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Simulation Paradigms in the Context of Supply Chain Simulations: A Pilot Study

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Abstract

The globalization of markets brings, besides many chances and opportunities, a constantly growing number of competitors. This makes it all the more difficult for companies to hold their own or even expand their market share. In order to remain competitive, optimization potentials must be exploited along the entire supply chain. In order to be able to make well-founded decisions in these complex networks, simulation studies help to analyze existing structures, run through scenarios and finally make data-driven decisions. In order to generate essential and valid scenario outputs, assumptions and simplifications, including choosing a suitable paradigm, have to be made. In the light of this statement, published simulation studies are examined with respect to their underlying paradigms, and is broken down to explain why the choice of the appropriate paradigm was made and which advantages and disadvantages it brings. The focus is on the two paradigms Agent-Based-Modeling (ABM) and Discrete Event Simulation (DES). It turns out that ABM is used mainly because of the manageability of dynamically emerging systems, as well as the representability of the human behaviour involved component. DES, on the other hand, is chosen in order to be able to test different scenarios on central systems with minimal resources. In order to check by means of a practical example, whether the statements regarding DES correspond to its own empirical values, a supply chain simulation is also carried out within the scope of this thesis, based on the framework presented by Furian in 2015, known as Hierarchical Control Conceptual Modeling (HCCM). The effects of different material flow routes on the performance measured by delivery time are investigated. The outputs generated by the simulation study show that the performance of a supply chain network can be significantly improved by close cooperation of involved suppliers. A networked information exchange results in better resource planning and shorter delivery times, which can improve the performance of the supply chain in the long run. At the end of the thesis, the knowledge gained from the literature research regarding the applicability of DES is compared with the experiences from the practical example. It is shown that the framework used had a positive effect on the creation of the model and that autonomous behavior can be represented to a certain extent with DES. Furthermore, the use of DES in this context, mainly supported by the framework, allowed a fast execution of simulation runs with different parameters, allowing the evaluation of various scenarios.

Kurzfassung

Die Globalisierung von Märkten bringt, neben vieler Chancen und Möglichkeiten, eine stetig wachsende Anzahl an Mitbewerbern mit sich. Das macht es für Firmen umso schwieriger, sich zu behaupten, oder gar ihren Marktanteil auszuweiten. Um in diesen komplexen Netzwerken fundierte Entscheidungen treffen zu können, helfen Simulationsstudien dabei, vorhandene Strukturen zu analysieren, Szenarien durchzuspielen und schlussendlich datengetriebene Entscheidungen zu treffen. Essenziell für die Generierung geeigneter und valider Outputs ist dabei das der Simulation zugrunde liegende Modell, und die in dem Zusammenhang getroffenen Annahmen und Vereinfachungen, mitsamt der Wahl des geeigneten Paradigmas. Unter dem Gesichtspunkt dieser Aussage werden publizierte Studien hinsichtlich ihrer zugrunde liegenden Paradigmen untersucht, und aufgeschlüsselt, warum die Wahl auf das entsprechende Paradigma gefallen ist und welche Vor- und Nachteile es mit sich bringt. Der Fokus liegt dabei auf den zwei Paradigmen Agent-Based-Modeling (ABM) und Discrete Event Simulation (DES). Es stellt sich heraus, dass ABM vor allem aufgrund der Handhabbarkeit von dynamisch emergenten Systemen als auch der Darstellbarkeit der menschlich involvierten Komponente verwendet wird. DES dagegen wird gewählt, um unter Einsatz von minimalen Ressourcen, verschiedene Szenarien an zentralen Systemen erproben zu können. Um an einem praktischen Beispiel zu überprüfen, ob sich die Aussagen hinsichtlich DES mit eigenen Erfahrungswerten decken, wird im Rahmen dieser Arbeit eine Supply Chain Simulation, basierend auf dem von Furian im Jahre 2015 vorgestelltem Framework, bekannt unter dem Namen Hierarchical Control Conceptual Modeling (HCCM), durchgeführt. Es werden dabei die Auswirkungen verschiedener Materialfluss-Routen auf die durch die Lieferzeit gemessene Performance untersucht. Die durch die Simulationsstudie generierten Outputs zeigen, dass die Performance eines Supply Chain Netzwerks durch enge Kooperation involvierter Lieferanten erheblich gesteigert werden kann. Ein vernetzter Informationsaustausch resultiert in einer besseren Ressourcenplanung und verkürzten Lieferzeiten, womit die Performance der Supply Chain langfristig angehoben werden kann. Am Ende der Arbeit werden die aus der Literaturrecherche gewonnenen Erkenntnisse hinsichtlich Anwendbarkeit von DES mit den Erfahrungen aus dem Praxisbeispiel verglichen. Dabei zeigt sich, dass sich das verwendete Framework positiv auf die Erstellung des Modells auswirkte, und auch mit DES, zu einem gewissen Grad, autonomes Verhalten dargestellt werden kann. Darüber hinaus ermöglichte die Verwendung von DES in dem Zusammenhang, vor allem gestützt durch das Framework, kurze Rechenzeiten von Simulationsdurchläufen, womit diverse Szenarien getestet und evaluiert werden konnten.

Contents

Abbreviations

ABCmod	Activity-Based-Conceptual-Modeling
ABM	Agent-Based-Modeling
ABS	Agent-Based-Simulation
CAS	Complex Adaptive Systems
CM	Conceptual Model
CCU	Child Control Unit
CU	Control Unit
DC	Distribution Center
DES	Discrete Event Simulation
ERP	Enterprise-Resource-Planning
FIFO	First In First Out
FITA	Fixed-Increment Time Advance
FW	Framework
HCCM	Hierarchical Control Conceptual Modeling
NETA	Next-Event Time Advance
OEM	Original Equipment Manufacturer
OR	Operational Research
SCM	Supply Chain Modeling
SCS	Supplychain Simulation
SD	System Dynamics
SIM	Simulation
THEO	Theory
TL	Trust Level

UR Utilization Rate

WSC Winter Simulation Conference

1

Introduction

Towards the end of the 20th century, companies focused on streamlining and coordinating internal processes that identified and optimized their core activities. Investments in Enterprise-Resource-Planning (ERP) Systems and data warehouses were considered a good way to strengthen the position of a company within the supply chain.

Due to the ongoing globalization of industry, which Gamboa [66] denotes as a key-trend of today's business world, a growing number of firms are extending their system boundaries to cover their field of investigation. They are realizing the strategic advantage of planning and controlling a supply chain as a whole [121]. Increasing competition in global marketplaces, which offers customers a wide range of potential suppliers, allows cross-comparisons in terms of quality, costs and innovation, and thus puts pressure on companies worldwide. Technologies, market ideas and price advantages are spreading faster than ever. Competitors can react quickly and put other companies under constant pressure. At the same time, however, the globalization of markets is opening up new opportunities and new paths. The worldwide access to potential sales markets can, if the acquisition is successful, have a positive effect on the sales balance sheets of companies. At the other end of the supply chain, it is possible to exploit regional market potentials through globally branched suppliers, distribution channels and own branches, and at the same time, react quickly to fluctuations to sustainably maintain the company's position in the market. [1]

The importance of an overall assessment of a supply chain was recognized by Braithwaite and Hall [29], attributing much of a company's risk to its networked processes rather than to the ongoing internal procedures. Planning and managing business processes within a supply chain is difficult, especially when it comes to factors that amplify throughout the whole supply chain's nodes [102].

To be able to provide a company with relevant, helpful decisions and information baselines, upon which decisions can be made, computer-aided arithmetic operations are used, linked to specially programmed system models. According to North and Macal [135], human cognition is no longer sufficient to encompass the complex environment and the influences upon it. Correctly conceived computer models can deal with interconnected systems and the resulting complex problems, such as those found in a supply chain network. However, only a properly constructed model, designed and developed for a specific problem with clearly defined outputs, is a suitable tool that can be used to support strategic decisions [111].

The process of modeling real situations represents a great challenge for many. There are various approaches, from which the process steps and tools can be used as supporting guidance. Numerous publications in literature are dealing with the modeling and simulation of supply chains. The focus of the work varies greatly and ranges from theoretical approaches of applicable frameworks, which act as a guide in the context of such simulation studies, to concrete practical application examples, in which case studies from the economy are taken up and searched for optimization potentials.

With regard to the approaches used, there is no clear validity here. At first glance, there is no general opinion of a single approach to be used. Depending on the area, preference or simulation goals, those responsible for the simulation use different approaches and paradigms.

This thesis aims to examine publications dealing with the modeling and simulation of supply chains to identify reasons for the use of the specific modeling paradigms in this thematic context. In addition to the personal preferences of the modelers, which are difficult to ascertain from pure literature research, the arguments and motivations for using these modules will be examined and compared for commonality. By means of this investigation, the opinion of the usability of different paradigms and approaches to supply chain simulation based on a literature search will be reflected and transparently described in this thesis. The motivations of the paradigm selection are to be quantitatively worked out in such a way that they can be assigned to the superordinate goals and basic conditions of the work and thus grouped thematically. Besides the insight into the argumentation chains of the use of paradigms, the acquired impressions can be used in the future as a guideline to select the appropriate module for given conditions.

The focus is put on supply chain simulation studies published within a certain time range (2005 to 2018), focusing on Agent-Based-Modeling (ABM) and Discrete Event Simulation (DES) within a range of sources. Furthermore, the scientific papers will be examined for similarities to their sources and consequently draw conclusions to filter out essential representatives of these paradigms and their work written on the specific subject, thus uncovering any possible concatenations. Specifically, the most frequently cited works per simulation paradigm will be highlighted and briefly summarized. The aim is to examine whether the subject matter mentioned in the most frequently cited works corresponds to the opinion of the broad mass of published works and whether it coincides.

Among the approaches found in the literature, which support the modeling process of real systems, there is also the framework, called Hierarchical Control Conceptual Modeling (HCCM), published in 2015 by Furian et al. [64]. It is a framework, which enables the application and implementation of centralized control policies using the principles of Discrete Event Simulation (DES). With the help of that framework, an exemplified supply chain will be modeled. The simulation study tests and evaluates the extent to which the modeling structure created by the framework can be applied to a supply chain study. In the course of this, conclusions are also to be drawn as to which extent there are parallels between the arguments for or against the use of DES in supply chain simulations, developed in the theoretical part, and the experience generated by the application of the HCCM framework, which is based on DES.

Structurally, the present master thesis is divided into two thematic parts. In the first section of the thesis, in addition to the topic of supply chain management in general, background concepts of simulation and modeling, combined with definitions of the relevant paradigms, are outlined. Subsequently, publicly available papers on applied supply chain simulation are examined to extract the anchored clues why the choice of the applied paradigm was made.

