However, it is not expected that changes in the dimensions of the SLCs will have a strong influence on the production output as the number of components remains constant. Similar to throughput, though, the production stops when the limits of the means of transport are exceeded. Referring to the abovementioned effect of assigning multiple material orders to a single means of transport, it is expected that the degree of utilisation is lower with bigger SLCs. A summary of the expected effects of the load carrier dimensions is displayed in Figure 3-6.

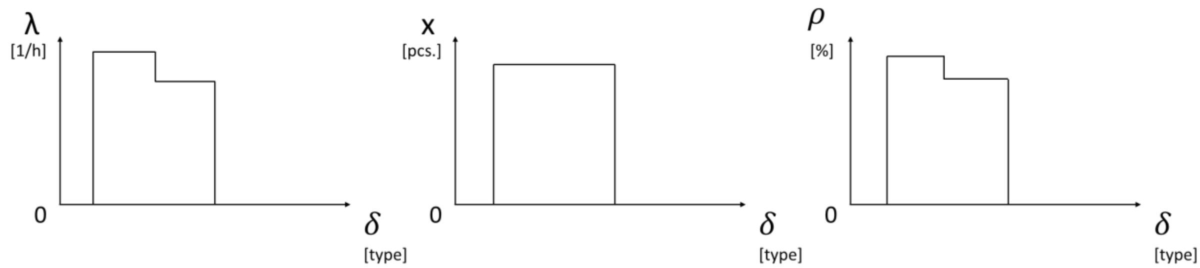


Figure 3-6: Expected behaviour of the load carrier dimensions

3.4.6 Load Carrier Weight

The fifth and last factor to be analysed is the effect of changes in the load carrier weight. In general, fluctuating weight of the load carriers within the system boundaries does not influence the throughput, production output, and degree of utilisation. When examining the load-handling capacities of the considered means of transport in section 2.5.4, it can be seen that all, except for the NeoKu, can only handle up to 10 kilograms. Thus, the system boundary for the maximum weight is 10 kilograms. The NeoKu, with its 14-kg load-handling capability, is not able to supply the production solely as it cannot transport the product fixtures nor the C-part load carriers.

In the considered logistics system of Werk150, the system boundary can be determined statically and without simulation due to its structure. For this reason, a simulation of this factor is not performed; only the procedure for implementing this factor in the simulation model is described. At this point, however, it is important to mention that the product weight can have a significant influence on a logistics system. In systems with differently dimensioned means of transport, an increased product weight could lead to failure of a means of transport. This, in turn, would have a negative effect on the system's degree of utilisation as well as on the throughput and possibly the production output.

Based on the new, generic definition of the three flexibility parameters for layout, throughput, and product, a total of six hypotheses stating the expected behaviour in intralogistics systems were derived. In order to examine the behaviour of the flexibility parameters and thus confirm or reject the developed hypotheses, the simulation model needs to formalised and implemented in a subsequent step.

Chapter 4 Simulation Model Formalisation and Implementation

This chapter addresses the formalisation of the model and the implementation of the real-world intralogistics system in the selected multimethod simulation software, AnyLogic. It describes in detail how the model is structured and how the different control mechanisms work. Furthermore, it discusses how the individual agents are structured and how they interact with each other.

4.1 Fundamentals of Simulation

Models and simulations of all kinds are as old as humans themselves. Plans were 'simulated' in thoughts in order to discuss, change, or implement them in reality. With the emergence of computer models, however, a multitude of interrelationships and the consequences of complex systems could be investigated (Bossel 2004, p. 13). Today, such complex systems are, for example, logistics systems, material flow systems, and production systems. According to the standard VDI 3633, a simulation is defined as a 'representation of a system with its dynamic processes in an experimentable model with the aim of reaching findings which are transferable to reality' (VDI 3633:2018-05, p. 28). In general, a simulation can be methodically classified into a continuous or a discrete simulation. Whilst in continuous simulations, the model state is represented over a continuous course of time, in discrete simulations, the model state changes at discrete points in time. Thereby, the progression of time can again occur according to two methods: event-driven or time-controlled. With a discrete time-controlled approach, the simulation time is increased by a constant time increment. In comparison, the progress of the model in an event-driven approach is controlled by events (Wenzel 2018, p. 10). For logistics systems, a discrete event-oriented simulation is predominantly used (Wenzel 2018, p. 11).

This approach can further be categorised into event-oriented, activity-oriented, process-oriented, or transaction-oriented. In an event-oriented simulation, changes are caused by an event. In an activity-oriented simulation, changes are caused by certain activities in a period, and in a process-oriented simulation, state changes are caused by a modelled process representing a sequence of events. A special case of process-oriented simulation represents the transaction-oriented simulation, however it is not further elaborated.

With regard to the simulation study, the simulation model of Werk150 can be classified as a discrete event-oriented simulation, the processes of which are represented in a process-oriented way.

4.2 Model Formalisation

The central concept of formalising the model is an explicit description of the system which allows an implementation in a simulation software without further explanation. Thus, the formalisation phase corresponds to the specification in the software development process (Gutenschwager et al. 2017, p. 155). In this thesis, elements of the Unified Modelling Language (UML) are used to formalise the simulation model. By means of this formal and standardised modelling language, object-oriented systems can be constructed, specified, documented, and visualised. For this purpose, the user is provided with different types of diagrams, which can illustrate static and dynamic structures. The class diagram is most frequently used for static structures whilst the activity diagram is for dynamic ones (Bobrik and Trier 2013, p. 87).

The main element of an object-oriented model using a class diagram is the class itself. Within a class, the properties (attributes) and behaviour (operations/methods) of the respective object are stored (Rau 2007). Thereby, the simplest form of an object is its mere representation by name. Through associations, the relationships with other objects can be illustrated. In total, there are three types of association: a simple connection, an aggregation, and a composition. A simple connection is displayed by a continuous line between the objects and a description. An aggregation refers to a contextually stronger linkage and is characterised by an unfilled diamond at the end of the line. It can be interpreted as ‘part of’ (e.g. an employee is part of a company). In a composition, the diamond at the end of the line is filled in. It represents the strongest connection and marks classes which cannot exist without each other. For all associations, so-called multiplicities are defined, which indicate how many objects of one class can be in relation to objects in another class. Furthermore, there can also be inheritances over classes. These are indicated by an unfilled arrow. The attributes and methods of the main class are passed on to the subclasses and can be specified individually (Bobrik and Trier 2013, p. 87).

To illustrate dynamic structures, the UML provides the user with activity diagrams. Thereby, actions in the form of rounded rectangles are linked between a start and end node using connecting arrows. Alternative paths can be visualised by conditional branching in the form of diamonds (Bobrik and Trier 2013, pp. 89–90). This enables the user to visualise complex business processes in the form of a flow logic chart (Rau 2007, p. 329).

The intralogistics system of Werk150 considered in this thesis is described as follows using a class diagram containing attributes, methods, and relationships (see Figure 4-1). In total, there are 10 different classes in the simulation model: workstation, transport order, SLC, fixture, location, means of transport, KollRo, MP400, handcart, and NeoKu.

The first class, workstation, represents the individual workstations in the production system and is defined by the attributes process time, availability, and location. Each station also has a unique identifier, which is used to ensure that the technical assembly sequence is maintained. Using the methods +setProcessTime() and +pickItem(), the object can modify its process time according to the city scooter variant to be assembled and remove the required components from their respective SLCs. If the last component is removed from a load carrier, a material request is triggered, which leads to a new transport order.

In the ‘TransportOrder’ class, the existing material orders are aggregated (+generatedTransportRoute()) and assigned to an available as well as suitable means of transport (+selectVehicle()). A transport order consists of three arrays: one for the materials in the order, one for their current locations (sources), and one for their destinations (sinks). As data type for the location, the class ‘Location’ is used, which contains the actual x- and y-position of the objects. The two classes are connected by an aggregation as the location is always part of a transport order. The same applies to the individual attributes of the classes ‘MeansOfTransport’ and ‘Workstation’.

The class ‘SLC’ represents all load carriers in the intralogistics system and consists of a unique identifier, a material name, the number of components inside an SLC, and the dimensions of the load carrier.

The ‘Fixture’ class for workpiece carriers is similarly structured. In addition to a unique identifier, the object has the information about the variant to be built (FlexBlue or FlexAir), the type (base or stem), and the dimensions.

In the end, the class ‘MeansOfTransport’ is used to carry out the process. It defines all attributes and methods relevant to the means of transport such as speed, acceleration, load capacity, and the determination of the next destination. The class passes all attributes and methods on to the respective simulated means of transport: KollRo, MP400, handcart, and NeoKu. By creating this generic class, the attributes do not have to be redefined for each created means of transport but can be instantiated and parameterised individually. With the method +getNextLocation(), the means of transport can determine its next destination in the respective transport order. Thereby, the sources and sinks defined in the TransportOrder class are iterated. The method +calcUtilisation() can be used to calculate the degree of utilisation over the simulation time by using the start and end time attribute of the transporter.

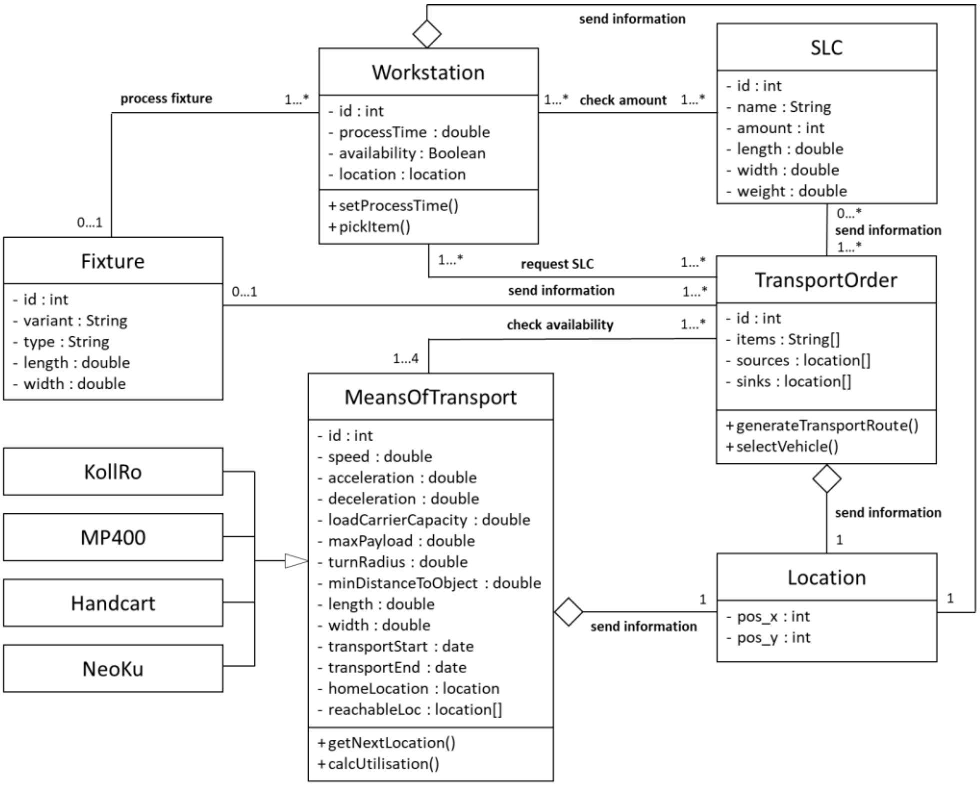


Figure 4-1: Class diagram of Werk150

4.3 Modelling Software AnyLogic

For the simulation of Werk150 with all its processes, the simulation software AnyLogic 8.6.0 Personal Licence Edition was chosen. The major advantage of this simulation software is that it offers a single platform for dynamic simulation modelling, which supports the simultaneous application of discrete event modelling, agent-based modelling, and system dynamics. Therefore, a simulation of different systems of any complexity is possible.

Another advantage of this simulation software is its simple structure. By simply dragging and dropping blocks from different libraries, such as the material handling library or the process modelling library, a functional and three-dimensional system can be built (AnyLogic 2020). Furthermore, as the software is based on the Java environment, it is not only platform independent but also allows the user to program extremely complex and specific processes, which cannot be achieved with the already predefined blocks of the libraries.

4.3.1 Description of the Used Simulation Methods

The fields of application for the three simulation methods of which AnyLogic is vary in terms of their levels of abstraction. Choosing the right level of abstraction is critical for the success of the simulation study. Whereas system dynamics is mainly used for a high level of abstraction (e.g. to simulate social systems or economics), discrete event modelling is used for a medium to low level of abstraction. The third simulation method, agent-based modelling, is capable of handling all levels of abstraction between both extremes. Thus, the modelling can be at a high level of abstraction but also at a very detailed level. Figure 4-2 shows the categorisation of all the methods according to Borshchev (2013, p. 12).

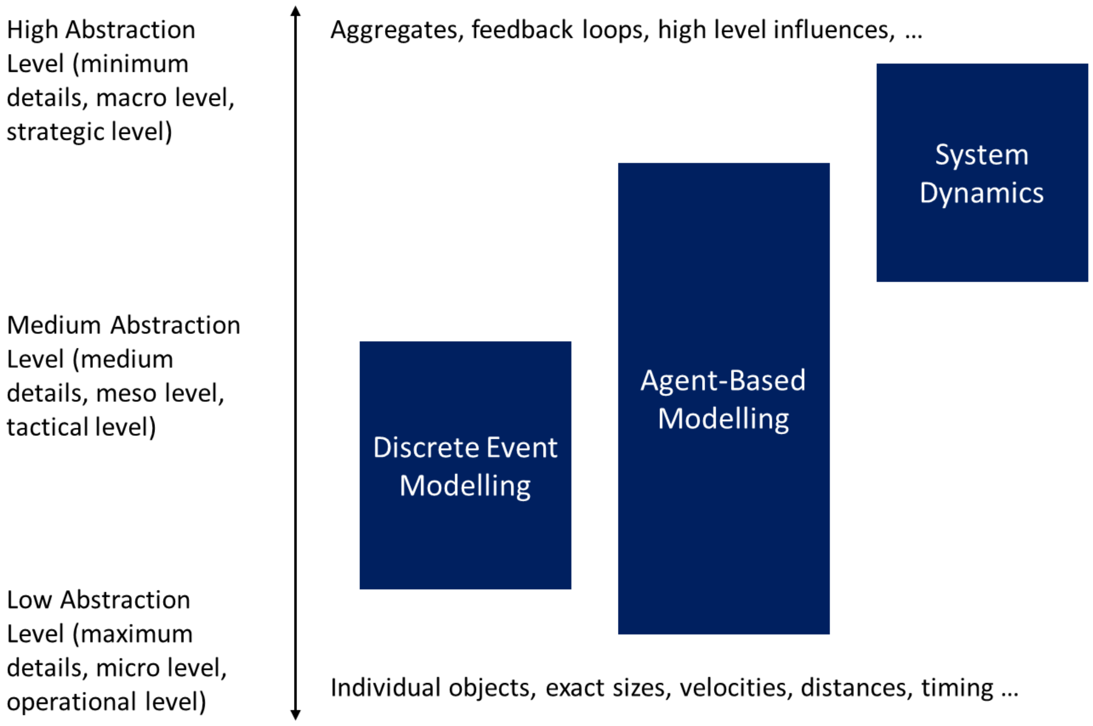


Figure 4-2: Methods in simulation modelling and their levels of abstraction

For the simulation of Werk150, a multimethod approach was chosen to cope with different levels of abstraction. To simulate the production process as well as the transporter and SLC handling, a discrete event modelling approach is applied as it responds to discrete events. For the transport order generation, SLCs, and product fixtures, an agent-based modelling approach is used. This enables a description of their local behaviour according to rules.

4.3.1.1 Discrete Event Modelling

The general idea behind discrete event modelling is that the simulation expert considers the system being modelled as a process using flowchart blocks. The entities which are flowing through these blocks are actually agents, which are also used in agent-based modelling (Borshchev and Grigoryev 2020, p. 10). In AnyLogic, the modeller is provided with two libraries to simulate, for instance, a complex manufacturing system: process modelling library and material handling library. These libraries consist of several process and material-handling relevant blocks to simplify the simulation model creation.

4.3.1.2 Agent-Based Modelling

In contrast to discrete event modelling, agent-based modelling is a more recent method which provides deeper insights into unknown systems compared to, for example, discrete event modelling or system dynamics. To build a simulation model using a bottom-up approach, objects (agents) must be identified and defined with regard to their behaviour. Thus, agents can interact with each other as well as with their dynamic environment (Borshchev 2013, pp. 49–50). As there is no standard language for agent-based modelling, most simulation tools provide a graphical editor in addition to scripts. Therefore, the behaviour of the agents can be specified in many ways. In AnyLogic, the agents can be defined by using statecharts, rules executed upon special events, or system dynamics or discrete event modelling. With regards to the simulation model of Werk150, both statecharts and external discrete event modelling were used.