The second part of the master thesis deals with a case study, which is intended to test the feasibility of implementing the Hierarchical Control Conceptual Modeling framework, itself used for conceptual work in supply chain theory. Finally, the outcomes of the simulation study itself and the thought processes developed by the project are presented, which conclude the project with a view to possible future applications and investigations.

2

Supply Chain Management

This chapter provides necessary information about supply chain management and challenges companies face today, laying the foundation for understanding the following chapters. First of all, the term supply chain management is discussed and its historical development analyzed. Based on this, it is delineated to what extent the linear structure of a supply chain has adapted to modern society and the globalizing economy, and which challenges have emerged as result.

2.1. Definition

In the 1980s, new manufacturing technologies allowed companies to reduce their production costs and compete in growing markets [162]. According to Simchi-Levi et al. [162], continuous improvement in the industrial sector of production led to a steady decrease in costs until a gradual stagnation. Unable to reduce the internal costs by a decisive factor, companies focused on their ambient processes. To increase profits, they shifted their focus of attention to the supply chain and the way it is managed.

Supply chains are integrated systems of three or more entities involved in the up- and downstream of materials and information, which should, on the one hand, maximize public satisfaction and, on the other hand, enhance and secure the competitive position of a firm and its supply chain partners by synchronizing inter-related business processes. These include acquiring raw material, adding value to products, and distributing parts. [120, 121, 169]

The integrated planning, control, and coordination of the businesses within the supply chain, together with the process of satisfying these stakeholders, is named Supply Chain Management (SCM) [176] and is becoming a critical competitive device for companies [119].

The term SCM was firstly used by two consultants, Oliver and Webber, to describe a logistics concept enriched by a strategic component. A unique definition has not been formulated and still does not exist in business literature. [136]

2.2. From Chain to Net

Against the widespread term Supply Chain Modeling, Christopher [43] proposes the switch to the (in his view) more appropriate term: demand network management. As modern supply chains are a network of interconnected co-operative working entities controlling the material and information flow, the value chain is no longer a linear structure. Instead, it represents disparities and interconnections between several suppliers and customers. According to Melo et al. [118], the supply chain is a network of entities performing their operations to contribute their part to the value chain.

Figure 2.1 shows an example of a complex supply chain, where the arrows indicate the material flow and delivery routes. The multitude of inbound and outbound routes between the various supply chain node levels (Suppliers, Plants, Distribution Center´s and Customers) creates a network that is increasingly distant from the actual meaning of a linear linkage between stakeholders and is thus increasingly complex to control.

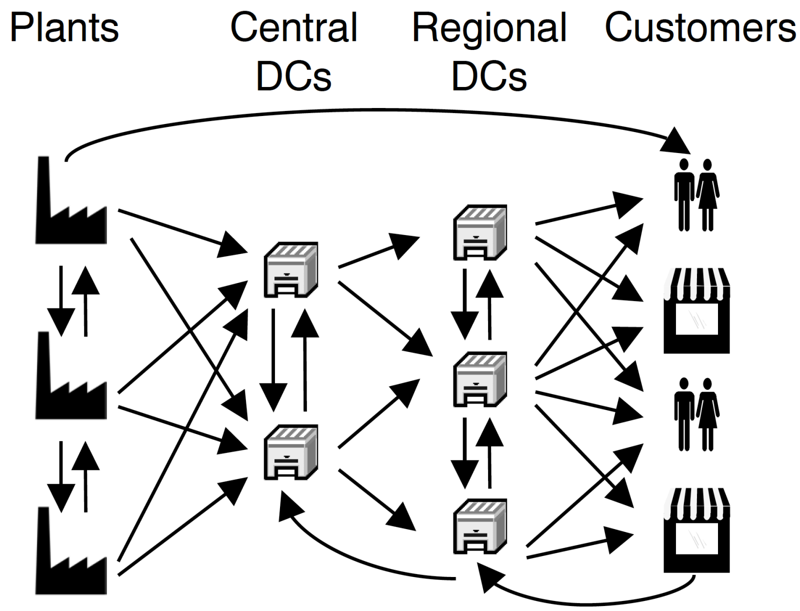

Figure 2.1: Example of a Supply Chain Network (Melo et al. [118])

2.3. Arising Challenges

Simchi-Levi et al. [162] have recognized the complexity of supply chains with parallel convergent and divergent flows of material and information within a network and emphasizes the difficulty of changing setups over time. Time-dependent fluctuations in demand and cost make supply chain management even more challenging. Mottley [127] notes that many problems of supply chain management have only recently developed, and their origins and effects are partly unexplored. This includes the simultaneous development of increasingly shorter product lifecycles and more extensive product ranges.

Simchi-Levi et al. [162] also discuss the difficulty of integrating and implementing supply chain strategies. The authors name two essential conflicts:

- Different objectives of involved companies
  While suppliers try to deliver constant quantities at a constant frequency, they have to be as flexible as possible in order to react to the demand curve of the customer. In other words, both goals are in direct conflict with each other. The same applies to inventory regulations for warehouses and the requirement for the manufacturer to produce large quantities at once.

- Dynamic evolving system
  The links and relationships between the different parties within a system develop and change over time. This includes not only restructuring, but also priorities that can change due to shifts in this balance and the impact of this on the involved parties.

According to Macal and North [111], supply chain systems are becoming too convoluted to understand the multitude of component parts and the way in which they interact. Human frameworks of thinking represent a barrier to analyzing all the possible effects of events, due to their linear structure. In contrast, simulation can be used to explore likely situations a company can face in order to predict, or at least to inform guesses for the future, and allows for quantitative analysis [135].

3

Modeling and Simulation

This chapter establishes the theoretical background necessary for the subsequent sections. It includes a general overview and definition of the terms modeling and simulation and provides an insight into different modeling methods. Furthermore, the topic of conceptual modeling is addressed, and finally, an insight into existing modeling frameworks is given.

Focus is applied primarily to the framework created by Furian [64], called Hierarchical Control Conceptual Modeling (HCCM), upon which the simulation study in Chapter 5 is based and put into use.

3.1. Definition

Modeling is the process of creating a construct that reflects the system to be simulated. In the course of this process, changes are made in the form of simplifications and assumptions in the model, which in most cases preclude an exact imitation of the original object [116]. Nevertheless, it should be ensured, that core aspects are identified and that the model remains usable for further investigations. However, the level of detail should not be exaggerated, since this leads to non-value-adding complexity [147].

This work deals specifically with the modeling of real systems and their transformation into computer models and simulations. Such models are defined by inputs and outputs to be mapped, and are mostly of a stochastic or dynamic nature.[116]

modeling that formally deals with the description and understanding of real scenarios and aspects of reality, whether physical or social, is called conceptual modeling [132], described more in detail in section 3.2.

Models developed for simulations are inherently complex due to their integrated relationships. However, they are what makes it possible and serve as a basis for predicting and explaining the behavior of complex systems through simulations [5].

According to Robinson [148], simulation is nothing alien to us, as we encounter the concept constantly in our everyday lives. Contrary to many opinions, Robinson argues that a simulation does not necessarily have to be performed with a computer. In his opinion, computer games and remotely-controlled mechanical elements like a boat, are, in the same sense, simulations, although a distinction can be made between virtual and physical simulation. Robinson [148] makes a further distinction between simulations by including the temporal aspect. If time is an important factor, and the process of the imitation is adapted to this, one speaks of a dynamic simulation. If this is not the case, and processes do not change over time, a static simulation is the subject of investigation.

A dynamic (computer) simulation, such as one needed for investigating a supply chain and its purpose, is defined by Robinson [148] as follows:

> ”*An imitation (on a computer) of a system as it progresses through time.*”

3.2. Conceptual Modeling

Conceptual Modeling is the process of abstracting reality into a computer model. Due to the ever-increasing complexity of simulations, the term has received more and more attention in literature throughout recent years, a tendency that continues to rise. A well-thought-out, structured Conceptual Model (CM) allows for an efficient implementation of complex simulation studies and is thus an essential success factor in the process of simulation development.

3.2.1. Definition

According to Robinson [152], conceptual modeling is generally agreed as the most complex, but simultaneously indispensable task to be carried out in the context of a simulation study. However, despite its importance, there is no uniform definition of the term. For example, Birta and Arbez [24] are defining the concept of CM differently than Robinson [150] or Wagner [179].

- Birta and Arbez [24] define a CM as a collection of all relevant functional and structural properties of the system to be investigated. It serves to create a uniform basis of communication to which all parties of interest can refer. One of the most important goals of conceptual modeling is the creation of a foundation for the subsequent software development process.

- Robinson [150] sees conceptual modeling as the abstraction process of a real-world system. It plays a pivotal role in terms of defining the critical aspects of the simulation model to be developed. Objectives, output, content, inputs, assumptions, and simplifications made are described, without referring to specific software environments. In this way, it can be ensured that the CM can theoretically be implemented in all software packages if they are suitable for the actual problem to be investigated. The more sophisticated and considered this process is, the better the chances are of achieving the legal goal of the simulation study.

- Wagner [179] interprets conceptual modeling as a solution-independent development process in the analysis phase of a simulation study. It may contain structural information as well as process-related information in order to achieve a holistic picture of the system. This helps to clarify the scope of the simulation study on one hand and supports variant management if research questions must be investigated on the other.

Despite the differing interpretations of conceptual modeling, there is a general agreement that this is an important step that must be involved in the early stages of a simulation study [150].

In this thesis, conceptual modeling will be considered an independent software abstraction of a real-world system that has been developed and is characterized by these attributes summarized by Robinson [150].

- Model foundation, outgoing from a problem situation
- Iterative process, reviewed continuously during the simulation study
- Independence from code and software
- Involvement of the modeler and client in the development to achieve the best-possible outcome
- Simplified version of reality

This transaction must not be seen as a strictly linear process, instead as an iterative adaptation of a real process that evaluates the processes already established within the model.

To fully understand the role and boundaries of a CM in the broader context of simulation, Robinson [152] sets certain artefacts in relation (see Figure 3.1).

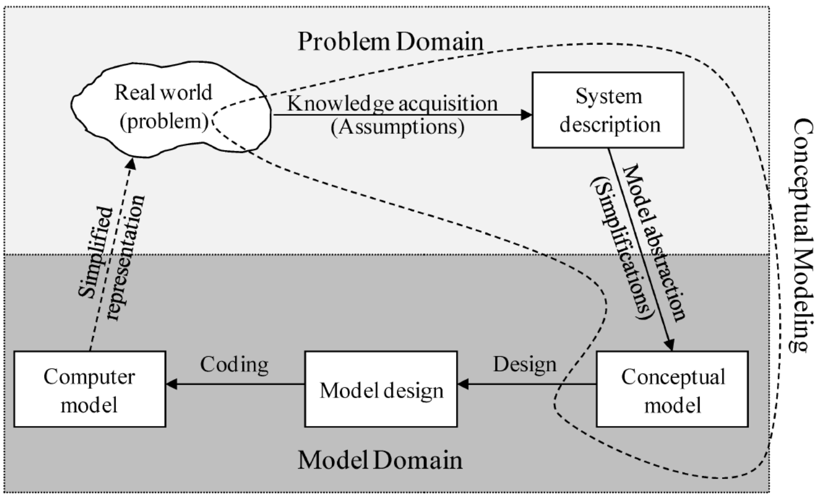

Figure 3.1: Artefacts of Conceptual Modeling (Robinson [152])

According to his definition, the perception of the real world and its description are directly involved in conceptual modeling. Model design and computer models are not strictly part of the CM, but instead belong to the holistic picture needed to abstract the real world suitably in the context of computer-aided calculations.

3.2.2. The Art of Conceptual Modeling

The success and usefulness of the results of a simulation study strongly depend on the quality of the conceptual model. Extracting information relevant to a simulation study from the real system is one of the most critical factors in achieving this [152].

The construction of a model based on a problem and the system associated with it is, according to Banks et al. [19], both science and art; thought driven by experience. The ability to define an appropriate model depends in consequence on the proficiency required to extract the needed data from the real-world system at an appropriate level of detail.

Banks et al. [19] evaluates the appropriate degree of detail, case specific to the underlying questions of the simulation study. He proposes to increase the level of detail, starting from a fundamental approach, to avoid making all assumptions at once. Determining the level of abstraction depends strongly on the availability of data, time, and resources put into the simulation study [152].

Figure 3.2 shows how the complexity and accuracy of a simulation study influence each other. This rule, $80/20$, which is frequently used in business, is also applied here. The rule, also known as the Pareto Law or Pareto Principle, allows the accuracy of the real system to be depicted. For further expansion of the system, it is assumed that 20% of the complexity of the conceptual model reflects 80% of accuracy, while the inclusion of additional details and attributes leads only to marginal improvements to the system, or in the worst case can negatively influence the model through false assumptions and negate the result. [89, 147]

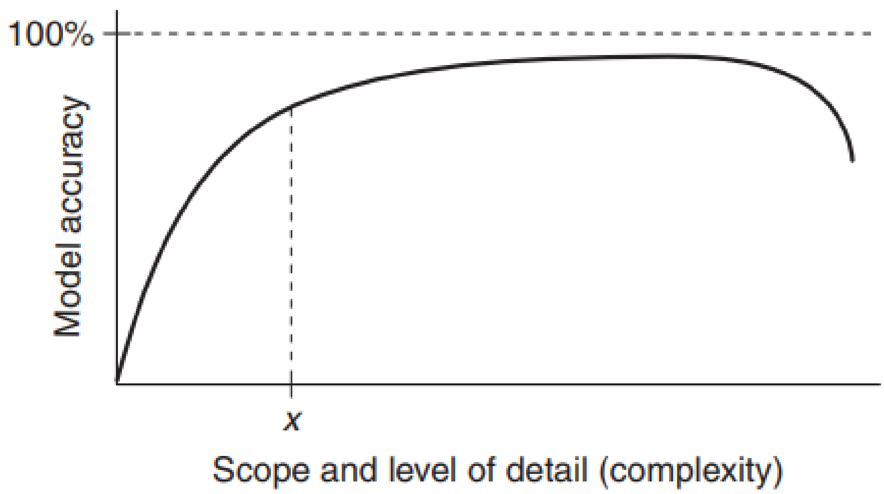

Figure 3.2: Simulation Model Complexity and Accuracy (Robinson [147])

According to Robinson et al. [153] one influential factor in conceptual modeling is the choice of the modeling paradigm. However, he makes no prediction on how the choice of paradigm affects the shape of the resulting paradigm, instead stating that it can affect the cognitive aspects and the views of reality generated.

The way the model is developed is therefore strongly dependent on the simulation paradigm chosen, since paradigms influence the ways in which problems and systems are perceived, represented, and handled [47]. Different modeling paradigms are described in the following sections.

3.3. Modeling Paradigms

Assumptions form the foundation of every modeling method, representing an influential factor in modeling practices and their outcomes [117]. According to Behdani [22], a grouped set of core assumptions and concepts characterize each simulation paradigm, reflecting the way that modelers perceive their environment, and can therefore be seen as a "mindset for modeling" [77]. From a more general perspective, different paradigms cause differences in system conceptualization [22]. Once applied, the following calculation rules can terminate their sequence [49].

In literature, several simulation methods are described. The following three are the most frequently used:

- Agent-Based-Modeling (ABM)
- Discrete Event Simulation (DES)
- System Dynamics (SD)

This master thesis primarily concerns ABM and DES, and these topics are described and covered in the following sections. For the sake of completeness, SD is also discussed.

3.3.1. Discrete Event Simulation

From the initial desire to improve the design and operational efficiency of manufacturing plants in the late 1950s, Discrete Event Simulation (DES) has become one of the most crucial decision-making tools in a variety of business areas. Especially in the area of Operational Research (OR), it is considered the mainstream simulation approach. Even if DES models are used in different ways, partly specialized towards real-world systems, each implementation follows the same basic principle. [28, 78, 149]

Discrete Event Simulation addresses the representation of a system that changes and evolves over time. System variables represent a collection of all necessary information to reflect system behavior and track system state at a defined level of detail. DES is characterized by the fact that these system state variables only change at a countable number of points in time as a result of a so-called "event". Between the discrete points in time, the system state variables remain constant. In this respect, an event can be defined as an instantaneous occurrence, which could result in a change of system state defined by the change of system state variables. [17, 99]

This approach does not correspond to our basic notion of processes in the real world. However, Cassandras and Lafortune [34] name four reasons why it is still logical to use this approach.

- Any computer, which is a given part of the system being sought, operates in a discrete-time fashion, driven by the internal discrete-time clock.
- Complex differential equations of a continuous-time model can only be solved numerically. Since the numerical solution is a discrete-time version of continuous-time functions, a discrete-time model may be useful.
- Due to the lower computing power required, discrete event models are usually more flexible, resource-optimized, and faster to execute than their continuous counterparts.
- For data, which are only available in discrete-time intervals, DES is sufficient because a smaller temporal resolution does not bring any additional value in informational content.

The thought process implemented in the DES model can be seen in a broader sense as a worklist of temporally fixed events and the associated reactions of the system state variables.

Historically, two approaches have been established for determining the time points needed for checking system reaction to the time change: Next-Event Time Advance (NETA) and Fixed-Increment Time Advance (FITA) [99]. Since NETA is used in most large simulations and the latter derives from this by scheduling dummy events at fixed points in time, only the principle of NETA is explained based on the description provided by Law et al. [99].

The illustration of the relationships of sequences and components of the Next Event Time Advance within a DES is shown in Figure 3.3.

At the simulation start, the initialization routine is triggered. The simulation clock, a variable that represents the current value of the simulation time, is set to zero. At the same time, the event list and system state variables are initialized. The event list is a central aspect of the simulation because events are logged with a timestamp, which is assigned immediately afterward and influences system behavior. After returning to the main program, the system checks which event is imminent and which timestamp it has as a start time. The simulation clock is automatically set to this time, and the algorithms lead back to the main program, which calls the event routine. This typically consists of three steps: (1) The simulation status is updated because an event occurred, (2) information about the performance of the system is collected and the associated statistical counter is adjusted and (3) future events are generated and entered into the event list in chronological order. Depending on the simulation, stochastic values may be required, which are obtained as a random variant from the so-called library routines. The main program then decides whether the simulation should be stopped based on the stored boundary conditions. If this is the case, the report generator is

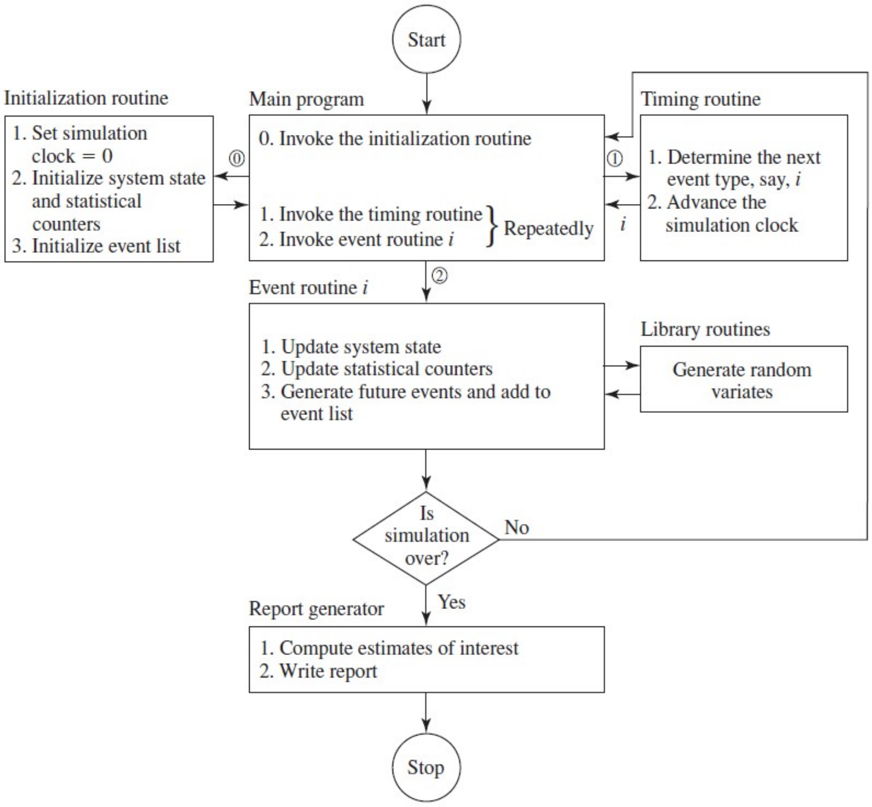

Figure 3.3: Flow control of the NETA approach ([99])

called. This is a subprogram that calculates estimates from the selected measures of performance and generates a report as soon as the simulation ends. If the stop conditions for the simulation are not yet met, the main program retakes control, and the cycle starts again by triggering the next event until the stop condition is met.