4.4 Structure and Control of the Simulation Model

In this section, the structure as well as the control mechanisms of the developed simulation model are described in detail. The model consists of 10 agents and one relational database with three tables. The agents can generally be separated into three categories:

- **Logic Agents**

  The logic agents are comprised of the main agent, the SLC agent, the fixture agent, and the transport order agent. These agents contain the fundamental logic of the processes of Werk150.

- **Flowchart Block Agents**

  The flowchart block agents are needed to divide the complex model of Werk150 into several submodules. These modules are primarily required to optimise the flowchart diagram in terms of repetitive logic blocks and, further, to separate the simulation model into submodels for the verification and validation process. In total, there are two flowchart block agents: the SLC_Logic agent, which simulates the individual SLC picking in the gravity flow rack at each workstation, and the Transporter_Logic agent, which manages the means of transport in terms of their transport order.

- **Animation Agents**

  The third category consists of animation agents. These are mainly introduced for verification purposes as they do not have any functionality built in. With the help of the animation agents, 3D-models can be assigned to MP400, MP700, handcart, and KollRo.

4.4.1 Logic Agents

In the following sections, the three logic agents are presented in detail. At relevant points, the exact flow logic necessary to simulate the system's flexibility limits and behaviour is examined in depth.

4.4.1.1 Main Agent

The main agent is the most important as it represents the primary modelling environment of Werk150. Within the main agent, all other agents, such as the SLC or fixture agent, reside. These agents are individually described in subsequent sections. In addition to the agents, the main agent contains all the production processes described in section 2.5.1 using the flowchart blocks in the material handling library and process modelling library of AnyLogic. In general, the main agent can be divided into four segments: the start-up screen, where the parameters to be simulated can be configured; the flowchart logic of the whole production processes; the two- and three-dimensional views of the simulation model; and a summary of the main output parameters to be analysed (throughput, production output, and average degree of utilisation of the means of transport).

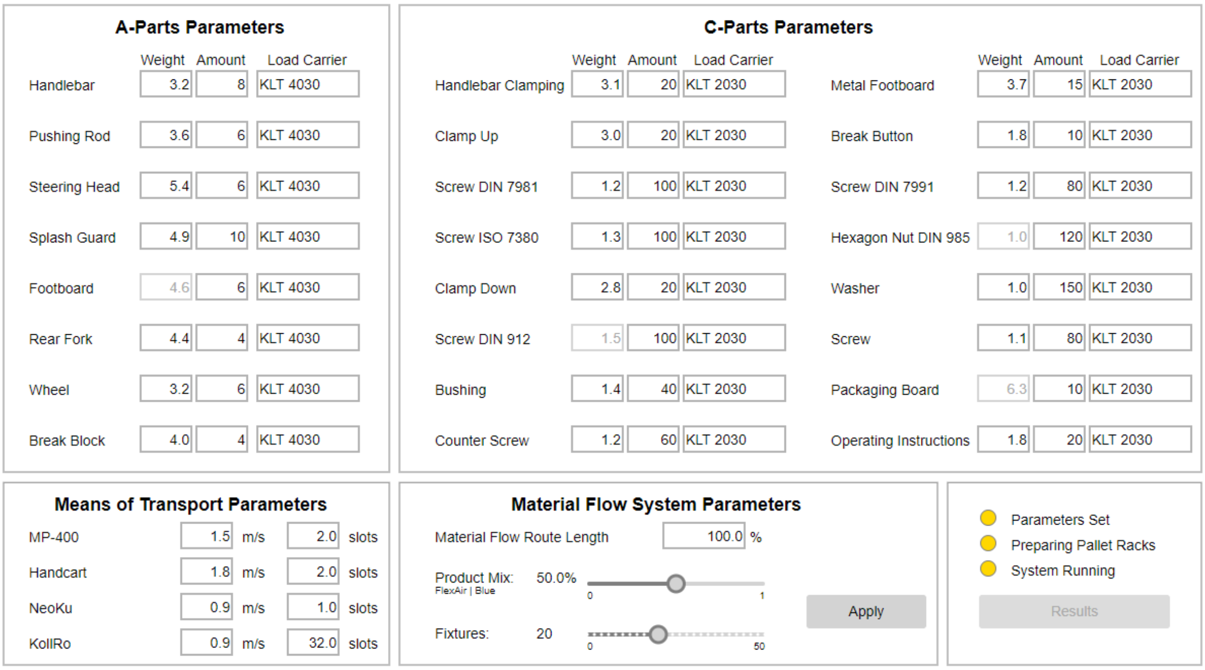


Figure 4-3: Start-up screen of the simulation model

The first segment is the start-up screen, which severs as the main user interface to define the research-specific parameters for each simulation run (see Figure 4-3). The model's main parameters are the number of components per load carrier, the selection of the load carrier type per component (according to the standards described in section 0), the speed of the used means of transport as well as their slots for transporting load carriers, the sources and sinks which an individual means of transport can reach, the material flow route length factor to manipulate the distances between sources and sinks, the number of product fixtures in the production process used, and the product mix. A typical customer order for a new city scooter is not explicitly generated as the number of product fixtures defines the overall degree of utilisation of the production system. During all simulation experiments, this parameter is set to 20 product fixtures to assures that there is always a fixture to be picked and therefore simulates the maximum utilisation of the production system.

Once all simulation-run specific parameters are set by clicking the 'Apply' button, the simulation process starts, and a total of 96 individual SLC agents are generated and placed on the gravity flow racks at each workstation. Consequently, the model starts every simulation run with two SLCs per component at each station to fulfil the two-bin principle premises. However, the first load carrier of each component is generated with a random quantity to simulate an already harmonised system. This avoids any model inconsistencies which may occur upon production ramp-up. After the simulation run, the output parameters to be analysed are automatically inserted into the database table 'results'. A summary of the most important parameters can be viewed by clicking the 'Results' button.

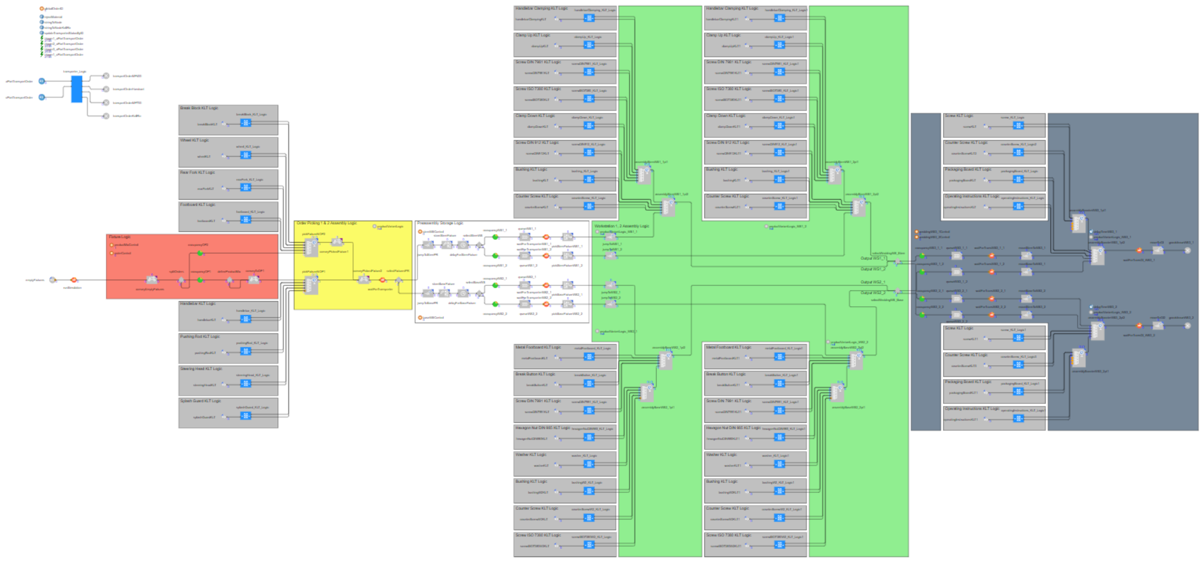


Figure 4-4: Flowchart logic of the simulation model

In the logic segment of the main agent, the production process of Werk150 is simulated using AnyLogic's flowchart blocks. Upon the start-up of the model, the set number of product fixtures is injected into the system via a source block and buffered on the conveyor line at the two order-picking stations, 1 and 2. The injected product fixtures contain a variable which describes the probability (also set via the start-up screen) of being either a FlexBlue or a FlexAir city scooter. The logic blocks for these processes are contained in the red area of Figure 4-4. Based on the variant, the corresponding order-picking station picks the required items out of the SLCs in the gravity flow racks (grey area in Figure 4-4). The exact flowchart is explained in more detail in the SLC_Logic agent in section 4.4.2.1. With the right components picked, the assembly process is simulated with the help of the assembler block in the yellow area of Figure 4-4. These blocks define the required quantity of components per fixture and the total process time depending on the variant to be assembled.

Afterwards, the picked product fixture for the stem or the base is conveyed to the end of the conveyor line, and a transporter request is sent to the relational database table 'orders'. Within this request, a unique order ID, the current location of the agent (source) and its destination (sink), the item type,[9] and its dimensions are passed on. Ideally, the locations of the source and sink should be sent via Java data type Node. However, a direct insertion of this type into the built-in database of AnyLogic is not possible without serialisation or hibernating. To reduce the complexity of the insert statement and improve the readability of the database table, these values are inserted as String, which requires later additional parsing (e.g. during transport order generation). For other, more complex simulation models, the first two options mentioned are recommended.

Once a means of transport is selected and the transport order is generated, the product fixture is transported to its corresponding workstation. Depending on the type, the stem assembly occurs at workstation 1.1 or 1.2, whereas the base assembly takes place at workstation 2.1 or 2.2. The selection of the corresponding workstation (e.g. 1.1 or 1.2) is based on its individual occupancy. The logical steps can be seen in the white area of Figure 4-4.

[9] The simulation model differentiates between three item types: A-parts, C-parts and product fixtures. Thus, the model is able to apply specific rules to certain items, for example, that only one product fixture per means of transport can be transported.

Once a workstation is selected and the fixture is transported, the picking process of the required components for the stem or base assembly is similar to the order-picking process and carried out via the SLC_Logic agent. If a C-part is missing, a material order is placed into the database containing again a unique order ID, the required material, its source, and its destination, as well as the length and width of the SLC. After being processed by the TransportOrder agent and Transporter_Logic agent, the missing C-part is transported via the KollRo to the respective workstation. The assembly process of all four workstations is simulated again with the help of the assembler block (green area of Figure 4-4).

After completing the assembly process, another transporter request is sent to the database for transporting the product fixture from its current workstation to one of the two final assembly workstations, 3.1 or 3.2. The selection of either one is similar to the four workstations mentioned above as it is based on an even distribution of the product fixtures. At these two workstations, the final assembly occurs, which is also called wedding. In this step, the stem and base is assembled to a complete city scooter. Once the assembly is done, two transporter requests are sent to the database. The first one contains the transport of the finished city scooter to the goods issue storage, and the second contains the transport of the empty product fixtures back to the conveyor line.

Included in this flowchart logic segment, there is also a reference to the Transporter_Logic agent in the top left corner. In addition, one event which triggers the transport order generation and two functions for further processing of the transport order can be found. In that event, a TransportOrder agent is generated every 30 seconds, which gets injected via the source block into the flowchart logic of the Transporter_Logic. The exact generation of the transport order is explained in section 4.4.1.3. With regard to the first function, the data type conversion of the sources' and sinks' locations takes place. As mentioned, the locations are stored as String in the database. To process the transport order in the Transporter_Logic flowchart, a conversion to type Node is required. This must be done in the main agent as a static reference to the defined nodes in the main agent is not possible within the TransportOrder agent. To convert the type, AnyLogic's findFirst() function is used. The second function handles the injection of the corresponding SLC into the gravity flow rack with the inject() function.

The third segment of the main agent represents the two- and three-dimensional model views and is comprised of the following assets:

- Several gravity flow racks for the goods receipt, supermarket, workstations, and goods issue.
- Workstations for the order picking, stem, and base assembly as well as the final assembly of the scooter.
- A conveyor line for the empty and picked product fixtures at the order-picking stations 1 and 2.
- Two collaborative universal robot UR10s which assist the worker during the order-picking process.

This view also contains the animation of the product fixtures, the MP400, the handcart, the MP700, and the KollRo. Furthermore, it defines the home location of the transporter if no transport orders exist.

The fourth and last segment of the main agent is a short summary of the main output parameters of the actual simulation run. This assures a fast and easy checking of the obtained parameters after each simulation run. In addition, all simulation run relevant parameters such as the defined velocity or capacity of the means of transports, their degrees of utilisation, the overall throughput and output of the system, and the material flow route length factor are automatically stored in the database table ‘results’. The structure of this table is described in section 4.4.4.

4.4.1.1 SLC Agent

The SLC agent is, along with the main agent, an important part of the model. The agent represents every single SLC in the production environment of Werk150. To distinguish the agents from another, the SLC-Agent has five parameters.

- **Parameter 1:** *name*
  The first parameter is the name, and it describes the component which is carried by the load carrier. The parameter is defined in the individual source block of the component.
- **Parameter 2:** *quantity*
  The second parameter is the quantity and describes the number of components inside an SLC. This parameter is set via the start-up screen in the main agent and can be changed for simulation purposes. During the production process, the number of components inside a load carrier is handled in the SLC_Logic-Agent. When a load carrier is empty, an order is placed, and the respective agent is generated at the goods receipt, waiting to be picked up by a transporter.
- **Parameter 3:** *length*
  The third parameter is the length, which describes the length of the SLC of the respective component. Similar to the quantity, this parameter is set via the start-up screen.
- **Parameter 4:** *width*
  The fourth parameter is the width of the SLC of the respective component. The parameter is set in the same manner as the length and quantity.
- **Parameter 5:** *weight*
  The last parameter is the weight of the SLC of the respective component. The parameter is set via the start-up screen of the simulation model.

4.4.1.2 Fixture Agent

During production, the main components of a single scooter are transported via a fixture. This product fixture is represented by the fixture agent and has two parameters and one variable which control the production process.

- **Parameter 1:** *variant*
  The first parameter is the variant and describes the product variant which is set via the probability of being a FlexBlue or FlexAir city scooter in the start-up screen. This parameter is essential because the products differ in terms of their components and process times. With the help of this parameter, the assembler blocks in the main agent dynamically adjust the required quantities and process times.
- **Parameter 2:** *type*
  The second parameter is the type of fixture during the order-picking process. Since every city scooter consists of a stem and base, a differentiation is required that for every stem, a base is picked. After the order is picked, the parameter distinguishes the fixtures to store them in their respective pre-assembly racks.
- **Variable 1:** *previousWorkstation*
  The first variable of this agent is the previousWorkstation, which describes the workstation which the fixture previously visited. The variable is required to trigger the hold blocks, which manages the occupancy of the workstations and thus the overall material flow. It is set directly after exiting the assembler blocks.

4.4.1.3 TransportOrder Agent

As described above, the TransportOrder agent is triggered by a cyclic timeout event every 30 seconds. This event generates a transport order for all existing components and fixtures in the database table ‘orders’ of the production environment. The order is processed depending on the availability of the means of transport, its maximum load capacity, and the individual reachability of the respective source and sink by the means of transport. In the following, an in-depth view of the order-processing part is given.

The first state after the generation of a new TransportOrder agent is the ‘checkForOrders’ (see Figure 4-5). In this step, a select statement is executed which checks the database table ‘orders’ for existing material orders. If there are any unprocessed orders, the first order and its corresponding information is retrieved from the database table. Otherwise, the transport order generation is terminated by the subsequent branch of the statechart.

The second state is the ‘selectAvailableTransporter’, in which the material order gets assigned to an available means of transport. To do so, the current position and destination of the material order must first be compared with the reachable locations of the respective means of transport set by the user. This is enhanced by checking whether a means of transport is capable of transporting the order with regard to its capacity and weight. A list of all means of transport capable of executing this material order results. In a next step, the means of transport are prioritised. If it is possible to execute the order with the MP400, the handcart, and the NeoKu, the following selection applies: If only one order exists in the database, the transport order is assigned to the NeoKu. In this way, any required capacities of the other means of transport can be reserved. If the NeoKu is already busy, the order is passed on to the MP400 or the handcart. If all means of transport which can execute the transport order are currently busy, the process gets terminated. If there are at least two material orders, the MP400 and the handcart are prioritised first. If both vehicles are busy, the order is assigned to the NeoKu. The process can also be terminated if all vehicles are busy. When a transport order can only be executed with the KollRo, the order is assigned accordingly whilst taking its availability into account. If all means of transport should be able to carry out the order due to changed input parameters, a user-specific prioritisation must be provided. In the case of this simulation model, the maximum number of unprocessed orders is determined and assigned to the means of transport which shows the optimum filling level with regard to the individual transporter capacity. As the maximum number of orders required to be processed is already achieved, the subsequent state is skipped. In case of a transport order in which the first order is a product fixture, the next state is also skipped to maintain the premises that only one product fixture can be transported on a means of transport. Lastly, once a means of transport is selected, its status in the database table becomes updated to ‘busy’. This ensures that a transporter cannot be selected twice during the transport order generation.