Such a calculation could theoretically be made manually. However, the complexity of the many real systems to be mapped exceeds the limits of what is feasible or justifiable in terms of the amount of data and the stored system interactions of the selected system state variables. [99]

3.3.2. Agent-Based-Modeling

This section of the thesis discusses the topic of Agent-Based-Modeling (ABM), to create a basic understanding of the paradigm. Its beginnings date back to the 1940s. However, the paradigm was popularized in the 1990s by SWARM, an open-source simulations package for agent-based modeling developed at the Santa Fe Institute. The reach of the application spread with the introduction of NetLogo, an agent-based simulation environment. Thus, this paradigm is a relatively new approach, made possible in the 2000s and further into the late 2010s with the development of specialized software. [11]

Even though general interest in ABM goes back a long way, there is no uniform definition of the paradigm in literature that reflects the actual core of the modeling approach.

According to Macal and North [111], the basic idea lies in the “bottom up” simulation, whereby independent entities, so-called agents, create the basis of the simulation by interacting independently over time with each other. Systems and organizations are considered and structurally analyzed as a collection of interacting agents, with each unit involved assigned their own rules and responsibilities. None of the entities comprehensively controls the behavior of the system, and rather each one contributes to the resulting behavior of the overall system through its behavior [135]. Law [99] defines this as a bottom-up modeling approach, with a focus on the behavior of the individual and their interaction with the environment.

Regardless of the definition, the naming of the paradigm is based on the so-called “agents”, which make up the core structure of the model. These are decision making components capable of handling logical behavior patterns, enabling them to affect their environment by the processing of influences [135]. Macal and North [111] ascribe to them the attitudes listed below, which define the agents in their role as sub-components of an overall system.

- Identifiable
  An agent can be clearly distinguished from other agents. At any moment, it is possible to determine if any part of a simulation is addressed to a specific agent.

- Interactivity
  Agents interact with their environment; they can interpret and respond to it.

- Goal-Directed
  Agents pursue goals, grouped with their behavior.

- Autonomous
  Agents can function independently within their environment, at least for a limited period.

- Flexibility
  Based on memory, agents can learn from the past and modify their logical processes accordingly.

Based on these tasks, agents have so-called decision rules that determine how they interact with their environment and with other agents. Such decision rules follow agents by executing three steps: (1) evaluation of the actual state and derivation of the resulting actions currently required, (2) execution of selected tasks and (3) evaluation of the actual state after execution of the actions, alongside re-evaluation and adaptation of the stored rules. Depending on the system and application, the complexity of these rules ranges from simple reactions to complex decision processes based on various boundary conditions. [135]

Two main elements of ABM, the agents and the environment, are interlocked with the third main element, the mechanics of interaction (see Figure 3.4) forming the main framework of Agent-Based-Modeling.

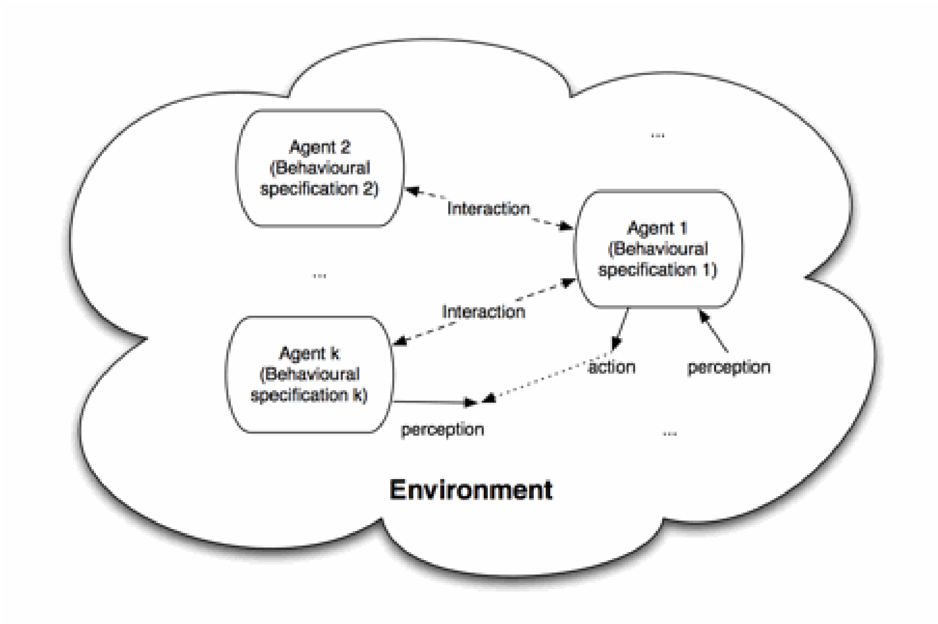

Figure 3.4: Abstract Model of Agent-Based-Modeling (Bandini et al. [16])

These processes and changes occur virtually at discrete points in time, which causes Law et al. [99] to define Agent-Based-Simulation (ABS) as a variation of DES, with emphasis on the interaction of the agents. Concerning time correlation, there are two approaches, as described in Section 3.3.1: NETA and FITA [99].

According to Law et al. [99] in contrast to DES, almost all ABS paradigms use the FITA approach, which has both historical reasons and functional backgrounds. It is possible that the events defined in the event list must be reset due to changes in circumstances, which harms the overall performance of the simulation. Even if it appears to be a variant of DES, Law et al. [99] advises to not diminish its importance in the study of complex systems.

From its beginnings, ABM has gained a foothold in many other fields and plays a crucial role in traditional modeling and simulation computation, allowing for the observation and investigation of patterns and emerging structures, and is capable of self-organization [135].

3.3.3. System Dynamics

The following section deals with a paradigm called System Dynamics (SD). Although it is not featured in the following literature review, it will be touched upon and explained in the following section to round off the overall picture of the three major dominant paradigms.

SD refers to policy analysis, modeling, and simulation in complex systems [146]. The first basic ideas were formed by Forrester after a conversation with representatives of General Electric, an American multinational conglomerate, in which they discussed the strongly fluctuating demand for labor in their plants. Based on the disclosure of policies on how inventory management and hiring decisions were made, Forrester used pen and paper to design an inventory control system for the temporally unstable system, which is considered the cornerstone of System Dynamics. [62]

In literature, there are various definitions of SD. Richardson et al. [146] describes it as the use of computer simulation to study policies applied in complex dynamic systems. Forrester, according to Morecroft [125], stated in an elevator pitch that SD is used to show how decisions affect the dynamic system under consideration, in order to define how to improve the situation in real-world competition by changing decision policies. Coyle [46] combines the term SD with the science of time-dependent behavior of systems and aims to understand the system under consideration by qualitative and quantitative models, then to improve it using feedback structures and control policies. Wolstenholme [185] gives a widely adopted opinion, which spans the arc of definition via the questions *What*, *Why*, *How*, and *Within*.

- *What?*
  A rigorous way to help thinking, visualizing, sharing, and communication of the future evolution of complex organizations and issues over time.
- *Why?*
  To solve problems and create more robust designs, which minimizes the likelihood of unpleasant surprises and unintended consequences.
- *How?*
  By creating operational maps and simulation models that externalize mental models and capture the interrelationships of physical and behavioral processes, organizational boundaries, policies, information feedback, and time delays. These architectures are used to test the holistic outcomes of alternative plans and ideas.
- *Within?*
  A framework that respects and fosters the needs and values of awareness.

System Dynamics models are not derived from time-series data, but statements about the system structure guides and decision systems [60]. Maidstone [114] says, that the approach focuses more on the flows around and within the network than the individuals themselves. This is achieved by the viewpoint graphically illustrated in Figure 3.5.

The loop shown represents the dynamics of a system in which the system is seen as a collection of its parts, arranged and organized to fly towards a target [46]. The status of a system is determined by the decisions made. At the same time, the status of the system determines the knowledge of the information carriers on which the decisions are based, thus closing the circle in the system.

The self-contained sequence of these three components can be declared as a feedback loop, a central element in the theory of system dynamics.

The ”*D*” in Figure 3.5 symbolically illustrates the delay that inevitably occurs in the flow of information in the real world.

One of the significant advantages of SD is its ability to handle complex, nonlinear feedback loop structures [61]. The key is the ability to predict a system’s behavior only by in-

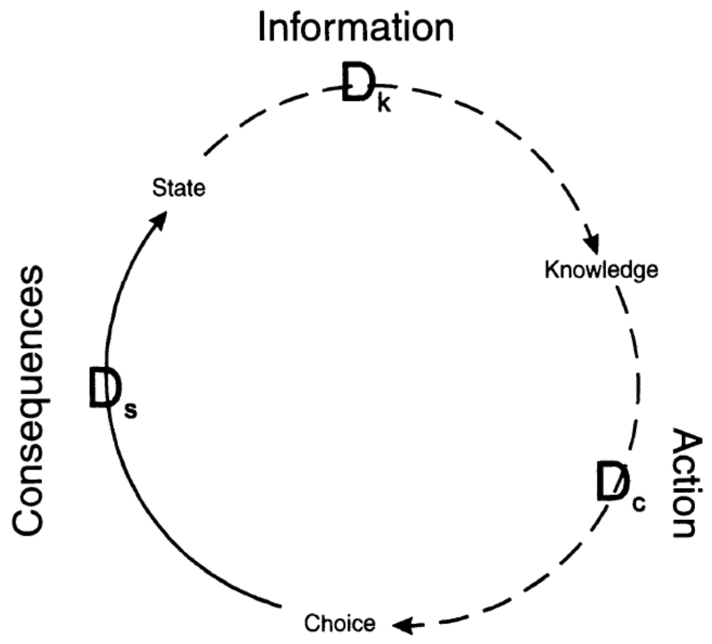

Figure 3.5: Feedback Cycle of SD Dynamics (Coyle [46])

vestigating the structure [114]. SD starts on concepts and information that people are already acting on (general available system structure and policies suffice), information that is transferred into a computer model, showing its consequences [60]. Real processes are represented in terms of stocks, flows between stocks, and the information that determines the value of the flows. Delays caused by the time required between the perception and reaction of an impulse complete the picture of the System Dynamics elements [114].

Due to the scope of this master thesis, more profound details will not be explained here. For further information please refer to the following literature: Coyle [46], Sterman [164] or Kanti et al. [86].

3.4. Frameworks for Conceptual Modeling

According to Robinson [152], there are endless modeling approaches suitable for one specific problem. Beyond that, it is very unlikely to find the optimal grade of complexity to extract the best result of a simulation study with the minimum of effort. Frameworks assist in nearing base requirements for an appropriate Conceptual Model (CM). Frameworks may be perceived as guidelines combined with tools, supporting the modeler to develop a CM. Nevertheless, specialized literature offers only a few viable approaches for the creation of frameworks.

In Table 3.1 some of the more popular frameworks in literature are listed. Some of these focus on a specific area, for example the framework of Van der Zee [177] on the topic of manufacturing, while others can be applied to a wide range of topics with minor adaptation, such as ABCmod from Birta and Arbez [24] or the HCCM framework from Furian et al. [64].