After a means of transport is selected and the first material order assigned to it, the third state, ‘fetchAdditionalOrders’, follows. In this state, an attempt is made to supplement the existing transport order with additional material orders from the database whilst considering the transporter-specific maximum capacity. The process ends if the maximum capacity of the transporter is reached, no further material orders can be assigned due to the load carrier dimensions or weight, or no further material orders exist.

In the last state, ‘setFlowchartLogic’, all final steps to generate the transport order are undertaken. These involve updating the individual material orders in the database, initialising the final array lists for the respective sources and sinks, and printing the created transport order to the console for verification purposes. Ultimately, the process ends, and the agent gets created.

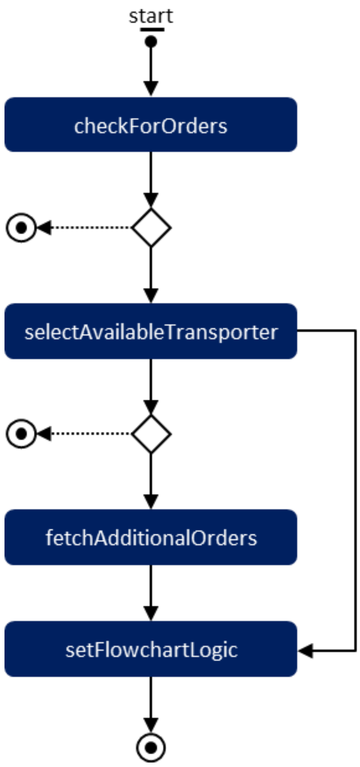


Figure 4-5: Statechart of the TransportOrder agent

4.4.2 Flowchart Block Agents

The following sections present the two flowchart block agents in detail. These agents form two submodules: the first handles the component-picking process required at each workstation, and the second module contains the logic of the transport system.

4.4.2.1 SLC_Logic Agent

The SLC_Logic agent is one of the two flowchart block agents. This block simulates the individual item-picking process in the main agent from their SLCs. Thus, a total of 48 SLC_Logic flowchart blocks are used (see grey areas in Figure 4-4).

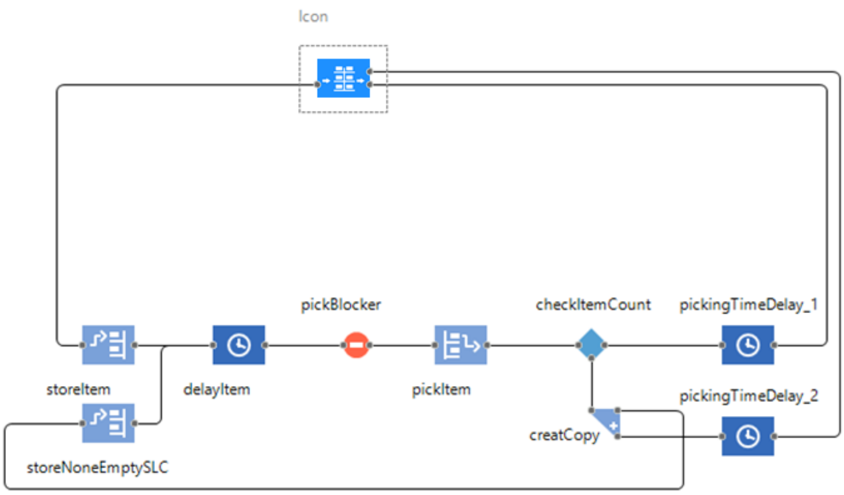


Figure 4-6: Process flowchart of the SLC_Logic agent

The block consists of one in-port (left side) and two out-ports (right side) (see Figure 4-6). The in-port is connected to a material and workstation-specific source block, whereas the two out-ports are connected to a workstation-specific assembler block in the main agent. On arrival of a transporter, the respective material is injected into the source block and enters the 'storeItem' block, which sets the SLC to the workstation-specific gravity flow rack. In 'delayItem', a delay for inserting the load carrier into the rack can be set. The next block in the process flow is a hold block called 'pickBlocker', which is initially set to 'blocked'. This prevents the SLC agent from being directly released from the gravity flow rack. It is triggered by the respective workstation in the main agent upon arrival of a new product fixture.

After unblocking the subsequent processes, the SLC enters the 'checkItemCount' block, which checks the SLC agent's quantity parameter. If the SLC has only one item left, the agent exits the true port, and a new material order is sent to the database. Afterwards, it is delayed by the 'pickingTimeDelay_1' block, which simulates the picking time of the worker. If two or more items are remaining in the SLC, the agent exits the false port of the 'checkItemCount' and decreases the number of items by one. Subsequently, a copy of the agent is created at the 'createCopy' block, which then enters the 'pickingTimeDelay_2' block. Similar to the other block, a delay for picking the item is simulated. The original agent with its reduced quantity, however, is stored back in the gravity flow rack via the 'storeNoneEmptySLC' block.

4.4.2.2 Transporter_Logic Agent

The second flowchart block agent contains the logic of all means of transport in the production environment (see Figure 4-7). It consists of one in-port (left side) and four out-ports (right side). The in-port is connected to source blocks of the TransportOrder agent, which is located in the main agent. All four out-ports are connected to sink blocks, which are also located in the main agent.[10]

If a TransportOrder agent enters the Transporter_Logic block, it gets delayed for a second by the 'processingTransportOrder' block to avoid latency issues during the order generation with AnyLogic's built-in database. This assures that all collections, parameters, and variables are set and ready for further processing. In the following select blocks, the incoming orders are separated based on the assigned means of transport. Whilst the process flowcharts of all four means of transport look the same, a distinction is necessary to assign the different vehicle animations to the transport order. If an incomplete transport order is generated (e.g. no transporters were available), the order is terminated at the 'emptyTransportOrder' block. Otherwise, if a vehicle has been selected, for example, the MP400, the collections containing the sources and sinks are transformed from type String to Node in the 'transformOrder_MP400' block. Now the means of transport is ready to seize its carrier at the first source of the transport order with the 'seizeMP400' block.

This block is followed by the 'moveByMP400' block, which sends the vehicle to the respective sink and drops off the carrier. In the subsequent select block, 'checkRouteMP400', the transport order is checked for further transports. If so, a seize block is used as a dummy to load the vehicle again as AnyLogic's standard flowchart blocks for transporters only consider one load carrier per means of transport. After seizing the transporter again, the loop closes with a connection to the 'moveByMP400' block. Once all positions of the transport order are processed, the agent enters the block 'returnHomeMP400', which sends the transporter back to its home location and updates its status in the database table to idle.

In the case of the KollRo, the means of transport enters the 'loadKollRo' block before terminating the transport order. This delay dynamically simulates the refilling time of the missing SLCs per

[10] See top left corner of Figure 4-4.

transport order. After successfully refilling the KollRo's trailer, its status gets updated to idle. Ultimately, the transport order exits the flowchart block and enters its corresponding sink block in the main agent.

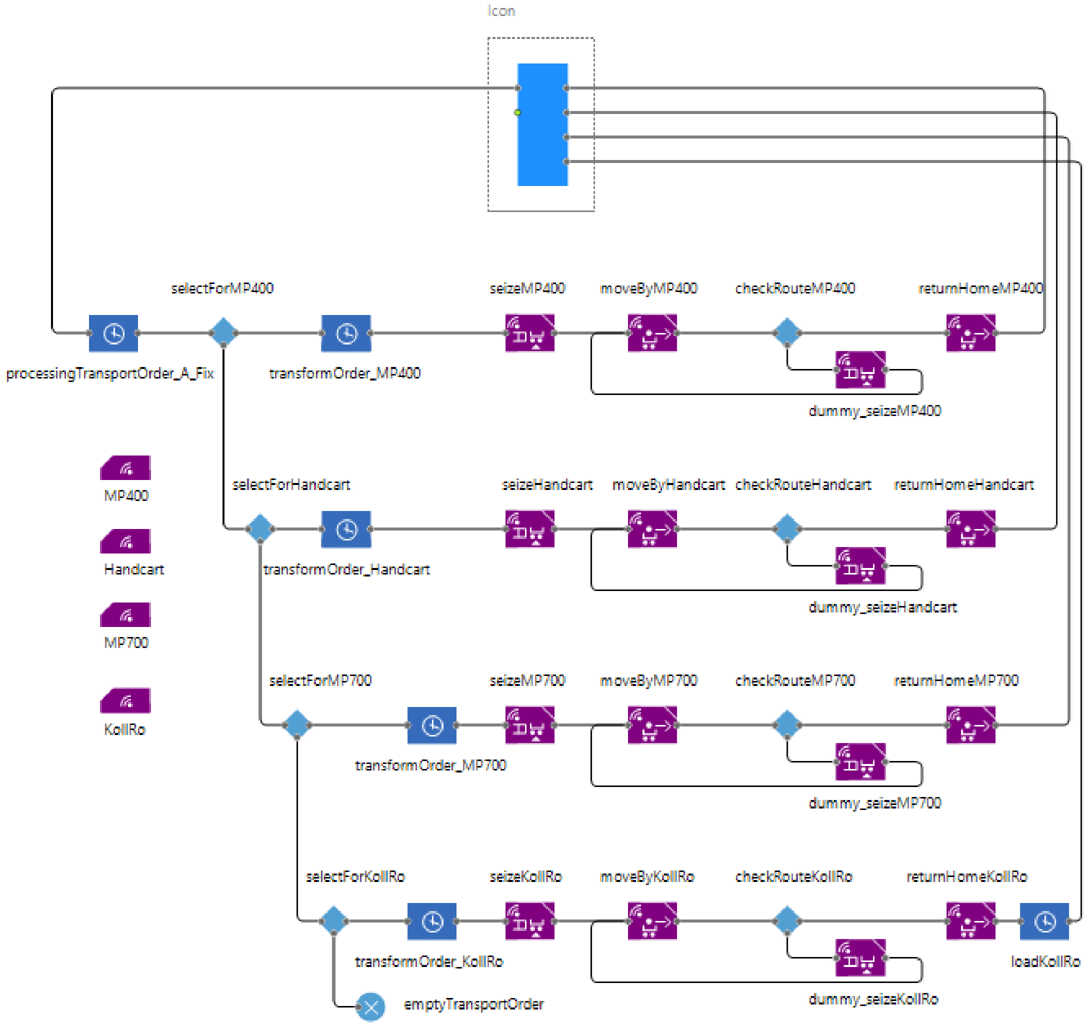


Figure 4-7: Process flowchart of the Transporter_Logic agent

Besides the flowchart of the transport order, four so-called fleet blocks are situated in the Transporter_Logic agent. These blocks define individually, for each means of transport, relevant parameters such as the velocity, acceleration, deceleration, turn radius, home location, minimum distance to obstacles, and animation agent. Based on these parameters and the defined 3D objects in the main agent, such as walls or machines, certain material flow routes can be, for example, blocked for an individual means of transport.

4.4.3 Animation Agents

The last category of agents used in the simulation model consists of animation agents. These agents do not have any logic built in and are solely created for visual representation and to determine the vehicles' dimensions. The individual loading capacities of the vehicles are defined in the transport database table.

The first animation agent is the MP-400 agent, which represents the corresponding transporter. Its dimensions are set according to the technical data sheet of Neobotix. In a similar way, the NeoKu, with its MP0-700 as a basis, is defined. The last two animation agents belong to the handcart and KollRo.

4.4.4 Database

To handle the material orders of the individual workstations, the transporter status of the simulation model, and the simulation results, AnyLogic's built-in Structured Query Language (SQL) database is used. In this database, three tables were created, which are explained below.

For the material orders, an empty table 'orders' with nine columns was created (see Table 4-1). The first column contains the unique order ID (OID) to precisely select a specific order (e.g. for updating its processing status). Next, the columns for the source, sink, item, and item type follow. This information is required to generate the first half of the transport order and to select an appropriate means of transport. Columns six, seven, and eight contain the length, width, and weight of the defined SLC during simulation. With the help of the capacity parameter of each means of transport, an optimal utilisation per transport order can be achieved. The last column contains the material order status, which is by default set to 'false'. After processing the material order in a transport order, it gets updated and set to 'true'. The orders table is automatically cleared upon every new simulation run.

Table 4-1: Structure of database table 'orders'

Orders								
OID <int>	**source** <String>	**sink** <String>	**item** <String>	**type** <String>	**length** <Double>	**width** <Double>	**weight** <Double>	**processed** <Boolean>
1	GR	OP1	Handlebar	A	40.0	30.0	5.0	FALSE

The second database table used for the simulation model consists of seven columns which manage the status, speed and capacity, maximum load capacity, and reachable locations of the four means of transport (see Table 4-2). Thereby, each transporter has its own identification number (TID) and name. The status gets updated from idle to busy during the transport order generation process. After completion of the transport order and eventual refilling processes, the status of the vehicle is set to idle again. When starting a simulation run, all transporters are switched to idle. The speed of the respective means of transport is set by the parameter screen upon start-up of the simulation. After each simulation run, the speed resets to the initial value defined in section 2.5.4.

The same applies to the storage capacity and maximum load capacity of the transporter. The storage capacity of each means of transport is defined by the available area for possible SLCs. In other words, the MP-400 is capable of transporting two SLC 4030s. Its resulting area is calculated by the dimensions of the load carrier times the amount: 40 x 30 x 2. This leads to a total capacity of 2,400 square centimetres. For the KollRo, an additional premise exists as it can only transport two SLCs of one component at a time. This aspect, however, is considered during the transport order generation.

Table 4-2: Structure and entries of database table 'transporter'

transporter						
TID <int>	**transporter** <String>	**status** <String>	**speed** <Double>	**capacity** <Double>	**max_load** <Double>	**locations** <String>
1	MP400	Idle	1.5	2400.0	100.0	GR;OP1;OP2;…
2	Handcart	Busy	1.8	2400.0	10.0	GR;OP1;OP2;…
3	MP700	Idle	0.9	1200.0	14.0	GR;OP1;OP2;…
4	KollRo	Busy	0.9	19200.0	10.0	SM;WS1.1;…

The last database table is called 'results' and is automatically populated after each simulation run with all research-specific parameters. Based on the simulation results in this database table, the subsequent diagrams for each factor are generated. In total, the table has 17 columns, which cover the following parameters:

- Simulation run number.
- Speed, capacity, and utilisation of all four means of transport.
- Material flow route length factor.
- Actual throughput.
- Production output of FlexBlue and FlexAir city scooters.

After the development of the formal model and the implementation in the simulation software AnyLogic, the simulation model needs to be verified and validated in a subsequent step. This ensures that the model developed reflects reality and that the results obtained are valid, precise and reliable.

Chapter 5
Verification and Validation of the Simulation Model

In this chapter, the developed simulation model of Werk150 at the campus in Reutlingen is verified and validated. Different techniques are used to ensure that the obtained results are valid and can be accepted by the research community. First, an overview is provided of all the techniques commonly used in the simulation of production and logistics across the development process of the model. Afterwards, the respective techniques are presented in more detail in the corresponding sections.

5.1 Overview of Verification and Validation Techniques

The literature describes a large number of verification and validation techniques. With reference to a simulation model, verification according to VDI 3633 means the ‘formal checking of the simulation model for correctness’ (VDI 3633:2018-05, p. 36). Balci (1998, p. 41) has also described verification as proof of the transformation of a model from one form into another, as intended and with sufficient accuracy. Often, the definition is also converted into a question (e.g. are we building the model right?). In comparison, validation according to VDI 3633 describes the ‘checking of sufficient correspondence between the model and the system, which is supposed to make sure that the model mirrors the behaviour of the real system accurately enough with regard to the examination targets and free from errors’ (VDI 3633:2018-05, p. 35). Balci (1998, p. 41) has defined validation as proof that the model behaves within its area of application with satisfactory accuracy and in accordance with the model and simulation objectives. Again, a question can be formulated (e.g. are we building the right model?).

Since there is no general approach to verification and validation, simulation experts should select the techniques which are relevant and meaningful for their model. Influencing factors are, for example, the purpose of the simulation study, the properties of the model, the phases of the simulation study, the knowledge of the user, and the availability of data (Rabe et al. 2008, p. 93). In principle, the techniques ensure that errors are minimised and provide for a higher credibility of the simulation model. Rabe et al. (2008, pp. 93–94) have also stated that several techniques should always be used or combined to increase effectiveness.

Based on the respective phases of the simulation study, different techniques are proposed. Balci (1998, pp. 45–47) and Rabe et al. (2008, p. 113) have presented a total of over 83 techniques. Derived from these overviews, suitable techniques were selected depending on the respective phases of the process model (see Figure 1-2). These phases are problem definition, system description, model design, implementation, and result analysis. Table 5-1 provides an overview of the selected methods.

Table 5-1: Overview of the techniques used for verification and validation

Technique	Phases of the Simulation Study				
	Problem Definition	System Analysis	Model Formalisation	Implemen-tation	Experiments & Analysis
Animation				●	
Trace Analysis				●	
Extreme-Condition Test				●	
Submodel Testing				●	
Face Validity	●	●	●	●	●
Internal Validity Test				●	
Event Validity Test				●	

5.2 Verification of the Simulation Model

This section describes the techniques used to verify the model. Thereby, the question of correctly building the model is answered. All techniques listed in this section apply to the implementation phase of the simulation model, as they require an executable system. The techniques are first explained theoretically according to Rabe et al. (2008, pp. 95–110) and then described in detail regarding how they were applied to the simulation model.

5.2.1 Animation

With the animation, the simulation model is graphically represented two- or three-dimensionally in the course of time. Thus, the animation can be used to show the model behaviour in specific situations. In this context, it is important to mention that a correct animation alone is no guarantee of a valid or accurate simulation model. By comparing the model with the real system, a plausibility check can be conducted. However, errors which rarely occur will most likely be undetected. One of the main advantages of this verification technique is that the behaviour of the simulation model can be checked over a short period of time in specific areas. This is especially useful if unexpected results occur when using other techniques. Due to the animation, the error can be localised effectively, or unexpected results can be observed.

During the application of the animation technique onto the developed simulation model, the large object database integrated in AnyLogic was used. By simply dragging and dropping 3D objects such as machines, workers, and other parts of infrastructure, these objects were placed in the model and linked to the flowchart (see Figure 5-1). For this verification technique, the animation agents were especially helpful as all relevant means of transport could be displayed graphically.

Particularly in combination with trace analysis, the extreme-condition test, and submodel testing, the animation proved to be helpful as errors in the program code could be found and corrected systematically.

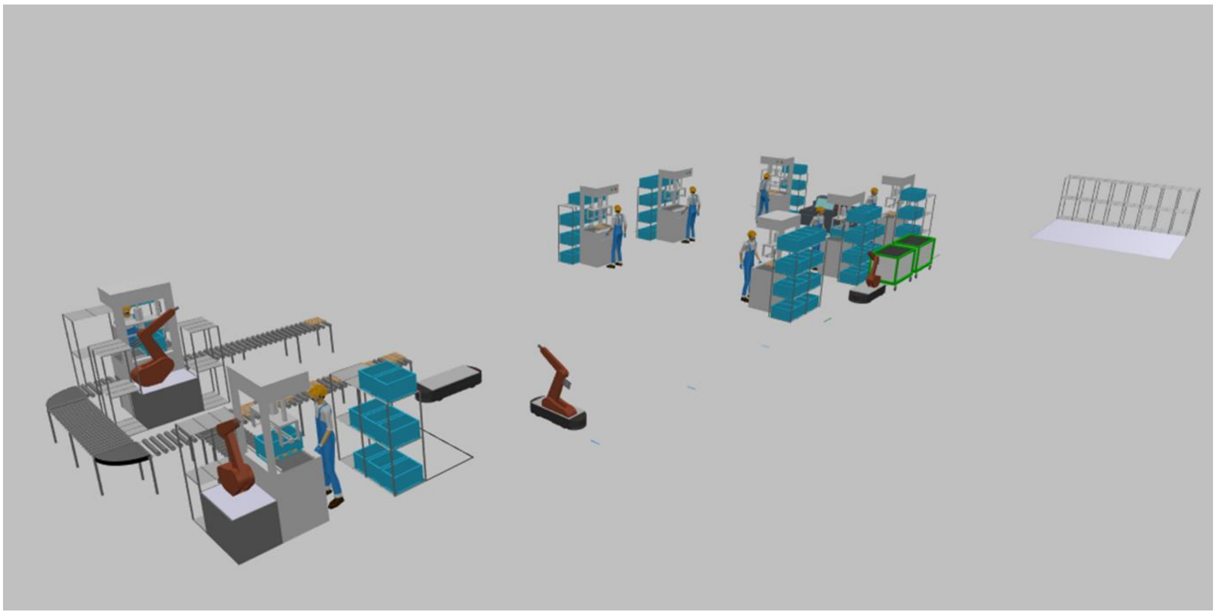


Figure 5-1: 3D visualisation of the simulation model

5.2.2 Trace Analysis

With the trace analysis, individual data records, so-called trace files, are taken from the executable model. This allows the logical behaviour to be checked for plausibility. The trace file contains information such as model time, identification number, or location of an object and can be printed to the console of the simulation software. In this way, individual objects and their decision paths can be traced along the flowchart. Trace analysis is a helpful technique, especially for the simulation of specific events as it allows users to follow the behaviour of the model exactly. According to Rabe et al., the combination with extreme condition tests is also useful here.

With regard to the simulation model, trace analysis was frequently used, especially during the development process. Using the built-in AnyLogic function traceln() or the Java function System.out.println(), texts can be output in the model console, enabling the tracking of different states. For example, the trace function was used to track the SLC contents and dimensions in the SLC_Logic agent, which are important for ordering materials. Furthermore, the product fixtures were monitored throughout the assembly process to check whether the process times of the workstations would change depending on the city scooter variant. Another example of the use of the trace function is the output of the generated transport order for each means of transport. This made it possible to examine how the transport order is structured, whether transporter capacities are exceeded, and which means of transport is responsible for the transport. In combination with the animation, it was ultimately possible to check whether the means of transport also transported the materials to the corresponding sinks.

5.2.3 Extreme-Condition Test

By considering extreme values as input parameters, the results of the simulation model can be checked for plausibility. These input parameters can also be a combination as long as all values are within the range covered by the simulation model. As an example, Rabe et al. have stated that the batch size of a production system can be set to the smallest intended value. This makes it easier to estimate the ratio of set-up time to machining time. Ultimately, the extreme-condition test can be used to find errors in the modelling of process times, such as invalid loading and unloading times of means of transport or incorrect conversion factors.

During the execution of the extreme-condition test on the simulation model, the lower limit of the input parameters was tested. For this purpose, the model was adjusted in terms of its parameters in such a way that exactly one city scooter was produced. Moreover, the number of product fixtures and the number of components per SLC required for a single city scooter were set to minimum. In this way, it was possible to track exactly whether all processes behave in accordance with the real system. Concretely, this means whether the process times of the individual workstation per city scooter variant change, how the fill levels of the SLCs behave depending on the built variant, how the transport of SLCs and product fixtures occurs, and whether the return process of the product fixtures to the conveyor belt at the order-picking stations is carried out correctly. Further extreme-condition tests were conducted to calculate, for example, the capacities of the means of transport depending on the dimensions of the SLCs, if adjustments to the speed of the used means of transport and conveyor belts affect the model correctly, and to verify the loading and unloading times of the means of transport. In this way, any errors occurring during the individual tests could be localised very precisely and corrected immediately.

5.2.4 Submodel Testing

Submodel testing, which is also called module testing, can be applied if the simulation model is hierarchically structured. Thereby, individual submodels, which result from the complete model, are simulated. In principle, this technique can be applied in all phases starting from concept development up to the executable model. The only difference is that for non-executable models, an additional verification or validation technique must always be used in combination; otherwise, no useful results are generated. For executable models, as in this use case, the input and output data of the respective submodels are recorded and individually validated. The validation is usually verified by a plausibility check of the data but can also be carried out by combining other techniques such as face validation. Since submodels are not always meaningful and executable, the required function can be assured by suitable measures, such as adding additional sources. Another advantage of submodel testing is the applicability throughout the development process of the simulation model. Thus, the individual submodels can be verified and validated before they are finally merged into the complete model. This process is called bottom-up testing. However, it should be noted that the verification and validation of all submodels do not replace those of the complete model but rather complement them effectively.

In the development process of the simulation model, it was ensured that the model was structured hierarchically and modularly, enabling its bottom-up testing. The developed model can basically be divided into three submodels: production system, transport system, and material retrieval system. For all three submodels, this technique was employed in combination with the abovementioned verification techniques and face validation.

The general logic of the production system is defined by the flowchart in the main agent. The submodel was iteratively tested during construction by adding submodel-specific sources and sinks depending on the development status. At the end, a correct production process could be determined.

The second submodel represents the transport system. This includes the Transporter_Logic and TransportOrder agents. For verification purposes, the material orders were manually added to the database. Again, it could be verified that the transport order generation, order assignment to the means of transport, and transport work under consideration of means of transport-specific parameters.

The last submodel is the material retrieval system, which monitors the fill levels of the SLCs in the gravity flow rack and, if necessary, triggers workstation-specific material orders. The corresponding logic was realised in the SLC_Logic agent.

In summary, the submodel testing formed the basic structure of model verification. By iteratively testing the submodels during the development phase, errors could be identified and eliminated at an early stage. The technique was supplemented by animation, trace analysis, and extreme-condition testing as well as by face validation. Finally, the complete simulation model was again verified with these techniques.

5.3 Validation of the Simulation Model

This section describes the techniques used to validate the simulation model. Similar to the verification section, a guiding question can be formulated. For the validation of a model, the question of whether the right model was built is answered. The techniques presented are also based on Rabe et al. (2008, pp. 95–110) and were applied, depending on the technique, to different phases of the simulation model. Whereas the face validity applies to the problem definition, system description, model design, implementation, and result analysis, the internal validity test and event validity test apply only to the implementation phase. Again, all techniques are first explained theoretically and then described in detail regarding how they were applied to the simulation model.

5.3.1 Face Validity

The validation in dialogue, also known as face validity, describes discussions with specialists that have an in-depth understanding of the respective system. Based on their experience, the specialists can assess the validity of the achieved results in the simulation model. One of the main advantages of this technique is that errors can be revealed very rapidly if the experts notice any discrepancies. As another beneficial side effect, the simulation expert is forced to explain his or her work to the technical expert, thus requiring him or her to rethink the simulation model. This rethinking process can lead to further discovery of errors and helps to improve the overall simulation model.

In the course of the simulation study, discussions were held with research associates from different departments of Werk150. Various aspects, ranging from the problem definition to the result analysis, could be questioned and checked for consistency of the model and its results. Identified weak points (e.g. in the modelling of the assembly process) could be eliminated easily and in such a way that the model reflects reality, and the results were found to be consistent. In addition to the dialogue, the associated rethinking process enabled further identification and elimination of inconsistencies and errors.

5.3.2 Internal Validity Test

In the test of internal validity, several simulation runs are performed with unchanged input parameters using different initial values of the random generators. The test is based on a stochastic model. The aim is to check whether the measured values of the performed simulation runs differ significantly. There can be two different conclusions drawn from the results. The first conclusion appears in the case of a significant difference of the measurement results. In this case, it can either be assumed that the model is faulty and the real system does not have such a fluctuation margin, or it reflects the real system. In this case, however, it must be questioned whether these fluctuations in the real system are acceptable. The second conclusion is simply that there is no significant difference between the simulation runs. In summary, the test provides information about the statistical uncertainty for a single constellation of input variables. When comparing this technique with a sensitivity analysis, the latter provides only information about how strongly the fluctuations of output variables are affected in relation to input variables. According to Sargent (2011, p. 187), variability is another statistical indicator in the test of internal validity. If the variability is large, the results of the model can be considered questionable, and, if necessary, the appropriateness of the system can be investigated.

In this simulation study, both the significance and the variability of the measurement series were calculated. The simulation model was examined in its initial state—in other words, with the parameters of the real system. The simulation runs only differed in their randomised number of components in the load carriers. For both measurement series, a total of 30 simulation runs with a runtime of one hour each were carried out. To check the significance by means of a paired t-test, three different output parameters were evaluated: throughput, production output, and degree of utilisation of the overall system. In the following, the average difference $\bar{d}$ of the output parameters, the standard deviation of the difference s_d, the standard error of the difference $SE(\bar{d})$, and the t-value of both measurement series are given for a total of 29 degrees of freedom df. The exact calculation of the individual values can be found in the appendix.

Table 5-2: Results of the paired t-test for internal validity test

	Throughput	Production Output	Degree of Utilisation
$\bar{d}$	4.2667	0.6667	0.3634
s_d	13.0831	2.2944	3.7615
$SE(\bar{d})$	2.3886	0.4189	0.6868
t	1.7863	1.5915	0.5291
p	0.0845	0.1223	0.6007

A significance level α of 0.05 is assumed. The t-value in both tails combined with 29 degrees of freedom is t=2.045. Since in all three observed output parameters, the p-value is greater than α, null hypothesis H_0 is accepted (see Table 5-2). A statistical significance is not present. When checking the standard deviation from the total of 60 simulation runs, the following values result for throughput s_T, output s_O, and degree of utilisation s_{DoU} results:

$$s_T = \sqrt{s_T^2} = 8.68 \tag{5.1}$$

$$s_O = \sqrt{s_O^2} = 1.52 \tag{5.2}$$

$$s_{DoU} = \sqrt{s_{DoU}^2} = 2.63 \tag{5.3}$$

The results of the standard deviation of the three parameters as a measure of variability show no extreme fluctuations. Therefore, a realistic representation of the real system can be assumed.

5.3.3 Event Validity Test

In an event validity test, occurring events in the simulation model can be compared with reality. The events do not have to be related and can be examined in individual experiments. If the results of the real experiment do not correspond to the results in the simulation, the simulation model is assumed to be invalid. To perform the event validity test objectively, hypotheses should be established which must be verified during the experiments.

The objective of practical validation within the context of an event validity test is to ensure that the simulation model correctly reflects the real intralogistics system of Werk150. For an objective evaluation and execution, hypotheses were formulated for the two events (E). In the first event, the aim is to investigate whether the speed of the handcart, which is derived from literature, is realistic.

In the second event, it is analysed whether the three flexibility parameters behave in the same way in a real intralogistics material flow system as in the simulation model.

E1	The speed of a worker with a handcart of 1.8 metres per second is realistic.
H_0	The difference between the measured speed and the assumed speed of 1.8 metres per second is less than ±2.5%.
H_1	The difference between the measured speed and the assumed speed of 1.8 metres per second is greater than ±2.5%.

For the investigation of the assumed maximum speed of 1.8 metres per second, according to DIN EN ISO 13855, a precisely measured material flow route was traversed several times with a handcart and an employee. The times which the employee required to traverse the distance with the handcart were measured. Based on these measured values and the length of the material flow route, the average speed could be determined per cycle. After more than 40 measurements, the average speed was 1.81 metres per second, which is within the tolerance range of the null hypothesis. Therefore, the null hypothesis can be accepted.

E2	With regard to the throughput of an intralogistics material flow system, the effects of the material flow route's length, means of transport speed, and capacity, as well as the product dimensions, are fundamentally the same as in the simulation model.
H_0	The parameters in a real system fundamentally behave in the same way as in the simulation model.
H_1	The parameters in a real system fundamentally do not behave in the same way as in the simulation model.

During the investigation of this event, a separate experiment was conducted for each influencing factor. The null hypothesis can only be accepted after confirmation that all factors fundamentally behave the same as in the simulation model.

To investigate the effects of the material flow route's length on the throughput of an intralogistics material flow system, the distance between a source and a sink was modified over several measurements. Thereby, the system throughput per hour was measured for each given distance. Afterwards, the generated data points were used to determine the behaviour of the influencing factor, which corresponded to the behaviour of the simulation model. The same approach was also used to analyse the effect of the speed of the means of transport on the throughput. In this experiment, a fundamentally similar behaviour was identified too. To determine the effects of the capacity of a means of transport on the throughput, the number of load carriers per means of transport was increased in the experiment in accordance with the simulation model. Again, the behaviour was found to be in accordance with the simulation model. A similar behaviour with regard to throughput could also be determined for the product dimensions. In conclusion, the null hypothesis can be accepted as the system behaviour of the physical system fundamentally matches to that of the simulation.

In over four verification and three validation techniques it was demonstrated, that the developed simulation model properly reflects the real intralogistics system of the logistics learning factory Werk150. In a next step, the behaviour of the flexibility parameters are simulated and subsequently analysed.

Chapter 6
Result Analysis of the Simulation Study

In this chapter, the results of the individual simulation runs of the respective factors and flexibility parameters on throughput, production output, and degree of utilisation of the means of transport are presented and interpreted. In total, more than 1,000 simulation runs were carried out for the analysis, which resulted in over 16,000 individual data points. In general, a total of 20 runs were simulated for each factor setting, and the time of a single simulation run was exactly one hour. The respective mean values were then calculated from the individual data points to obtain a single data point for the respective throughput, production output, and degree of utilisation curve. The number of data points obtained for the curve generation varied depending on the factor of the respective flexibility parameter.