Table 3.1: Examples of CM Frameworks

Authors	Designation	Description
Van Der Zee and Van Der Vorst [178]	n.a	Framework focuses on the simulation control of manufacturing plants.
Birta and Arbez [24]	ABCmod	Activity-Based Conceptual modelling framework structuring the usual practice of CM.
Robinson [151]	n.a	One of the first step-by-step guidelines for developing a CM, based on 5 key activities.
Furian et al. [64]	HCCM	Hierarchical Control Conceptual Modelling framework, focusing on model behavior, policies, and routines by introducing control units.
Tako et al. [170]	Parti-Sim	Focus on communication with various stakeholders and experts during the CM process.

In the following sections, the two frameworks of Robinson [151] and Birta and Arbez [24], as well as the HCCM framework of Furian [64], are described in detail. There are two reasons for this: Firstly, the HCCM framework is based on the former, and secondly, it is used as a basis for the simulation study carried out in Chapter 5.

3.4.1. Activity-Based Conceptual Modeling

Birta and Arbez [24] developed a framework that should provide a clear insight into the system to be investigated for various stakeholders, as well as a CM as a result. The latter should serve as a specification for a later simulation study. The developed framework is known in literature as Activity-Based-Conceptual-Modeling (ABCmod) framework. In order to investigate mechanisms and the emergent behavior of a system, the framework assumes the idea that behavior is merely the result of interactions between different objects. In order to realize this, there are two essential modeling artefacts within the framework: entity categories and behavioral artefacts [24].

Behavioral artefacts are split into two categories: firstly, activities, which are the primary modeling artefacts needed to characterize changes in behavior. Activities can be further divided into scheduled, conditional, and triggered activities, according to the temporally implemented occurrence mechanism.The second element of behavioral artefacts are actions. These are equivalent to events that do not occur within the framework of activity at a single point in time. Like activities, actions can also be divided into scheduled actions and conditional actions, if they occur depending on the individual or diverse system configurations. Entity structures provide the specification of each entity that appears in the model in the form of a name and a description of the attributes assigned to it. Four main entities can be identified: resources, groups, consumers, and queues. Figure 4.3 shows this illustratively.

Modeling Artefacts	Entity Category	Ressources	
		Groups	
		Consumers	
		Queues	
	Behavioural Artefacts	Activities	Scheduled
			Conditional
			Triggered
		Actions	Scheduled
			Conditional

Figure 3.6: Modeling Artefacts ABCmod (based on Birta and Arbez [24])

Birta and Arbez [24] divided the development process of the conceptual model into two steps. The first step, called high level, aims to give a rough overview of the model without going into too much detail. This level of detail allows it to serve as a basis for discussion with various stakeholders. Information necessary for the computer aided implementation of the model is defined and formulated in the so-called “detailed level”, which can be used as a specification and as a tool for the translation of the conceptual model into a computer program.

3.4.2. Robinson Framework

Robinson provides a framework, based on his 20 years of experience as a developer and user of simulation models, which includes a guide to the activities he believes are necessary for developing a conceptual model. His framework is aimed at both beginners, who are dealing with the topic for the first time, as well as experienced modelers. It is intended to serve as a guideline, which should have an informative and disciplinary effect on the developers in the context of model conception. [151]

In one of his recent works, Robinson [151] prepared his framework and the steps contained therein graphically (see Figure 3.7). The five core activities are listed below.

- Understanding of the problem
- Definition of the model and general objectives
- Identification of model outputs (also known as responses)
- Identification of model inputs (also called experimental factors)
- Definition of the model content including scope and level of detail, as well as all assumptions and simulations

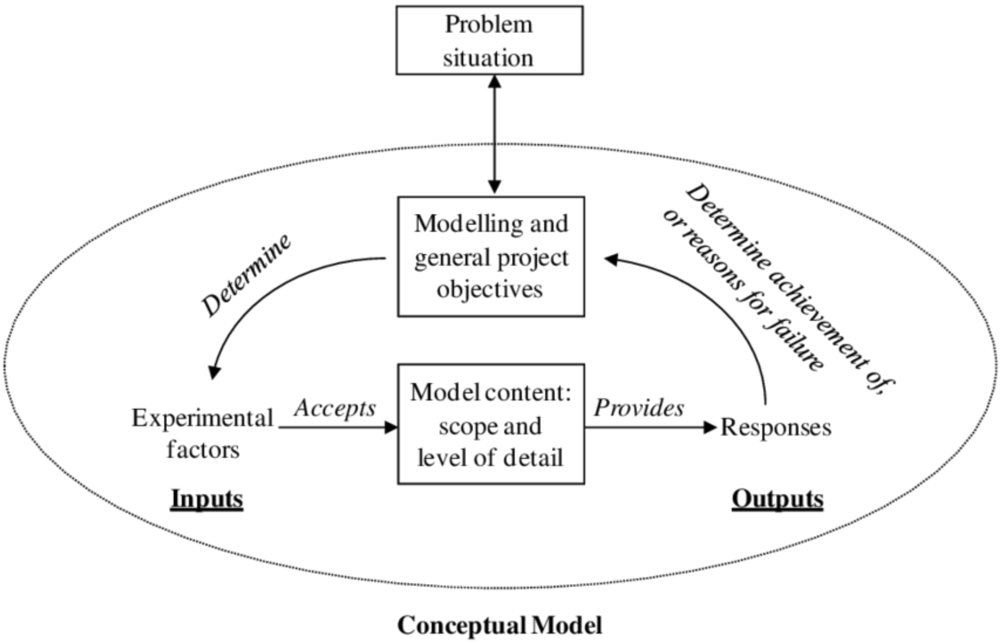

Figure 3.7: CM Framework of Robinson [151]

The sequence for the individual steps is not strictly predetermined. The iterative approach in the modeling process does not allow for linear working methods but emerges as a dynamic, flexible process.

Since a requirement of a simulation study is usually the goal of improving a real given situation, understanding the initial situation is the first step to create suitable initial base [151]. Understanding the problem situation is part of the process of conceptual modeling, even if it is formally not part of the conceptual model. From the understanding of the problem, the modeling objectives are derived, from which the required simulation outputs can also be defined. Their purpose is to check whether modeling objectives have been met, and if not, to provide support to determine why. After the model inputs, which Robinson [151] also calls experimental factors, have been refined, the modeling content can be defined.

According to Robinson[151], the model content consists of two components. The scope defines the system boundaries of the system under investigation; the level of detail describes the granularity of the information to be modeled. The assumptions and simplifications made in this process are the last elements of the framework presented by Robinson and complement the conceptual model.

3.4.3. Hierarchical Control Conceptual Modeling (HCCM)

Based on the described topic of frameworks and their importance for the ease of development of conceptual models, the following chapter focuses on the framework presented by Furian et al. [64], Hierarchical Control Conceptual Modeling (HCCM). A theoretical insight into Furian's work, on which the simulation study of the practical part is based, is provided here.

The HCCM framework challenges the widespread assumption that DES systems are approached best by queuing systems, adding more flexibility to the process of conceptual modeling [64]. This flexibility is defined by an activity-based perception of the system to be investigated and the derivation of the adaptation of this behavior into the model.

Activities, defined by Banks [17] as a duration of time, are delimited by a starting point and an endpoint, both defined by calculations, data, or estimates. In broad terms, Furian et al. [64] agree with the definition of an activity provided bye Banks [17] albeit with one exception. Banks [17] states that a resource (an element that can be used by different elements of the simulation) must always be associated with an activity. Furian et al. [64], however, dissociates himself from this opinion.

Nevertheless, the authors agree on similar definitions of certain aspects, which are listed below.

- An activity is an intangible unit.
- Activities are defining the interaction between different entities.
- An activity always purposes a goal.
- The time period over which the activity is stretched is greater than zero.

In order to be able to describe the behavior of a model in all its dimensions, events are needed to trigger certain actions. In contrast to activities, events are linked to a clearly defined point in time [20]. Depending on the trigger mechanism, Furian et al. [64] categorize behavior into four different groups (see Fig 3.8.

While behavior according to the standard literature is divided into scheduled or into sequential behavior, Furian [64] differentiates in his designation of the third main division. While the literature speaks of conditional behavior, Furian uses the term controlled behavior. This emphasizes even more the intentions of the framework and the role of the central control structures.

The framework combines findings and steps proposed by Robinson [151] as well as elements investigated and described by Arbez and Birta [12]. Furian et al. [64] created a four-level framework known as HCCM shown in figure 3.9.

- Phase 1: Understanding the Problem Situation

  Banks et al. [19] states the formulation of the problem as the first step of a simulation study. Before a question can be formulated and defined, however, the problem and the system must first be understood. Furian et al. [64] draws on the findings of Robinson [151] which suggest the lack of qualified communication as one of the primary hurdles in this first phase. The overall goal is to facilitate a clear description of the problem in an understandable form for all parties of interest.

Behavioral	Scheduled		Data, or in the models used key figures, are triggering activities/events. These figures might be empirical based, technical conditions or statistical evaluations.
	Controlled	Requested	Actual activity, requested by an entity, triggered by status, history or process.
		System	System activities are triggered by the status of the system, activated by the control structure.
	Sequential		Consecutive processes, which are triggered by the completion of the previous step(s).

Figure 3.8: Behaviour Types of HCCM Based on Trigger Mechanism (based on Furian et al. [64]

- Phase 2: Identification of Modeling and General Objectives

  This step aims to define clear goals. Like Robinson [151], Furian et al. [64] distinguish between two different types of objectives: General Objectives, concerning the model itself (e.g. runtime, visualization type, re-usability) and Model Objectives, focusing on the added value in the form of information and findings, which the clients hope to gain from the simulation study.

- Phase 3: Defining In-and Output Factors

  The third circuit of the framework combines the delimitations of inputs and outputs generated by the model, by which the results of the simulations are evaluated. Furian et al. [64] associates the term 'input' with data that can vary over different experiments and is thus tailored to the problem to be investigated. According to Furian et al. [64] it is important to clearly define the field of applications and the interfaces through which data are applied in a simulation. Regarding outputs, the author refers to the different forms an output of a simulation study can take. From single numerical values, up to continuous data representations, illustrated by plot diagrams, the type and basic structure of the output depends strongly on the initial situation and questioning.

- Phase 4: Model Content (Scope, Level of Detail)

  According to Furian et al. [64], the model content to be defined consists of 3 building blocks: Model Structure, Individual Model Behavior and System Behavior.

  A model structure is defined and shaped by the structure of the elements involved, together with their properties and behavior.

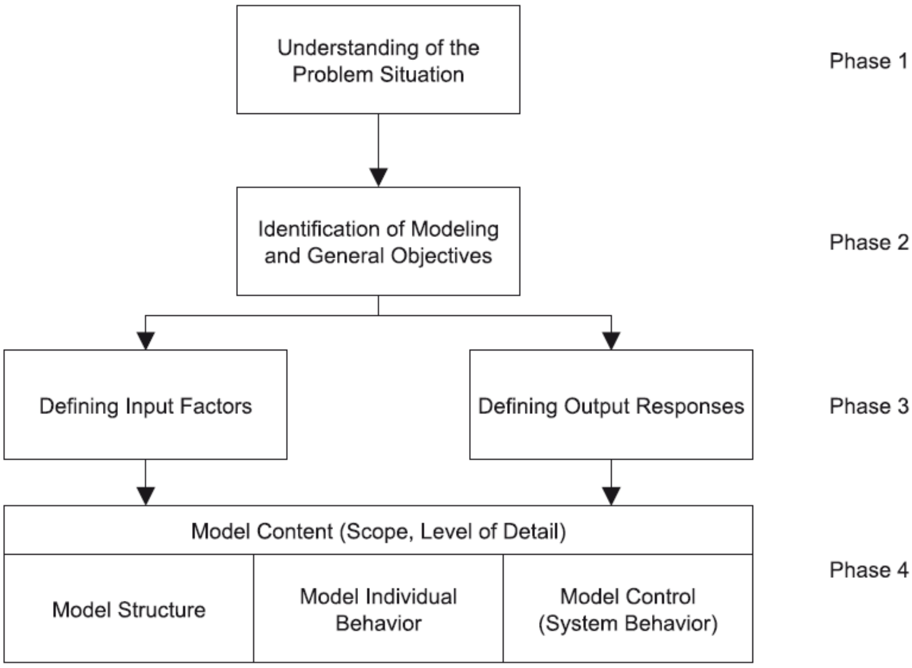

Figure 3.9: Structure of HCCM Framework (Furian et al. [64])

Furian et al. [64] do not diversify the elements between resources and consumers, as other frameworks do (see Arbez and Birta [12]). Instead, common types are aggregated, combined, and controlled from a central point.

An essential step in model structuring is the decision which entities in the real world are placed within the system boundaries to be investigated, interacting with it and with each other. Those must be abstracted and included in the simulation study. Furian et al. [64] recommend using graphical illustration tools to simplify this process.

Before definitions of entity group-specific attributes can be made, the modeler must choose the desired degree of detail. This is part of the definition of individual model behavior. If the entity or entity group has a vast or considerable influence on system behavior, meaningful attributes shall be assigned. Which artefacts are assigned at which degree of detail to the entities depends on the circumstances and is different from study to study.

In order to facilitate this step efficiently, Furian et al. [64] propose to graphically illustrate the interactions and movements of individual elements through the system in order to better understand status changes, possible requests, and sequences, as well as to extract the required attributes from the system.

This sub-item of system behavior aims to describe one of the basic ideas of the HCCM framework presented. Furian et al. [64] name activities, events, and controls as necessary elements of the presented framework. The first two are merged and structurally subordinated to the control units, thus creating a hierarchical construct. In the control structures, a series of rules are grouped, which decide the trigger times of the subordinated units and at the same time influence the overall behavior of the system. Thus Furian et al. [64] break up the groups and structures known from DES and enables a more precise analysis of the individual behaviors of the elements under consideration.

In addition to a control view, all control rules should be defined in this step. This is the last screen of the HCCM framework.

To summarize, the following questions shall be clarified within this step:

1. Which decisions are made?
2. Who made the decision?
3. Which motivation was mentioned
4. Structure of decisions

Overall, it can be seen that there is a large number of approaches and guidelines available in the literature to structure the modeling process. People recognize how important it is for the quality of simulation to make good assumptions at an early stage and are therefore becoming increasingly concerned with this topic.

However, there does not seem to be a single correct approach. From different paradigms to various guidelines, so called frameworks, there is a variety of tools available, which developers can use to model problems and finally implement them in simulations. In this decision process, the selection of the simulation paradigm is indispensable, which, as a basic building block, influences the entire modeling process.

The next section focuses on the motives for the selection of the selected paradigms, the boundary conditions that the developers take into account in their decision, and the guidelines that can be derived for future developments. In addition, reference lists of researched works are analyzed quantitatively in order to filter out the most cited works. These will be used to identify possible main representatives of the different paradigms.

4

Literature Review

This chapter of the thesis deals with published papers addressing the application-oriented modeling and simulation of supply chains. As mentioned in Chapter 3, the literature offers a variety of approaches and paradigms that can serve as a foundation and guide for a simulation study. In order to reveal possible motivations for specific paradigm choices, as well as to identify key pieces of work within each paradigm through quantitative analysis of references, a literature review is conducted.

4.1. Objectives

The aim of the literature review to be carried out is to identify motives for paradigm choices in the context of supply chain modeling and simulation. Questions, such as if modelers rely on the one paradigm they are most familiar with and the one they can best handle, or if they first investigate what to model and what questions to answer before making a decision, shall be addressed. As an outcome of this process, arguments and opinions which are in favor or against the paradigm used and which justify the use of the paradigm shall be collected, thematically bundled and prepared in such a way that a general picture of the strengths and weaknesses of the respective paradigms in this context can be derived and compared. Based on this, a statement in the form of a recommendation for action is to be formulated, under which boundary conditions which paradigm is to be recommended.

In a second step, the sources used in the individual works will be examined for similarities. By quantitatively evaluating the frequency of use, the main representatives of the individual paradigms and their works will be identified, and their opinions will be checked against the generally valid ones.

The thesis focuses exclusively on the following paradigms.

- Agent-Based-Modeling (ABM)
- Discrete Event Simulation (DES)

A more detailed description of the two paradigms can be found in Section 3.3.1 and Section 3.3.2. Within the framework of this pilot study there were general conditions regarding time frame and data sources used. The study is limited to papers published between 2005 and 2018 and focuses on papers published on IEEEXplore and the Winter Simulation Conference (WSC). The described thematic division of the focus is also reflected in the structure of this chapter.

First, the procedure of literature searches is described, including the process of selecting scientific papers, used data sources, and the definition of the search grid used. Based on the selection of the scientific papers, the arguments of paradigm selection are examined, and the results are shown in graphical and tabular form, including a cross-reference to the results found in the literature.

In a concluding step, it is explained how the source selection study was treated, the results of which are then presented and discussed in graphically illustrated form.

4.2. Data Sources and Selection Criteria

For the literature research, existing digital libraries, that specialize in scientific publications, are used: the Winter Simulation Conference (WSC) and a database called IEEE Xplore. A brief description of these data sources is given below.

- WSC (Webpage: https://informs-sim.org)
  The WSC is an event that takes place every year, where recent developments in computer simulation are disseminated. In the early versions of the WSC, the discussed topics were limited to discrete-event and combined discrete-continuous simulation but have been broadened over the past 60 years [71].

- IEEE Xplore (Webpage: https://ieeexplore.ieee.org)
  IEEE Xplore is a digital research database with over $5,147,354$ items (at date 2020-04-01) [2], including the most cited journal articles, papers and technical standards.

The advantage of the WSC is that the scope of published papers is limited to the theory of computer simulations and thus facilitates the examination of the contents with subject-specific limitations. Disadvantageous, compared to IEEE Explore, are missing filter measures.

Various filter measures are available on IEEE Explore, which makes it possible to limit the spectrum of available scientific papers quickly. When reviewing the documents and evaluating their relevance for this master thesis, it should be noted that documents from the WSC were also part of the IEEE Explore database and, therefore, should not be counted and viewed twice.

In order to limit the variety of available scientific papers to a relevant quantity that can be examined, selection criteria were defined in advance, after which the articles were pre-filtered. Figure 4.1 gives an overview of the filtering process with the respective numbers of the resulting papers according to the individual steps. The descriptions indicate the conditions that the publications have to meet in order to be considered further. The magnifying glass as a symbol indicates that this step was performed automatically due to the database query. The symbol image of the person indicates that the step was performed manually due to the content analysis of the papers. The exact descriptions of the individual steps are described below.

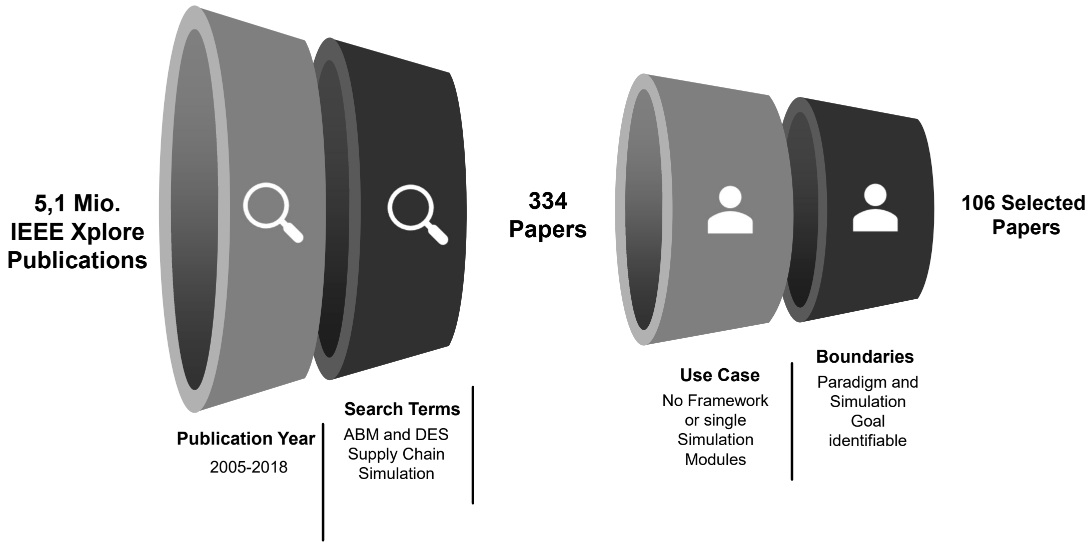

Figure 4.1: Overview of Publication Selection Process

The most important prerequisite is that the papers must deal with the topic of investigating a supply chain. Whether risks were examined, if the performance was to be improved, or whether various inventory policies were reviewed, are not primary selection criteria.

The second important point that must be fulfilled is whether the scientific work addresses the topic of the supply chain based on DES or ABM, as the present work focuses on these two paradigms. Due to the different data structures of the sources used, the selection of proper papers is described separately.

To narrow down the scope of the items available via the online database IEEE Explore, appropriate search criteria are set according to Table 4.1.