6.1 Layout Flexibility

6.1.1 Reachability of Sources and Sinks

The first factor to be analysed in the scope of layout flexibility is the reachability of sources and sinks. As described in section 3.4.1, the impact of the reachability of sources and sinks is examined in this thesis in two stages. The first stage represents the initial situation in which all parameters are the same as in the real system (see section 2.5 and Figure 4-3). The second stage simulates 100% reachability of all sources and sinks. Thus, a completely layout-flexible system is simulated. With the help of the two simulation results, it is possible to compare the respective states and to determine the limits of the system with regard to layout flexibility. The limit, however, is system-specific. A decisive factor for the limit levels is the means of transport used. At this point, it should again be mentioned that the modular structure of the simulation model enables the simulation expert to simulate different layout-flexible means of transport. The vehicle-specific parameters are added analogously to the existing vehicles. By further eliminating the process times per workstation specified in the simulation model, the theoretical maximum utilisation of the transport system can be determined. The results of this simulation can be used to supplement and support new planning or expansion plans.

Within the scope of this analysis, only the means of transport presented in section 2.5.4 are examined with regard to their reachability. When examining the throughput of the initial state of the simulation model, a system-specific actual throughput of approximately 190 load carriers per hour is established (see Figure 6-1). In the second state, where all means of transport can reach all sources and sinks, the actual throughput is 216 load carriers per hour. This increase in throughput is attributable to better utilisation of the means of transport. Since every vehicle can reach every station in the system, it is possible to optimise the allocation of material orders in terms of the means of transport-specific capacity utilisation.

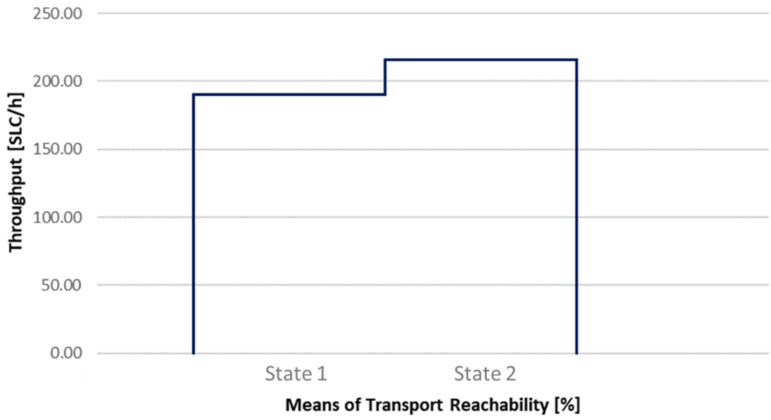


Figure 6-1: Influence of the reachability on throughput

The logical consequence of an increasing throughput is a higher production output. Thus, in the initial state, only 14.6 city scooters were produced on average in the simulated period, whereas in a fully layout-flexible system, almost 18 were produced (see Figure 6-2).

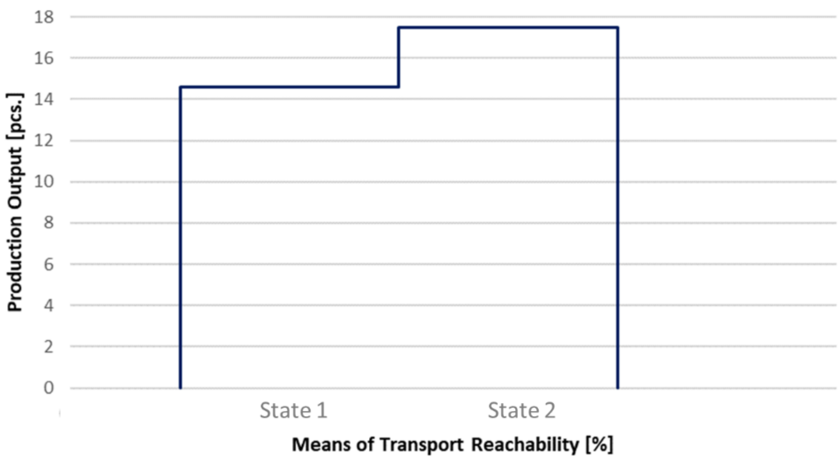


Figure 6-2: Influence of the reachability on production output

Lastly, assessing the degree of utilisation of the system, a slight increase is seen (Figure 6-3). As the vehicles have a wider range of application, their degree of utilisation is correspondingly higher. This effect is particularly noticeable with the collaborative tugger train KollRo. Whilst its load factor is approximately 25% in the first state, it is around 51% in the second. Due to its high SLC storage capacity, it can handle a large number of material orders at once and thus ultimately manages to minimise the degree of utilisation of all other vehicles. The NeoKu has particularly been able to reduce its capacity utilisation considerably as single-material orders are no longer placed that frequently due to the high transporter capacity available.

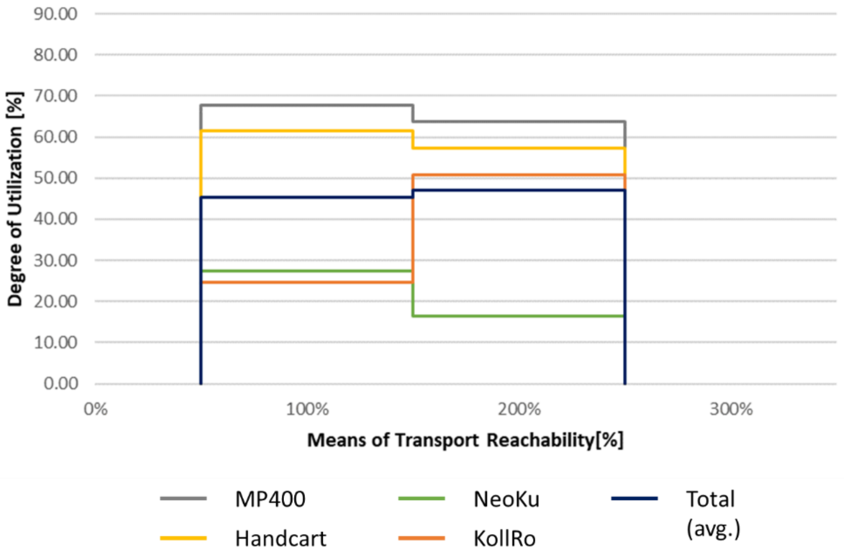


Figure 6-3: Influence of reachability on the degree of utilisation of the means of transport

6.1.2 Material Flow Route Length

The second factor analysed in the scope of layout flexibility is the material flow route length. To change the length of the material flow routes, a so-called material flow route length factor was introduced. As AnyLogic does not have a precise and simple possibility to expand the premises by a factor to achieve a lengthening or shortening of the material flow route, the speed of all vehicles is adjusted accordingly by means of the material flow route length factor. The physical relationship amongst speed, distance, and time (see Formula 3.5) shows that if the distance is theoretically doubled, the speed must be reduced by half to maintain the actual time required for a real extension. The x-axis used for the analysis is the material flow route length factor in per cent. A length factor of 100% is equal to the initial system. In general, this factor provides an insight into the overall length of the material flow routes in the system. Especially in the planning phase of a logistics system, the following curves provide an indication of the extent to which the routes in a system must be shortened and whether layout changes to the workstations may be necessary. The decision can be made on the basis of the corresponding limits shown.

As can be seen in Figure 6-4, for an extremely short material flow route length, the throughput of the intralogistical system has—other than what was expected in the hypothesis—a plateau. The level of this plateau corresponds to the maximum actual throughput of the system. The difference between the assumed theoretical and obtained actual throughput is, namely, that the actual throughput is limited by system-inherent factors. In the case of the simulation model, these limitations include, for example, the frequency of the material retrieval method for generating a transport order. Another limitation, for instance, would not necessarily be the speed of the means of transport but rather the acceleration and deceleration as the material flow route is not long enough to reach the maximum velocity. When examining the further course of the function, the assumption from section 3.4.2 regarding the regressive course can be confirmed. Minor changes in the length of the material flow route around the initial operating point of the system have a more significant effect on the throughput than those for longer material flow routes.

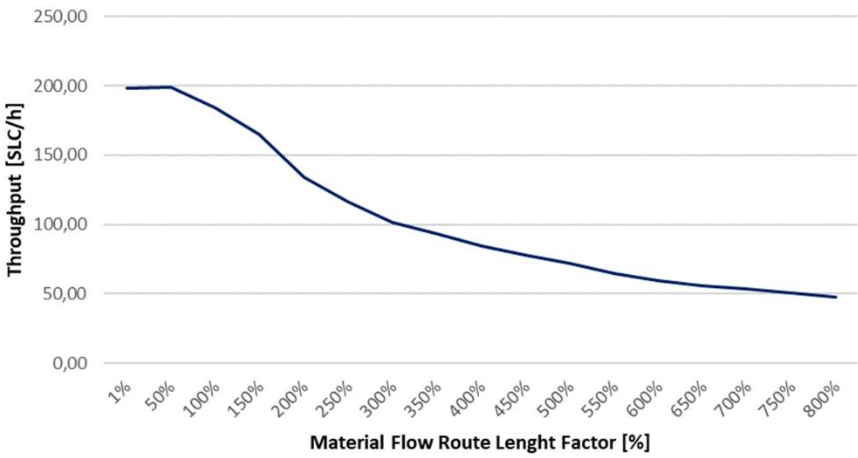


Figure 6-4: Influence of the material flow route on throughput

A similar behaviour can be observed for production output as for throughput (see Figure 6-5). With a small material flow route length factor or, to be more precise, extremely small material flow routes, the production output corresponds to the maximum production output of the production system under the given parameter settings. A further increase in output can be achieved most easily if, for example, the process times of the workstations and order-picking stations are minimised. Furthermore, it can be assumed that with very short process times, the material retrieval method also represents a potential limitation as it controls the transportation of the product fixtures and assembled city scooters. When considering the further course of the curve, it can be seen that slight changes in length around the initial operating point of the system lead to a significant change in output. As the material flow route length factor increases, the influence on the production output is reduced due to the regressive function course. Overall, the expected behaviour for the production output stated in the hypothesis can be confirmed.

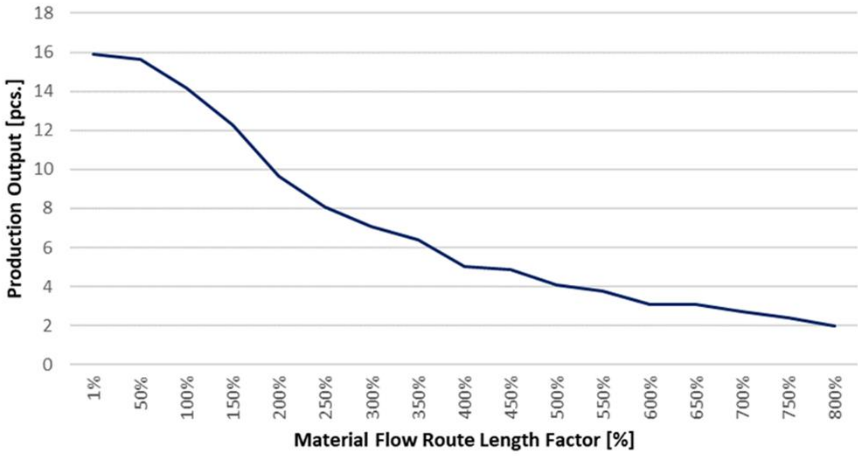


Figure 6-5: Influence of the material flow route on production output

When looking at the graphs of the degree of utilisation of the individual means of transport and the average overall utilisation of the system, interesting effects can be observed (see Figure 6-6). Considering the curve of the MP400 and the handcart, it can be assumed that both means of transport approach full utilisation as the length of the material flow routes increases. Their high degree of utilisation is not only due to their relevance for the production process—namely, the transport of the product fixtures—but also to the low quantity of A-part components per load carrier. The fluctuation in the degree of utilisation of approximately 5% depending on the material flow route length factor is attributable to the randomised quantity of components per load carrier.

In principle, this behaviour was expected in the hypothesis and confirmed in the simulation. In contrast, however, the automated guided vehicle NeoKu and the collaborative tugger train KollRo, which is responsible for all the C-parts, behave differently. With increasing transport distances, NeoKu approaches a plateau of approximately 55 to 60% degree of utilisation. This behaviour is a result of its application and task as the NeoKu is only used to support the MP400 and the handcart if the available transport capacity is not sufficient. Because it can only move one load carrier at a time, its use and influence are therefore very limited. For the KollRo, a contrasting utilisation curve emerges in comparison to the other three means of transport. The degree of utilisation of the tugger train initially increases as expected and then forms a plateau for about four factor changes in length. After this plateau, the degree of utilisation then begins to decrease continuously. This initially contradictory development is the result of the effects of reducing throughputs and outputs as well as the high quantity of C-parts per load carrier and the total simulation time. Due to larger material flow routes in the system, the time until a product fixture reaches one of the six assembly stations is significantly longer. Thus, the probability of a material order for a new C-part within the simulated time of one hour is reduced enormously. As a result, the degree of utilisation flattens out.

If the utilisation curves are aggregated from all vehicles, the average overall system utilisation is obtained. Due to the two effects of the NeoKu and KollRo, a utilisation plateau of approximately 60% is formed for the entire system. However, it is assumed that the effects of the KollRo are reduced to a certain extent with a longer simulation time, which ultimately results in a higher overall system utilisation.

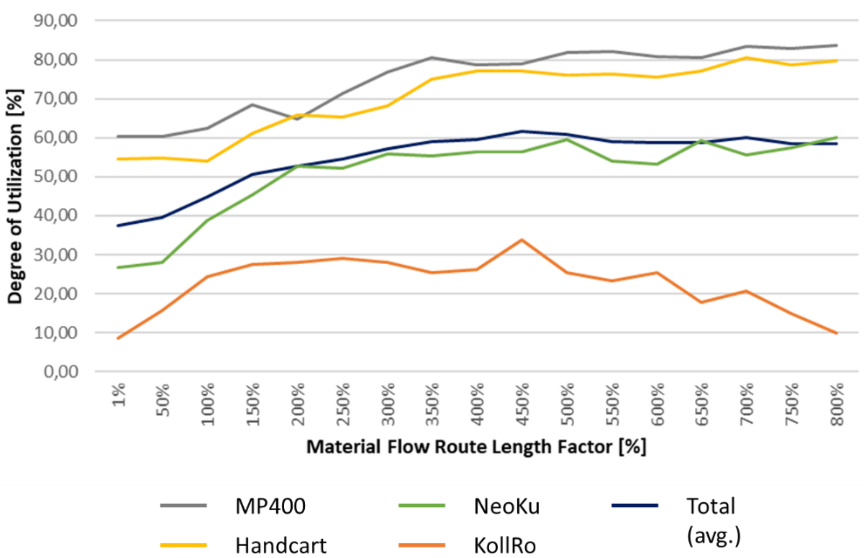


Figure 6-6: Influence of the material flow route on the degree of utilisation of the means of transport

6.2 Throughput Flexibility

6.2.1 Means of Transport Speed

In the context of throughput flexibility, this simulation study examines two factors. The first is the speed of the means of transport in the intralogistics system. In the simulation, the speed of all means of transport is altered in percent. This way, the effects on the system's behaviour can be analysed. The x-axis of the following figures in this section are in percentages; 100% represents the initial state. By analysing the speed of the means of transport, a general understanding of the current situation can be gained (e.g. with regard to restrictions caused by the speed of the means of transport). This knowledge can then be used to better plan or optimise the system regarding the speed of the means of transport. If, for example, the current operating point of the system is close to the maximum utilisation, an increase in speed would have no benefit in terms of throughput or output.

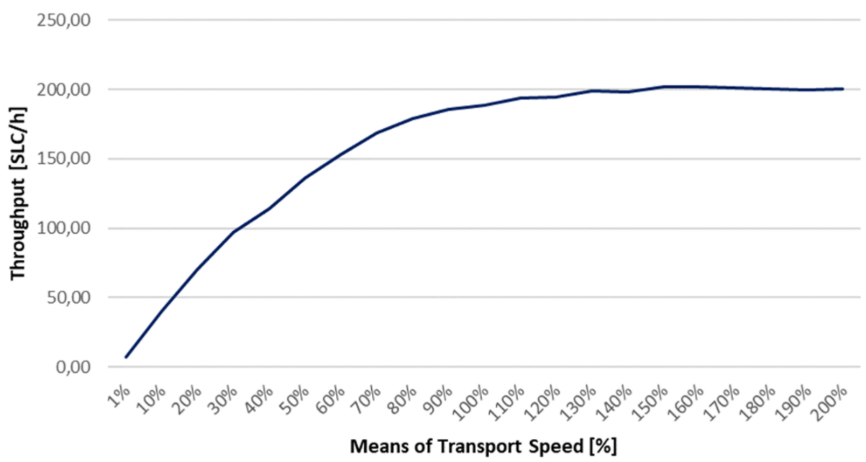


Figure 6-7: Influence of the means of transport speed on throughput

As mentioned above, the individual speeds of the means of transport were adjusted in percentage during the analysis of the influence of the speed of the transporter on the system. The results were recorded at intervals of 10% and ranged from 0% to 200%. Contrary to the hypothesis, the overall throughput of the system showed a degressive trend (see Figure 6-7). The linear relationship of the throughput assumed in the hypothesis was due to Formula 3.1. Thereby, the theoretical throughput behaviour of an isolated material flow route was projected onto the system. This determination by the formula resulted in an idealised correlation of speed with the theoretical throughput. However, in the context of this simulation study, the actual throughput is considered. Therefore, similar to the layout flexibility, the throughput is limited by the material retrieval method to a maximum of 200 load carriers per hour. In the case of the simulation model and thus Werk150, this limit is reached at x1.3 the actual speed of each means of transport. As a result of the degressive function, changes in the velocity of the means of transport at higher speeds have only a slight effect on the throughput compared to those at lower speeds.