Table 4.1: Search Criteria IEEE Explore

		ABM		**DES**
search option		meta data		meta data
search terms	AND	supply chain simulation agent based modeling	AND	supply chain simulation discrete event simulation
year range		2005-2018		2005-2018

The online archive of the WSC does not have a filter option, so it must be browsed manually. Although the WSC publications are part of the IEEE Explore database, this is useful in including papers that have been filtered out.

It is important to note that all documents that were available online in the respective archives by October 10, 2019 were included. All papers uploaded later are not part of the investigation, even if they fit into the search grid.

After this first containment, 334 scientific papers based on the treated topic and underlying paradigm remain for further investigation.

To extract the most representative statements about paradigm selection and to be able to draw accurate conclusions, the following further selection criteria were applied.

- Frameworks excluded
  If the publication mainly deals with the description of developed modeling frameworks, it is no longer considered, even if it describes supply chain issues based on ABS and/or DES. The grade and reason of applicability of the paradigm to the problem cannot be determined if the supply chain context is only listed as a possible application and not the central subject of the study.

- Objective not clear
  The aim of a paper has to be clear to qualify the paper as a candidate for the literature study. The purpose and consequently, the evaluation of the choice of the paradigm is crucial.

- Developing of Simulation Modules
  If the paper presents the development of a new software module, it is not taken into further investigation. Its applicability to different areas, supply chain topics in this case, cannot be evaluated in the context of this work. The factor of promoting their work must not be reevaluated.

- Paradigm Statement not defined
  Papers without reasoning as to the paradigm selection do not fit into the study.

After applying the filters to meet the defined requirements, 106 papers were used for the investigation of paradigm selection as well as for their referencing behavior. Figure 4.2, created with an online tool (*https:/rawgprahs.io*), shows the temporal distribution of the papers divided between the two paradigm types: ABM and DES.

The transparent colored section of the graph indicates all documents that deal with a supply chain topic using the corresponding model fitting the first search grid. The non-transparent sections correspond to the number of papers that are used for further investigation, thus, Figure 4.2 shows the influence the last step of the selection process. The color differentiation helps to distinguish between ABM (blue), DES (green) and hybrid approaches (marked orange).

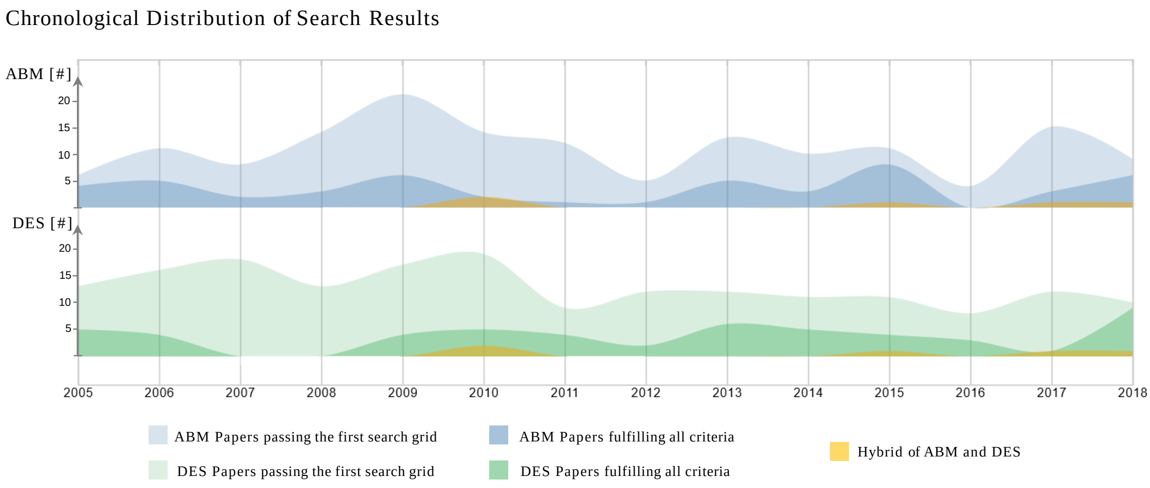

Figure 4.2: Amount of papers fitting the different search criteria, by publication year

The orange-colored area corresponds to all scientific papers that deal with a hybrid paradigm of ABM and DES with a supply chain topic and therefore, cannot be limited to one paradigm. A complete list of papers can be found in Table A.1 in the appendix.

4.3. Evaluation Approach

To draw conclusions about the strengths and weaknesses of the paradigms in the field of supply chain simulation, mentioned related advantages and disadvantages are extracted from the works, numerically recorded, and described. The focus of interest is on arguments and statements with which authors and modelers justify and prove the case-specific application of the paradigm. These arguments are to be emphasized explicitly since they give a precise insight into the chain of argumentation of the paradigm application in the real case.

Besides the arguments directly related to the use of the paradigm, descriptive statements are also taken up and noted. Despite the fact that such descriptive elements are not related to the direct argumentation for the use of the specific paradigms, they facilitate a certain insight into the authors' way of thinking or general attitude influencing their decision regarding the paradigm choice. This extended consideration also allows for an evaluation of the extent to which general statements of the paradigm coincide with those used to explain and justify its use. In addition, the quantitative number of statements is increased, which allows more substantiated conclusions to be drawn.

Both, directly expressed opinions as well as cited statements drawing conclusions about the strengths and weaknesses of the paradigms in the field of supply chain simulation, are thematically grouped and presented in tabular form for comparison. In addition to the umbrella term, under which various arguments are grouped together, also the absolute frequency of the occurrence of the statements grouped will be pointed out. Important when considering the following evaluation is that arguments, mentioned more than once in the same paper, were only counted once to not give too much weight to an argument, caused

Table 4.2: Reasons for ABM Selection

		Papers							
Statement	**freq.[#]**	[32]	[88]	[167]	[36]	[93]	[15]	[13]	[155]
Autonomy	1	o							
CAS	1		o						
Commonly Used	1			o					
Decentralized Structures	2		o		o				
Emerging	1		o						
Granularity	1					o			
Human Behaviour	3	o		o			o		
Interactions	3	o		o			o		
New	3				o			o	o
Reality Based	1	o							

by the descriptive nature of the paper.

In addition to the core terms and statements and their associated frequencies, reference is made to the works in which these arguments can be found. The number refers directly to the bibliography numbers of this work and can be referenced in the bibliography in the Appendix.

4.4. Evaluation of Paradigm-specific Statements

This section investigates papers fitting the filters defined in Section 4.2, trying to reveal reasons for paradigm selection, based on the evaluation approach described in Section 4.3. Both, thematically and structurally, ABM and DES are initially investigated separately. Then, statements of both paradigms will be compared and conclusions drawn in a separate section. Finally, an outlook, based on the arguments found, will be provided, which will serve as a support for the selection of paradigms in the supply chain topic.

4.4.1. Selection Arguments Agent-Based-Modeling (ABM)

Table 4.2 shows those arguments that have not been used to describe Agent-Based-Modeling (ABM) itself but are directly linked to the argumentation as to why modelers have chosen the paradigm, or why they consider it right to have made this decision. In addition to the umbrella term, reference is also made to the absolute frequency as well as to the individual bibliography entries of the papers in which the statements can be found.

The terms on which Table 4.2 is based are explained in more detail below.

- Autonomy: This argument describes the applicability of agent-based modeling to the supply chain issue, given the ability of the individual agents to autonomously navigate their environment, make their own decisions, and thus actively control the output of the simulation study. [32]
- CAS: Kessentini et al. [88] justifies the use of agent-based modeling in this study by ar-

guing that supply chains can be considered as modular complex systems, and thus that the structure of agent-based modeling is best suited to implement these structures in a computer-aided environment. This can also be summarized under the term Complex Adaptive Systems (CAS).

- Commonly Used: The argument that agent-based modeling is already widely used in many areas and applications of summation is also used in scientific papers as an argument for its use. The reasons range from good applicability in supply chain management to popularity in the modeling of the dynamics occurring in the supply chain. [167]

- Decentralized Structures: The term Decentralized Systems summarizes the strength of agent-based modeling with regard to the representability of distributed structures. The manageability of networks with heterogeneously distributed sub-structures is increasing and its upswing in recent years in combination with ABM, uses Chan [36] as an argument for the use of this paradigm. Kessentini et al. [88] emphasizes the correlation between supply chain networks and the described decentralized structures, and thus concludes the applicability of the paradigm to the supply chain issue.

- Emerging: The argument that agent-based modeling can be used to realize self-developing systems, the development of which depends on the behavior of the individual components, is made by Kessentini et al. [88]. They also suggest modularity as a further argument as to why agent-based modeling can map a supply chain. Thus, the dynamics of the simulation and the simulation model are not restricted, and the system can develop based on the individual decisions of the agents.

- Granularity: According to [93], the agent-based structure of the paradigm opens up the possibility of viewing and analyzing the system as a whole as well as its individual components, with which various system complexes can be determined.

- Human Behaviour: The ability to map human character traits such as reactions to the unavailability of products, as well as social dependencies, was presented as the reason why agent-based modeling was used by Avegliano and Cardonha [15] to examine the effects of social aspects on the order strategies of retailers. The proactive social behaviour, and the autonomous decision making in terms of social interactions and behavioural patterns, are also mentioned as arguments for the use of ABM by Cabral and Grilo [32] and Sun et al. [167].

- Interactions: The most frequently found argument actively voiced in favor of agent-based modeling is the ability to map human interaction. Although this is a partial aspect of the human behavior mentioned above, it is nevertheless mentioned independently in the literature. The ability of agents to exchange information, resources, and risks, and the investigation of this emerging attitude in social networks, is considered as one of the main reasons why agent-based modeling is suitable for the representation of supply chain networks. [15, 32, 167]

- New: The argument that ABM is relatively new in the supply chain field is used as an argument to test it in scientific papers that re-examine or re-evaluate its applicability to a more specific field of supply chain simulation [13] [36]. Furthermore, the latest achievements in the field of artificial intelligence and data processing and their compatibility with agent-based modeling is mentioned by Rouzafzoon and Helo [155] as reason for the use of ABM.

- Reality Based: Cabral and Grilo [32] name the ability to represent models realistically in the simulation as their reason for the use of agent-based modeling. Although this is mentioned here as a separate point, it can be used as a summary or umbrella term for the arguments mentioned above.

In general, only a few authors explicitly spoke out in their papers about the use of the paradigm and substantiated or proved their choice. Mostly there was only a general description, which the authors did not refer to in their argumentation of the modeling method, text of a descriptive character that served as an introduction.