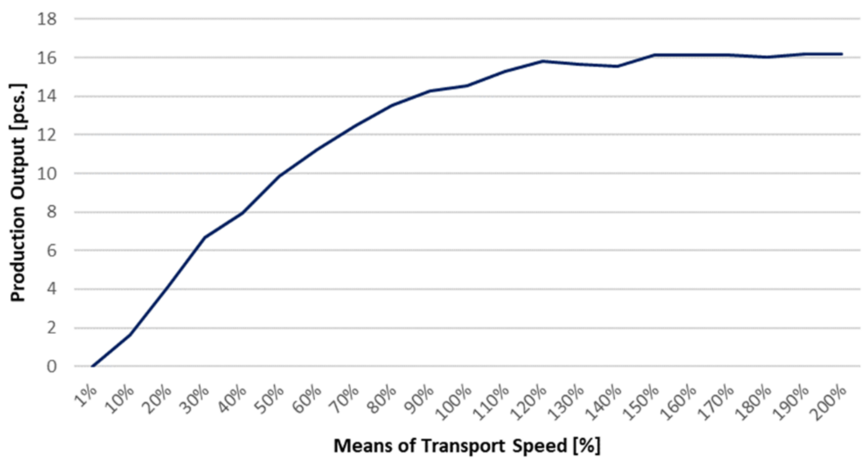


Figure 6-8: Influence of the means of transport speed on production output

With regard to production output, the intralogistics system behaves similarly as with throughput (see Figure 6-8). By means of the accumulated data points, a degressive graph could be demonstrated. Whilst the hypothesis was based on the assumption that the output increases more significantly with an increasing speed of the means of transport, the simulation demonstrated exactly the opposite behaviour. Changes in the speeds of slow means of transport have a stronger effect on the production output than those operating at higher speeds. Ultimately, a plateau is established for high speeds which corresponds exactly to the maximum output of the production system under the limitations already mentioned above.

In the case of the degree of utilisation of the system or the individual means of transport, the hypothesis was confirmed that the respective degree of utilisation decreases with increasing speed (see Figure 6-9). The graph shows a regressive trend. Thereby, the means of transport or the system have their highest utilisation rate at lower speeds. In addition to the general confirmation of the hypothesis about the trend, a further finding was identified. With increasing speed, a plateau emerges for the degree of utilisation around 40%. This has been furthermore confirmed by extreme value tests. It is assumed that the transport system is approaching both its kinematic limits (i.e. the acceleration and deceleration of the means of transport) and those of the production system. The degree of utilisation achieved thus corresponds to the system-inherent base utilisation to comply with the existing production process. The same degree of utilisation of the plateau can also be seen in Figure 6-6 for extremely short material flow routes, underlining the aspect of the system-inherent base utilisation.

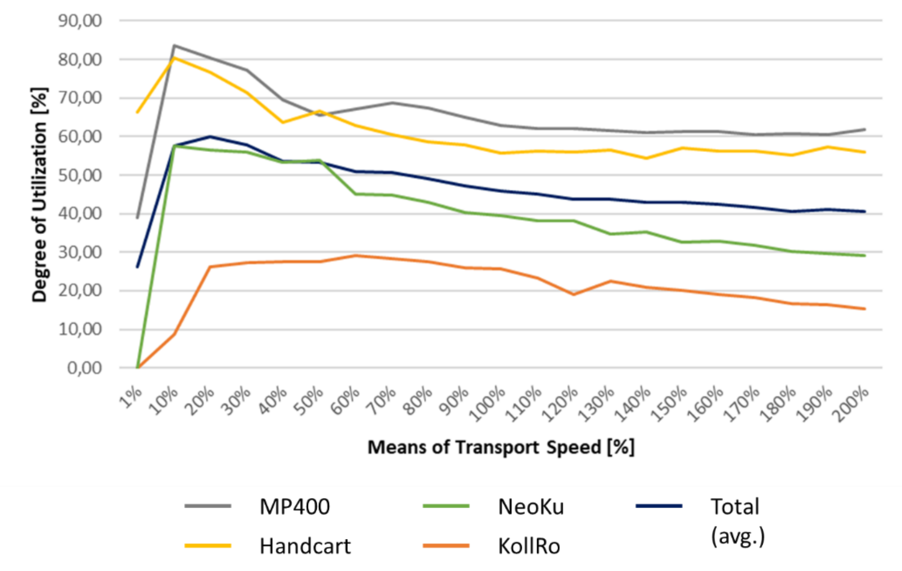


Figure 6-9: Influence of the means of transport speed on the degree of utilisation of the means of transport

6.2.2 Means of Transport Capacity

In addition to the influence of the speed of the means of transport on throughput, output, and degree of utilisation, the influence of the transporter capacity was also examined within the scope of throughput flexibility. In the simulation model, the means of transport capacity determines the number of load carriers which a vehicle can transport. Thereby, the number of SLCs to be transported is not directly defined, but the area on which SLCs can be placed is. The MP400 or the handcart, for example, can transport up to two SLC 4030s at once. Due to the dimensions of the load carriers, a required storage area of 1,200 cm² per load carrier results. Accordingly, a maximum storage area of 2,400 cm² is specified for the two means of transport. In addition to the storage space, further means of transport-specific premises can be defined, such as the sole transport of product fixtures by the MP400 and handcart. This has the advantage that capacity changes to the means of transport can also be simulated in intermediate stages. Furthermore, new load carrier types with different or individual load carrier dimensions can be simulated and mapped.

To assess the effects of the transport capacity on the overall system, the simulation is conducted in stages with different capacity percentages. The x-axes of the following diagrams are thus given in per cent. By simulating the capacity, it is possible to make both systemic and transport-specific statements (e.g. whether or not an increase in capacity is appropriate for a particular means of transport). Furthermore, the simulation of the capacity can also provide information on whether the current system can cover future requirements with its capacities. If this is not the case, it is possible to simulate which means of transport must be upgraded, replaced, or supplemented.

Table 6-1: Simulated means of transport capacities and their related SLC slots

	25%	50%	75%	100%	125%	150%	175%	200%
MP400	0.5	1	1.5	2	2.5	3	3.5	4
Handcart	0.5	1	1.5	2	2.5	3	3.5	4
NeoKu	0.25	0.5	0.75	1	1.25	1.5	1.75	2
KollRo	8	16	24	32	40	48	56	64

Not only for throughput but also for the output and degree of utilisation, several prominent steps can be seen. These steps can be explained with the help of Table 6-1, which shows the SLC slots of each individual means of transport in relation to the simulated percentage. Therein, it can be seen that the two production-relevant means of transport MP400 and handcart can only transport a complete A-part SLC at a capacity of 50%. This transportation ensures the production of a city scooter in the first place. When looking at the throughput of the system over the means of transport capacity, three main steps can be seen (see Figure 6-10). The first step is the initial increase in throughput, which comes from the two vehicles MP400 and handcart, as described above. The second major step in throughput can be observed when the NeoKu with its first slot is used in combination with the doubled transporter capacity of the other two vehicles. With a further increase in the transporter capacity, it can be seen that there is no increase in throughput. The MP400, handcart, and KollRo now operate at a capacity level, at which no effects on throughput can be realised. However, with a second SLC slot for the NeoKu, a slight increase becomes apparent.

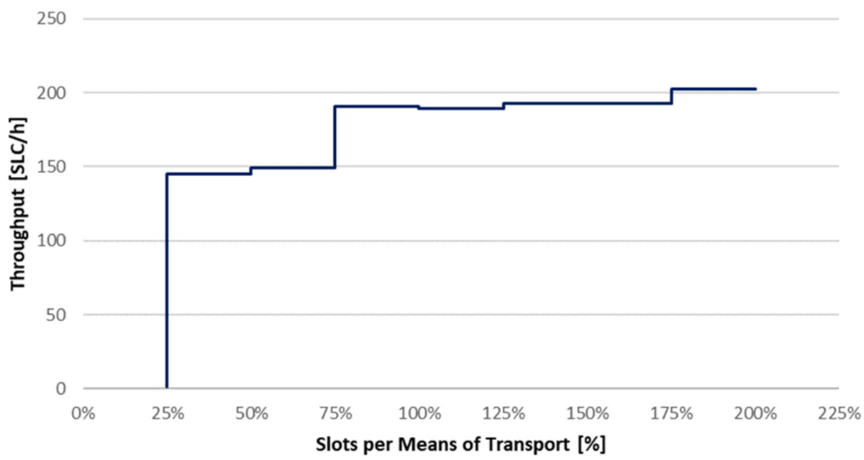


Figure 6-10: Influence of the means of transport capacity on throughput

Similar to the throughput, a graph with three steps can be created for the production output (see Figure 6-11). In the first step, an average of slightly more than 10 city scooters is mounted. The second stage reflects the initial system, in which about 15 city scooters are mounted. Only after the second SLC storage space in the NeoKu (in the third stage) can a further increase in output be seen. At this stage, the maximum output of the system in this configuration is reached, and a total of 16 city scooters can be assembled.

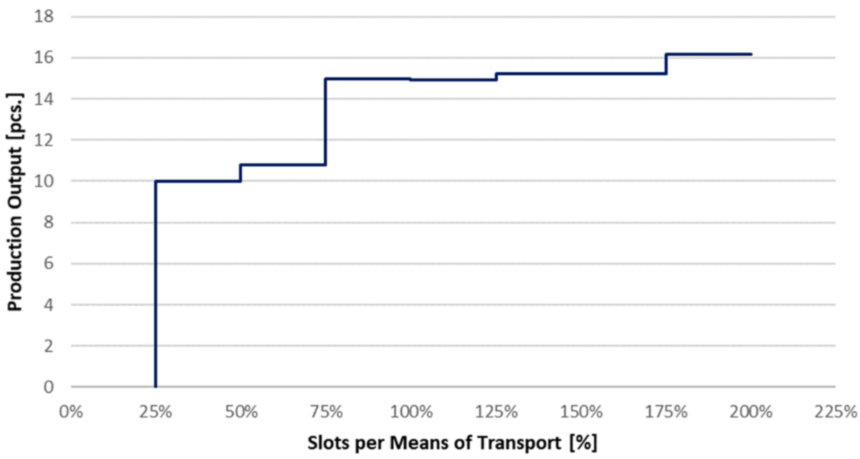


Figure 6-11: Influence of the means of transport capacity on production output

The last diagram shows the effect of transport capacity on the system's degree of utilisation as well as on the individual means of transport (see Figure 6-12). Again, the three steps can be identified to a certain extent. This chart also illustrates that effects on the means of transport as well as on the system can only be observed in certain configurations. For a low capacity (< 100%), the utilisation of the MP400 and handcart is very high. These are the only means of transport which can transport load carriers and product fixtures. As the output to city scooter is low in this configuration, fewer C-parts are required, so the utilisation of the KollRo is initially low. With a transporter capacity of more than 100%, the NeoKu supports the MP400 and handcart, which, in turn, reduces their utilisation. As a result of the increased production output, the consumption of C-parts rises, which ultimately increases the collaborative tugger train's degree of utilisation. With a transport capacity of 200%, the utilisation of the MP400 and handcart remains the same. This means that an increase in capacity will not lead to a lower degree of utilisation. The second added SLC slot for the NeoKu, however, leads to a reduction in its degree of utilisation. Lastly, as again more load carriers can be transported, the degree of utilisation of the KollRo increases as more city scooters can be assembled.

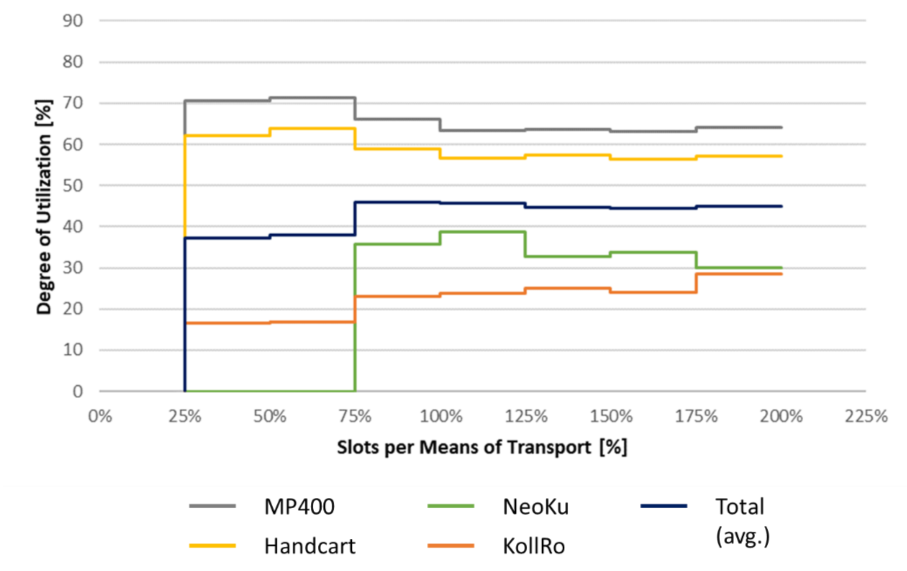


Figure 6-12: Influence of the means of transport capacity on the degree of utilisation of the means of transport

6.3 Product Flexibility

6.3.1 Load Carrier Dimensions

The last flexibility parameter for material flow systems is product flexibility, which is influenced by the product weight and dimensions. As the influence of the product weight can be statically determined by means of a limit value observation, only the product dimensions are considered in the course of the analysis. The products of the material flow system are the load carriers, which can vary in size. Consequently, any type of load carrier can be simulated in the built-up simulation model. In addition, it enables the simulation expert to change the load carrier type of an individual component to map special transport processes. With the simulation of this factor, valuable knowledge about the system behaviour can be gained, especially in planning but also in optimisation. For example, larger load carriers with higher filling quantities can be simulated for individual components. Whilst the findings for a 1:1 material flow could still be determined statically, this is no longer the case for complex n:n material flows. This is especially not the case if a large number of means of transport can perform this transport and where the allocation is done dynamically. Within the scope of this research, however, only two system configurations are considered. The first represents the initial system, in which all A-parts are contained in an SLC 4030 and all C-parts in an SLC 3020. The second configuration assumes a proportional size change. According to this, all A-parts are transported in an SLC 6040 and all C-parts in an SLC4030. In this configuration, both the MP400 and handcart, as well as the KollRo, can continue to operate. Only the NeoKu is violated in its transport restrictions, which leads to a failure of the transport device.

When considering the throughput over the two simulated load carrier dimensions, the effects of the doubled number of components can be seen (see Figure 6-13). Whilst in the first configuration, the throughput was approximately 190 SLC per hour, in the second configuration, it is only 152 SLC per hour. The assumption described in section 3.4.5 could thus be confirmed.

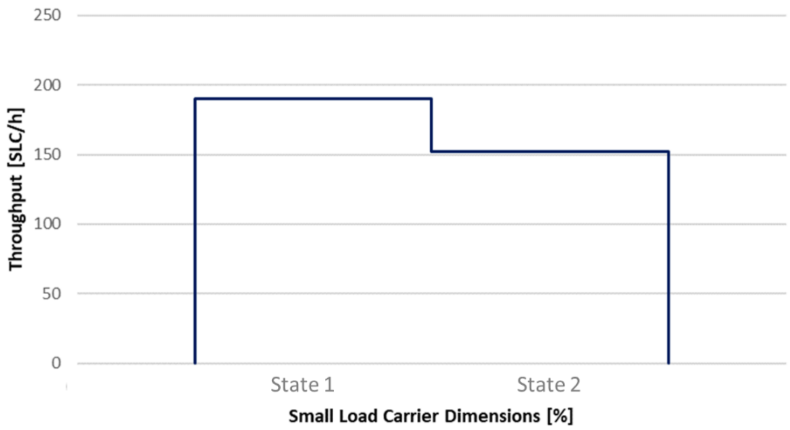


Figure 6-13: Influence of the product dimensions on throughput

In terms of production output, an interesting effect can be seen (see Figure 6-14). Contrary to the previous relationship between low throughput and low output, a constant output is apparent due to the double number of components in the larger load carriers. In concrete terms, this means that the number of transports and thus the systemic throughput can be minimised at the same output if the load carriers double in size and thus filling quantity.

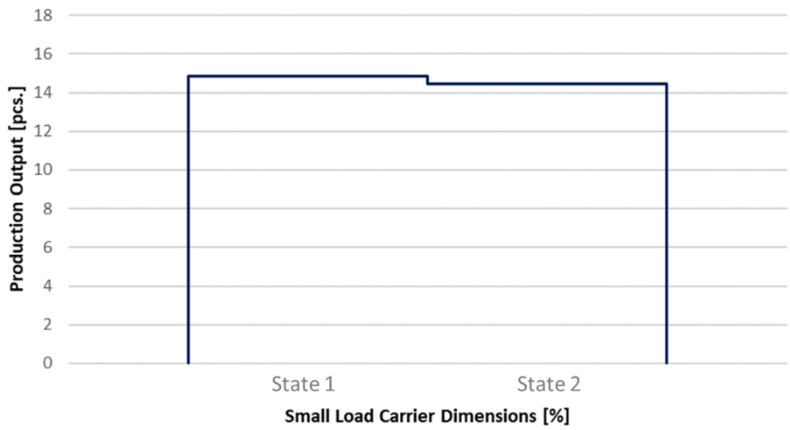


Figure 6-14: Influence of the product dimensions on production output

The last factor examined with regard to the effect of changes in the load carrier dimensions is the degree of utilisation (see Figure 6-15). For the initial state, the known degrees of utilisation are shown. The system is, for example, utilised to an average of 45%. If the load carrier dimensions change, the system is in the second state, where it can be seen that the degree of utilisation of the MP400 and handcart increases slightly. This increase is due to the fact that the NeoKu is not operational for this configuration. Its degree of utilisation is therefore 0%.

In addition to this effect, another one emerges for the KollRo. Its degree of utilisation is reduced for larger load carriers as it is only responsible for the C-parts supply. These components have a filling quantity anyway. If these are doubled in the case of a larger load carrier, material orders over the simulation period are significantly lower.

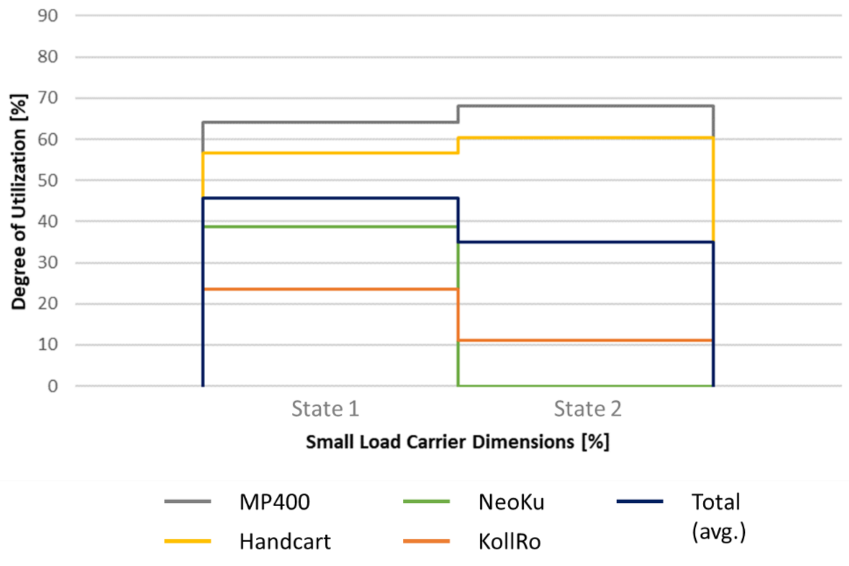


Figure 6-15: Influence of the product dimensions on the degree of utilisation of the means of transport

After the system-specific behaviour of the flexibility parameters and their influencing factors have been analysed with the help of the simulation model, the results can now be applied to the practical problem.

6.4 Practical Application of the Simulation Results

As already described in chapter 1.1 and 1.2, intralogistics material flow systems are characterised by constant change. The challenges of turbulent markets and constantly changing requirements can be managed by making the system flexible in the three dimensions of layout, throughput and product. However, it is often not possible to meet these requirements, as maintaining a high and unused flexibility capacity is very expensive. Planning or evaluation methods that effectively and efficiently support companies to determine the required degree of flexibility do not exist. With the knowledge gained about the individual behaviour and effects of the flexibility parameters on the intralogistics system, companies are now in a position to better plan strategic decisions regarding the activation of flexibility potentials. In doing so, current as well as future market requirements are combined with the simulation results to define optimal investment times for system expansion. In the following, an exemplary strategic planning process is described.

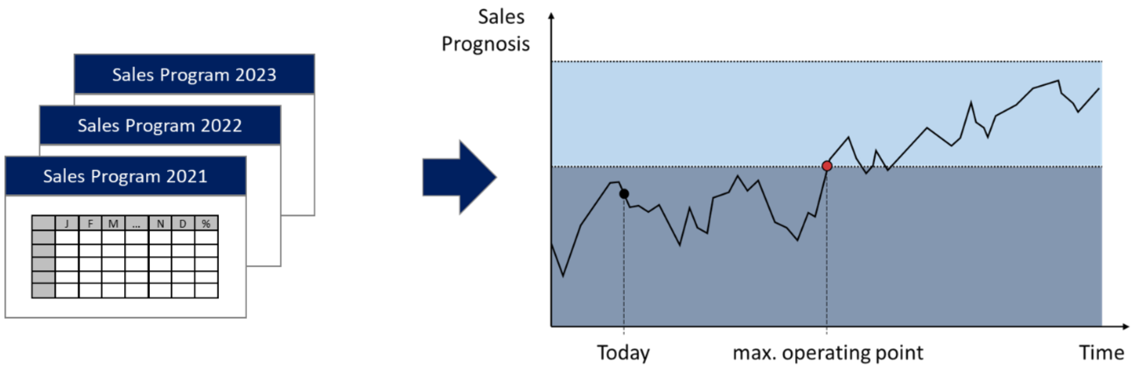


Figure 6-16: Sales forecast with maximum operating point of the intralogistics system

At the beginning of strategic planning, the current sales figures and forecasts from the sales department are required. The data should include current and future required product quantities with the corresponding product mix. Subsequently, the figures are graphically displayed in a line chart over the years. For a first analysis regarding the operating time of the current intralogistics material flow system without technical adjustments, the maximum operating point regarding the production output is marked in the sales forecast (see red dot in Figure 6-16). Furthermore, a horizontal line that intersects the maximum operating point is drawn to show the maximum production capacity of the system over time (see dark blue area in Figure 6-16). Due to the assumption of producing at full capacity in the simulation, the maximum operating point represents the initial state of the system. The resulting maximum operating time is valid under the assumption that the product mix is unchanged. A more precise forecast of the maximum operating time results from a renewed simulation with the correspondingly adjusted future product mix. With the information about the time until the current production capacities are fully reached without any changes, companies can now start to make provisions at an early stage and plan scenarios for capacity or system expansions. Assuming that the product mix remains unchanged, planners can use the knowledge about the system impact of each flexibility parameter and influencing factor to assess which system adjustment is most effective and economical (see light blue area in Figure 6-16): increasing or decreasing reachability, material flow routes, means of transport speed or capacities, product dimensions, or product weight. Should the product mix or required components change in the forecasts, the simulation model can be adapted individually and easily via the databases and processes as described in chapter 4.4. Ultimately, companies are able to efficiently asses the volatile market requirements in terms of their intralogistics material flow system capacities to initiate corresponding measures at an early stage. Thus, it is possible to control change.

Chapter 7 Summary, Conclusion, and Outlook

This chapter gives the reader a brief overview, in three sections, of the research conducted in this thesis. For this purpose, the first section summarises the individual chapters with regards to their content. The second section describes the approach used and the respective results of the research questions defined in section 1.2. Ultimately, the chapter concludes with an outlook on further research projects.

7.1 Research Summary

The environment in which logistics systems operate today is characterised by uncertainty and constant changes due to rising demand for customised products, short product lifecycles, and a large number of variants. To cope with the increasing complexity, logistics systems and in particular intralogistics material flow systems require a high degree of flexibility in three dimensions, namely layout, product, and throughput. As the literature review reveals, the three parameters are described in their scope, however, their effects on an intralogistics material flow system are unknown. Therefore, exact planning or evaluation of the degree of flexibility is not possible.

To examine the behaviour of these parameters, the most important terms were first defined with regard to their scope. Besides intralogistics and material flow systems, this also included various flexibility taxonomies, reactability, changeability and versatility. According to the conducted literature review, various influence factors for the flexibility parameters were identified.

Based on these results, a new definition was developed for each parameter, which determines the influencing factors to be investigated. Subsequently, hypotheses regarding their behaviour in intralogistics systems were formulated, which were investigated within the scope of a simulation study.

The framework of the simulation study is formed by the logistics learning factory Werk150 of the ESB Business School at the campus of Reutlingen University. After a system analysis with regard to the products, components, processes, and the means of transport used, a concept model was developed. In a further step, the model was formalised with the help of the Unified Modelling Language. Thereby, the key elements of a simulation model for analysing the behaviour of flexibility parameters were represented using a class diagram. Afterwards, the formal model was implemented in the simulation software AnyLogic.

To ensure that the simulation model adequately represents the real intralogistics system and that the simulation results to be obtained are valid, reliable and precise, different verification and validation methods were performed. This also included practical experiments in the Werk150, which demonstrated in various cases that the simulation model reflects the real system.

Ultimately, the analyses on the behaviour of the three flexibility parameters for layout, throughput and product were carried out. The effects on the intralogistics material flow system were measured based on the actual throughput, the production output, and the degree of utilisation of the means of transport. The results showed that the hypotheses could be confirmed in almost all aspects. Furthermore, the data provided information about the remaining flexibility potential in the system and where the limit to changeability is located. In general, it can be seen that the performance of the system increases significantly with increasing flexibility. By implementing the simulation model and results into a strategic planning process, it is possible to efficiently plan the activation of the required flexibility potential. Thus, the system is able to meet the constantly changing requirements of dynamic and turbulent market environments.

7.2 Conclusion of the Research Results

This section summarises the results of the primary and secondary research questions and presents the key findings and conclusions of this research.

PRQ	How does the level of layout flexibility, throughput flexibility, and product flexibility affect an intralogistics system in terms of its logistical throughput, production output, and degree of utilisation regarding the means of transport?

The behaviour of the flexibility parameters for layout, throughput, and product in intralogistics material flow systems was investigated within the framework of a simulation study. The key figures for the impact of a parameter on the system are the logistical throughput, the production output, and the degree of utilisation of the means of transport. For the simulation model, the logistics learning factory Werk150 was chosen as a reference system. At Werk150, two different variants of city scooters are assembled in eight different workstations, involving four means of transport as well as a variety of different components and load carrier types. Due to its equipment and processes, the system is ideally suited for the purposes of the study.

With the simulation model successfully developed, verified, and validated, the effects of the behaviour of the individual parameters on the system were investigated. The results of the investigations show that the characteristics of the flexibility parameters are system-specific. This is particularly noticeable in the observations of the degree of utilisation of the used means of transport. When prioritising the respective vehicles differently, the individual degree of utilisation varies. However, general trends are recognisable, the patterns of which also apply to other intralogistics material flow systems. For instance, an increase in layout, throughput, and product flexibility is associated with an increase in performance with regard to throughput and output. In addition to the system-specific knowledge regarding the behaviour of the three flexibility parameters within an intralogistics system, the results of the simulation study can also be used to derive changeability of the respective intralogistical material flow system. This can be determined by simulating a full layout, throughput, and product-flexible system. As a result, information can be provided on what the technical side of an intralogistics systems is capable of without spatial changes (e.g. to workstations).

SRQ1	How are the flexibility parameters for layout, throughput, and product defined in terms of their influencing factors?

To answer the secondary research question, existing definitions of these three flexibility parameters were analysed by means of a literature review. The research showed that there is no uniform definition for these parameters. Therefore, based on the existing definitions, new uniform ones were developed. A material flow system can be considered as fully layout-flexible if any material flow route in the system can be used to transport goods from different sources to different sinks in order to keep the corresponding machines operating as required. As main influencing factors of layout flexibility, the reachability of the individual sources and sinks as well as the length of the material flow route were defined. In terms of throughput, the system should be able to cope with fluctuations by means of appropriate and economic measures such as additional operational resources and increased transporter speed or capacities. In this thesis, the means of transport speeds and capacities are considered as the main influencing factors. Lastly, a product-flexible material flow system should be able to transport a range of products and variants without setup processes. Thus, the products can differ in terms of their dimensions and weight. Both of these requirements represent the main influencing factors on product flexibility.

SRQ2	How must a simulation model be structured to analyse the material flow system-specific potentials of the three flexibility parameters regarding layout, throughput, and product?

In the course of the formalisation and implementation of the simulation model in the simulation software AnyLogic 8.6.0 Personal Licence Edition, it became apparent that a simulation model for the analysis of the flexibility parameters must be structured analogously to the class diagram in Figure 4-1. The core aspects are the classes for the means of transport, load carriers, workplaces, and transport orders. They define the fundamental structure and parameters for the analysis, such as load carrier dimensions and weight, means of transport speed and loading capacity, existing sources and sinks, and transport order generation, which have a decisive influence on the behaviour of the flexibility parameters in intralogistics material flow systems.

By using suitable IT infrastructure such as databases, the simulation model can be designed in a highly modular way to have a wide range of applications. In concrete terms, this means that the user can change the means of transport or load carriers in the simulation model without much effort. Thus, several use cases can be simulated and assessed.

7.3 Outlook

In the course of analysing the behaviour of flexibility parameters in intralogistics systems, a number of limitations were identified. These limitations provide the basis for further research activities, allowing a more efficient determination of the limits and the degree of flexibility in material flow systems. These topics are further described and presented below.

Optimisation of the flexibility parameter analysis: The analysis of the three flexibility parameters can be further improved by integrating an automated parameterisation of the simulation model. The user can be provided with the option of defining the analysis spectrum of all three flexibility parameters via a Graphical User Interface (GUI) to automatically carry out the relevant simulation runs and evaluations. By doing so, new parameters do not have to be set manually. Furthermore, the use of virtual computing resources, such as cloud computing, can significantly shorten the overall simulation runtime in order to efficiently investigate new system configurations in the planning process of material flow systems.

In addition to the automatisation, it would be conceivable to extend the simulation model by importing existing CAD layout files, which would enable a more realistic simulation in terms of material flow routes, distances of sources and sinks, or reconfiguration of the workstations of the production system.

Development of new planning methods: As described in the problem definition, there is no planning method for material flow systems which takes all three flexibility parameters into account. In the context of this thesis, it was demonstrated that the effects of the flexibility parameters on material flow systems can be determined by an adequate design of the simulation model. Consequently, in a further research project, the findings from this simulation study could enhance the planning process by adding, for example, a flexibility planning phase. In this phase, the degree of flexibility required to comply with the future sales programme can be determined. This enables an efficient and future-oriented intralogistics material flow system to be planned.

In addition to the new planning of such systems, the re-planning of existing material flow systems can also be part of this method. In particular, companies with a high-variant, small-series production could determine their flexibility limits, identify weak points, and generate suitable and future-oriented solutions by means of simulation.

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Appendix A
Analysis of Planning Methods for Material Flow Systems

In the following, a comprehensive literature analysis of existing planning methods for material flow systems which incorporate flexibility was performed. The analysis should underline the research claim that there is no planning method for material flow systems which accounts for all three flexibility parameters for layout, throughput, and product.

For this analysis, the method of a semi-systematic literature review was chosen to find all planning methods in the English literature. To enhance the quality of the gathered results, an additional German literature review was conducted (see Figure A-1). The results were then analysed with regard to the three defined parameters of layout, throughput, and product flexibility (chapter 3).

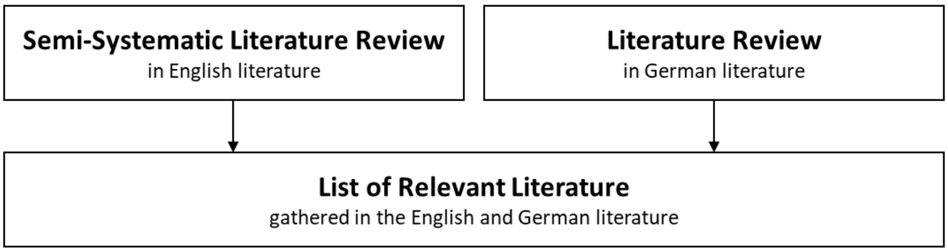

Figure A-1: Literature review process conducted in English and German

A.1 Methodology of the Semi-Systematic Literature Review

The first step in the semi-systematic literature review involved initial research on planning methods for material flow systems. From this review of articles, papers, books, and dissertations, relevant key terms were defined. In a second step, related scientific research databases were identified and evaluated. The main criteria for the evaluation of adequate databases were the degree of thematic coverage, peer-reviewed publications, and good analysis/filtering functionalities. After selecting the scientific research databases, the search strings were derived from the gathered key terms.

In the fourth step, the search algorithm must be developed, validated, and eventually optimised using the previously defined search strings. For validation, the algorithm was entered into the database. If the results represented relevant literature, the algorithm was validated. Otherwise, optimisations should be made.

After finalising the search algorithm, the search in the relevant databases was conducted. Thereby, the algorithm looked for the key terms in all metadata (title, author, abstract, full text, etc.). The result of this search was a broad list of topic-related literature which must be further filtered. Therefore, the next step of the semi-systematic literature review was the application of the search algorithm only on the metadata abstracts and filtered for open-access publications. The selection for these search settings was mainly that authors with relevant publications would also use the key terms in their abstracts. Moreover, by adding the open-access criteria, only publications with full texts were provided. If there was any publication on the list of topic-related literature which did not fulfil the criteria, it was automatically excluded from the reviewing process. All other publications were then obtained and roughly examined in terms of planning methods for material flow systems. Publications which included planning methods were analysed in more detail and selected for the final list of relevant literature. All others were excluded from the reviewing process. Figure A-2 provides a holistic overview of the conducted semi-systematic literature review.

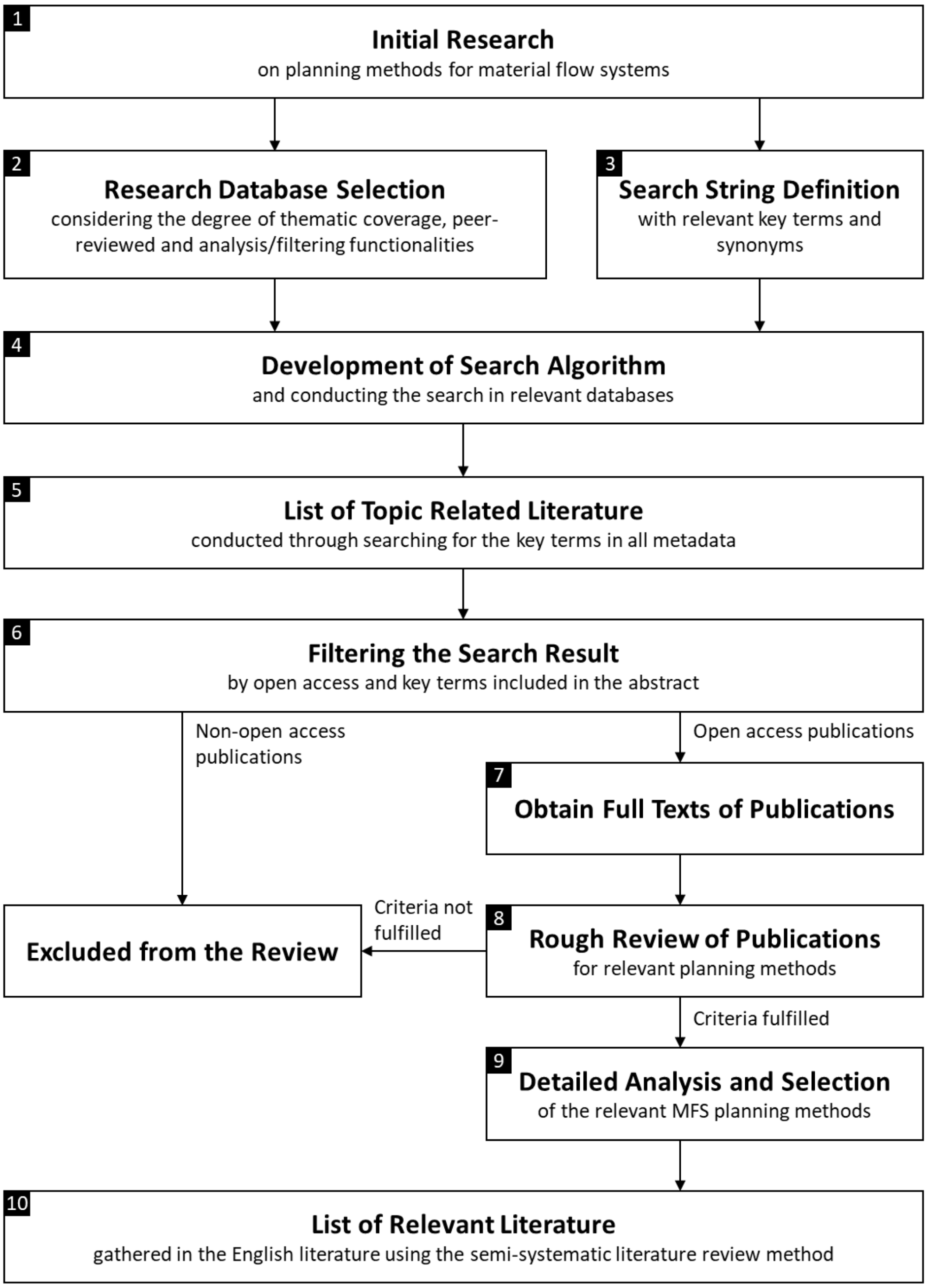

Figure A-2: Processes of the semi-systematic literature review of English literature

A.2 Conducting the Literature Reviews

The first literature review conducted was the semi-systematic one on English literature. In the initial research, the review of topic-related scientific articles, papers, and books led to the following list of relevant key terms: *logistics*, *intralogistics*, *material flow*, *production*, *planning*, *flexibility*, *and versatility*. The term *planning method* was deliberately not included because it would limit the results by, for example, excluding phrases such as ‘method for planning’.

In the second step, in addition to defining the key terms, the analysis and selection of adequate databases led to the following scientific research databases: IEEE Xplore, Emerald Insight, ScienceDirect, and Sage Journals. All databases have a peer-review process, assuring the quality of the publications, and offer a wide variety of analysis, filtering, and export options. Furthermore, the degree of thematic coverage was validated by the total number of 1,496,235 results[11] in all four databases with the list of previously defined key terms, excluding 'flexibility' and 'versatility'.

After selecting the databases and defining the key terms, the third step was the definition of the search strings by splitting the list of key terms into three search term groups. The first group included *logistics, intralogistics, material flow,* and *production*. The second group was solely comprised of the term *planning,* whereas the last search term group included *flexibility* and *versatility*. Based on these search terms and their groups, 11 search strings were developed (see Table-A1). It should also be noted that the search string 'Production AND Planning' was logically excluded since relevant literature should at least include the terms *logistics, intralogistics,* and *material flow*. Thus, all relevant publications for production planning and planning material flow systems were already included in search strings 1, 4, and 7. The search algorithm was validated by obtaining a total of 1,216,108 publications with all 11 search strings found in all metadata. These publications also represented the list of topic-related literature.

Table A-1: Search strings developed for the semi-systematic literature review

No.	**Search term 1**		**Search term 2**		**Search term 3**
1	Logistics	AND	Planning		
2	Logistics	AND	Planning	AND	Flexibility
3	Logistics	AND	Planning	AND	Versatility
4	Intralogistics	AND	Planning		
5	Intralogistics	AND	Planning	AND	Flexibility
6	Intralogistics	AND	Planning	AND	Versatility
7	Material Flow	AND	Planning		
8	Material Flow	AND	Planning	AND	Flexibility
9	Material Flow	AND	Planning	AND	Versatility
10	Production	AND	Planning	AND	Flexibility
11	Production	AND	Planning	AND	Versatility

The sixth step of the semi-systematic literature review was filtering the list of topic-related publications. For this purpose, the search strings were only applied to the metadata abstracts and filtered by open access. With these settings, 964 relevant publications with the full texts available were obtained. As a next step, all duplicates were removed, leading to a total of 832 possible relevant publications. Figure A-3 shows, on a logarithmic scale, the numbers of publications during the filtering process.

[11] IEEE Xplore: 17.350, Emerald Insight: 105.934, ScienceDirect: 884.852 and Sage Journals: 488.099

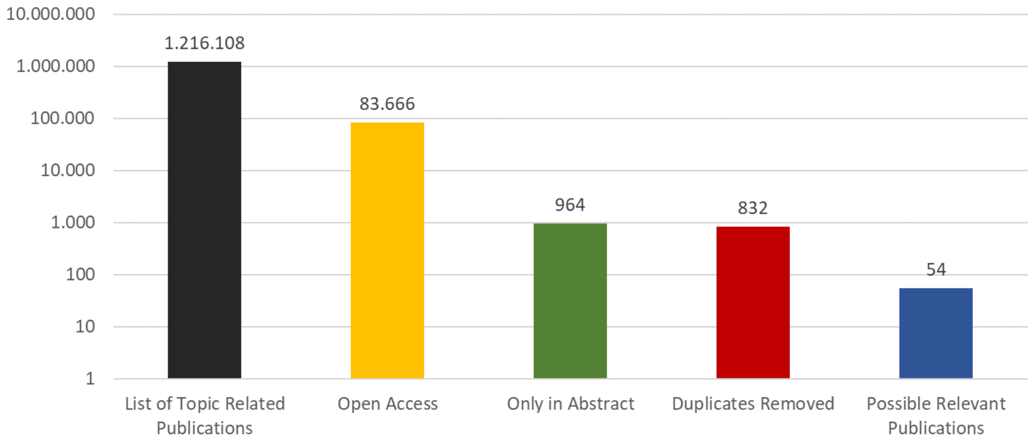

Figure A-3: Topic-related publications identified during the filtering process

In a next step, all 832 publications were reviewed by looking at the title and reading the abstract. This process led to a total of 54 full texts to be analysed in more detail. All other 778 peer-reviewed publications were excluded for not fulfilling the criteria of mentioning a planning method for material flow systems. The result of the next-to-last step in the semi-systematic literature review, the detailed analysis and selection, was exactly one publication including a planning method for material flow systems. The other 53 publications mostly focussed on enhancing the flexibility of a company by incorporating Reconfigurable Manufacturing Systems (RMS). As these methods solely address the production process and do not consider logistical processes, they were excluded from the list of relevant literature.

The second literature review to be conducted was the one in German to further enhance the results of the semi-systematic English literature review. By analysing relevant authors, books, and papers with the German translation of the aforementioned key terms, seven additional planning methods were found.

A.3 Results Analysis

As a result of the two conducted literature reviews, a total of eight planning methods for material flow systems were identified. Such a low thematic coverage even at the international level demonstrates the relevance, and underlines the research gap, of this work.

In the course of the analysis of the three flexibility parameters in the planning process, all eight planning methods were examined in depth. This involved checking whether the influencing factors from the definition of the respective flexibility parameter were incorporated into the planning phases. Thus, it was examined whether alternative transport routes (lengths) or changes in the source/sink relationship were considered in the context of layout flexibility. Regarding the throughput flexibility, it was checked whether additional load carrier capacities or changes in the speed of the used means of transport were considered. Lastly, with regards to the product flexibility, it was determined whether changes in the product dimensions or weight were considered.

As can be seen in Table A-2, no single planning method for material flow systems takes all flexibility parameters into account. Only the method developed by Dürrschmidt and the Verein Deutscher Ingenieure VDI account for two factors: product flexibility and throughput flexibility. In the methods of Ten Hompel et al. and Martin, throughput flexibility is considered. The methods from Allgayer, Gudehus, Jünemann and Koechling et al. do not incorporate any of the three flexibility parameters. Ultimately, none of the eight planning methods consider layout flexibility at all.

Table A-2: Results of the analysis regarding the three flexibility parameters

No.	**Author**	**Layout Flexibility**	**Product Flexibility**	**Throughput Flexibility**
1	Allgayer (1999, p. 25)	○	○	○
2	Dürrschmidt (2001, p. 94)	○	●	●
3	Gudehus (2010, p. 70)	○	○	○
4	Ten Hompel et al. (2018, p. 348)	○	○	●
5	Jünemann (1989, p. 556)	○	○	○
6	Koechling et al. (2016, p. 194)	○	○	○
7	Martin (2014, p. 456)	○	○	●
8	VDI 2498:2011-08 (VDI 2498:2011-08)	○	●	●

Appendix B
Statistical Evaluation of the Simulation Model

This section describes the procedure of the internal validity test, which was carried out as part of the verification and validation of the simulation model in chapter 5. It first describes the generic procedure of a paired t-Test according to Rasch et al. (2010, p.43–53) and then analyse the simulation model of the Werk150.

B.1 Procedure for Carrying out a Paired t-Test

Within the scope of the paired t-test, two population means of two observations (measurement series) are compared with each other. The aim is to determine whether a difference in the results is only random or described by a certain significance. In order to do so, the sample size n is first defined, which is the same in observation x and observation y. The sample size n is the same in both observations. Next, the calculation is as follows:

1. Calculation of difference d between the two observations y and x of each pair i

$$d_i = y_i - x_i \tag{B-1}$$

2. Calculation of the mean difference $\bar{d}$
3. Calculation of the standard error of the mean difference $SE(\bar{d})$, using the standard deviation of the differences s_d

$$SE(\bar{d}) = \frac{s_d}{\sqrt{n}} \tag{B-2}$$

4. Calculation of t-statistic T, which follows a t-distribution with $n - 1$ degrees of freedom

$$T = \frac{\bar{d}}{SE(\bar{d})} \tag{B-3}$$

5. Comparison of T value to t_{n-1} distribution, which in turn gives the p-value

B.2 Conducting the Paired t-Test

As described in the procedure above, at first the two measurements series are recorded. Both series use a different simulation seed in order to vary the random numbers required for the arbitrary fill levels of the SLCs in the model. The fluctuations between each measurement value of series are a result of the randomized fill levels of the small load carrier in the production process. In addition, three variables are recorded per measurement series. Thus, the t-test is carried out a total of three times for throughput, output and degree of utilisation. After aggregating the individual measurements, in a next step the difference is calculated for each pair and parameter (see Table B-1). Subsequently, the mean difference for throughput, output and degree of utilisation is determined. Based on the standard deviation of the differences s_d and the root of the sample size n, the standard error of the mean differences $SE(\bar{d})$ can be calculated. Ultimately, the t-statistic T is determined for each parameter and compared to the t_{30-1} distribution, as $n = 30$.

Table B-1: Recorded measurement series and calculation of the difference

No.	Measurement Series 1			Measurement Series 2			Difference		
	Throughput	Output	Utilization	Throughput	Output	Utilization	Throughput	Output	Utilization
1	190	15	47.513	197	16	43.894	7	1	-3.619
2	192	14	45.878	189	16	45.406	-3	2	-0.472
3	182	15	43.798	170	11	40.820	-12	-4	-2.978
4	166	11	38.388	187	15	42.556	21	4	4.167
5	187	15	45.864	192	15	47.465	5	0	1.601
6	196	15	46.639	185	14	45.909	-11	-1	-0.730
7	167	11	39.863	195	15	44.251	28	4	4.388
8	152	9	34.836	203	16	49.367	51	7	14.531
9	173	11	43.835	189	15	48.155	16	4	4.320
10	187	16	44.812	188	16	45.435	1	0	0.623
11	192	15	47.408	199	16	50.002	7	1	2.594
12	187	15	44.350	188	15	45.314	1	0	0.965
13	186	15	44.979	192	15	46.804	6	0	1.825
14	186	15	46.672	196	16	47.670	10	1	0.998
15	193	15	48.629	191	13	44.812	-2	-2	-3.817
16	190	15	45.465	189	15	46.414	-1	0	0.950
17	188	15	45.211	192	15	45.368	4	0	0.157
18	195	15	48.234	186	14	44.431	-9	-1	-3.803
19	196	16	48.895	201	16	48.571	5	0	-0.324
20	187	15	46.354	189	15	45.972	2	0	-0.382
21	189	15	44.853	191	15	46.422	2	0	1.568
22	186	14	45.923	192	16	46.685	6	2	0.762
23	199	16	47.209	186	15	44.435	-13	-1	-2.774
24	196	16	46.591	178	12	40.738	-18	-4	-5.853
25	189	15	45.305	191	15	43.996	2	0	-1.309
26	187	14	47.220	193	15	44.273	6	1	-2.948
27	188	15	43.932	184	15	44.675	-4	0	0.743
28	178	12	44.507	188	15	45.060	10	3	0.553
29	187	14	48.130	190	14	44.294	3	0	-3.836
30	177	12	41.438	185	15	44.442	8	3	3.003

Appendix C
Research Environment Werk150

This appendix contains pictures of the logistics learning factory Werk150 of the ESB Business School located at the campus of Reutlingen university.

C.1 Production Environment

Figure C-1: Overview of the Werk150

C.2 Means of Transport

Figure C-2: Collaborative tugger train KollRo with wagon

Figure C-3: NeoKu with its Kuka iiwa

Figure C-4: Handcart with one SLC6040

Figure C-5: MP400 with two SLC4030

C.3 Products of the Werk150

Figure C-6: City scooter FlexBlue

Figure C-7: City scooter FlexAir