To acquire a more in-depth insight into the use of the paradigm in connection with supply chain simulation, and to reveal advantages or common strengths of the paradigm, statements regarding strengths and weaknesses of the paradigm are noted. Citations of such statements are also included in the search grid. For the evaluation, the strengths of the statements concerning the paradigm are recorded in terms of quantity and content, again grouped and prepared in a thematic manner.

The results of this study were 19 key arguments that were named as advantages and strengths of Agent-Based-Modeling. A complete list of the arguments and referenced statements in the papers can be found in Appendix A, Table A.2. This table contains both arguments that were used to justify the use of the paradigm (see also Table 4.2) and those that were used indirectly as descriptive elements in the paper. The six most common topics are addressed and evaluated in this chapter.

For the evaluation, a so-called radar or spider chart is used. This diagram type can be used to graphically represent strengths and weaknesses of a person, discussed and evaluated as part of a personality test [55], but it is well suited for the representation of corresponding strength distributions of the agent-based modeling method. In this context, the further from the center a point is located, the more pronounced this trait is, or in this context, the more often the statement of advantage was expressed in the papers. A presentation of the five main arguments is given in the form of a radar chart diagram in Figure 4.3.

Figure 4.3 shows two graphic expressions of the presentation of the strengths of ABM. The inner dashed line describes how often the associated argument was used to justify agent-based modeling for a specific case study. The outer, solid-line line describes the total number arguments assigned to the outer category, including the arguments handled by the

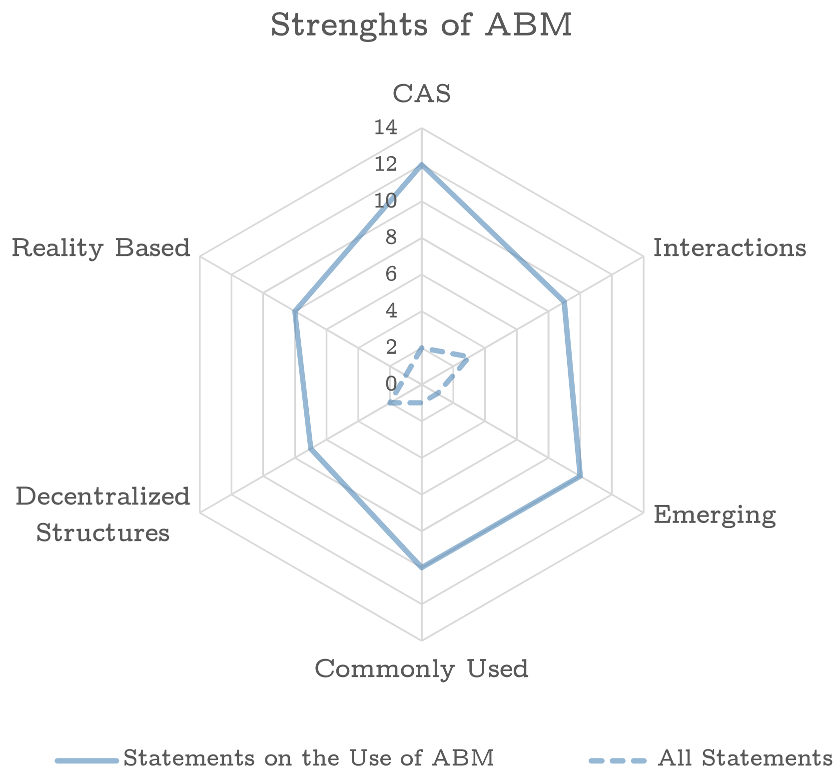

Figure 4.3: ABM most named Strenghts

inner pentagon. The five most frequent argument categories were also determined based on the frequency of the outer rounding. The vertically arranged numbers define the limits through which one can identify how many arguments were considered.

The most frequently-mentioned strengths of agent-based modeling are thus as follows. A description of the individual points can be found in this chapter of the description, related to Table 4.2. The statement regarding the handling of Complex Adaptive Systems (CAS) is the point most frequently mentioned and described.

- Representability of complex adaptive systems (CAS)
- Presentation and handling of interactions
- A dynamic structure, which facilitates an emergent behavior and development of the system
- Interest and experience resulting from the frequent application in various fields
- Representability of structural centralized systems and logics
- Realistic representation and intuitive adaptation of the real environment

Another notable point is that the most frequently mentioned strengths of the paradigm have all been used at least once to directly argue the use of the paradigm in the context of a case study. Thus, they do not have a descriptive character, but were noted in the form of a

Table 4.3: ABM named Weaknesses

		Papers				
Argument	**freq.[#]**	[8]	[144]	[88]	[171]	[67]
Framework Dependent	1	o				
High Effort	1	o				
New	3	o		o	o	
Objective not Ensured	1					o
Required Data	1		o			

statement on which the use of an agent-based modeling methodology was based. From this, it can be deduced that authors who write the reasoning behind the choice of paradigm are generally aware of the strength of the paradigm and apply it consciously to the appropriate problem situation. However, the number of arguments is limited in the papers. In this study, it is only possible to track what has been directly written down: it is not possible to gain insight into the unwritten thoughts of the modelers, which makes an evaluation difficult.

If one considers all the main arguments, which are repeatedly mentioned in connection with the strengths of agent-based modeling, one can summarize and structure these points even further. All human or sociologically versed arguments, such as interaction, decision making, and autonomous behavior, can be summarized under the term Human. Dynamic Emergent Behavior joint with the mapping of CAS, which enables the agents to structure the real world, can be summarized under the term Structure. The last point that captures the curiosity and experience that drives developers to use this special modeling methodology in a supply chain simulation is summarized under the term Experience. This leaves at the end three main arguments with which the use of ABM is and can be argued: Human, Structure and Experience.

Although the arguments given as to why ABM is suitable for the modeling of supply chain issues, there was no information in any of the papers as to why a different paradigm was not applied. Thus, it is difficult to conclude what advantages ABM has over other paradigms for a given use case.

Using the same method as for the strengths of the paradigm and the correlating arguments to be found in the papers, the statements concerning weaknesses are also presented quantitatively in tabular form to facilitate comparisons in frequency (see Table 4.3). On the left side of the table are the overarching terms under which the arguments are summarized, again showing absolute frequency compared to other statements regarding the weaknesses of agent-based modeling. The table also provides information on which papers contain statements regarding weaknesses. The number shown refers to the numbering in the bibliography and can be looked up in the Appendix of this paper.

A tabular overview of the statements based on which the key terms are formed, can be found in Table A.3 in the Appendix.

The points from Table 4.3 are described in more detail below. It is important to note, however, that none of these arguments were used to evaluate the non-use of agent-based modeling but were of a descriptive nature in each work. All works in which the descriptions occur use ABM as a paradigm and do not switch to DES on the basis of these findings. Only Reddy and Telukdarie [144] use a hybrid variant between DES and ABM to compensate for weaknesses and to strengthen the individual paradigm.

- Framework Dependent: The fact that the success of a model depends strongly on the appropriate framework has already been discussed in Section 3.4, page 17. This argument is also used by Achter et al. [8] to underline the challenges of ABM. In his opinion, it is one of the three greatest challenges in agent-based modeling, along with modeling effort and understanding human interaction.
- High Effort: Achter et al. [8] express in their scientific work opinions on the high effort connected with agent-based modeling. Above all, they notice that the effort, which is expressed by the definition of the interactions, but also the allocation and definition of tasks of the individual agents is, according to them, an important source of effort in ABM. This effort is then only visible in the late phase of the simulation study.
- New: Achter et al. [8], Kessentini et al. [88] as well as Tan et al. [171] challenge ABM, suggesting insights are needed that have not yet been explored. While Kessentini et al. [88] and Tan et al. [171] are refering more the fact that there are still few use cases in the field of ABM for supply chain modeling, and therefore experiences in this field are not so common, Achter et al. [8] goes deeper into the topic and notes that the advantages of ABM are only noticeable when human interaction and human behavior are fully understood from a psychological point of view. This opens a new branch of research, which must be investigated before revealing the full potential of ABM in sociological Systems.
- Objective not Ensured: Gao et al. [67] expresses that the strict internal communication structures and the moderately available cooperative efficiency of achieving the actual simulation objective cannot be guaranteed with ABM and therefore is a challenge that must be faced when using this paradigm.
- Required Data: Reddy and Telukdarie [144] name the amount of data required is one of the largest challenges to be solved when using the paradigm to solve a problem.

4.4.2. Selection Arguments Discrete Event Simulation (DES)

Table 4.4 shows a quantitative processing of the arguments as to why DES was the right paradigm for the authors to approximate the problem and the use case.

In the following, the chosen umbrella terms of the argumentation are described in more detail.

- Complex Systems: According to Pfeiffer et al. [138], Discrete Event Simulation (DES) makes it possible to depict dynamic operational processes of a complex nature with

Table 4.4: Reasons for DES Selection

		Papers			
Argument	**freq.[#]**	[138]	[68]	[85]	[161]
Complex Systems	1	o			
Different Data Sources	1		o		
Easy to Use	1			o	
Large Nr. of Variables	1				o
Scenarios	1	o			

ramified dependencies and to examine these case specifically for different impact factors.

- Different Data Sources: Garcia-Herreros et al. [68] see the possibility of integrating different data sources into the simulation as a core element of the argumentation for the use of DES in the modern data-driven machine industry with inventory systems, and accordingly use it as an argument for why DES was chosen as the paradigm.
- Easy to Use: Kabirian [85] relates the temporal consideration of discrete time steps in a supply chain to the uniform discrete consideration of DES. this consideration allows users to generate a simulation quickly in Microsoft Excel, which has the advantage that no additional tools and, in general, no additional training for a new simulation are necessary. The Microsoft Excel standard tool “Solver”, which can numerically find an optimal result for a test set by changing single parameters, is outlined in his argumentation because, in his opinion, it leads to a simplification of optimization processes.
- Large Nr. of Variables: Due to the many variables that appear in connection with the computer-aided examination of a supply chain, Sharda and Vazquez [161] no longer use mathematical programming approaches, as the complexity and effort required would exceed the benefits. This is also given as a reason for the use of DES. Whether this is a definite advantage over other paradigms such as ABM, or if it is only generally based on the computer-aided simulation, cannot be deduced from context.
- Scenarios: Besides the argument that DES is suitable for dynamically complex problems, Pfeiffer et al. [138] mention the flexible adaptation of the model as a basis argumentation for the use of DES as a paradigm. Thus, different scenarios can be played out to optimize various parameters across iteration steps.

It is noticeable that, compared to the argumentation for ABM, the number of explanations as to why DES was used is quantitatively much lower when counted in frequency. When DES and the characteristics of the paradigm are described, the statements have a general tendency, but do not refer to the use cases in which they are applied. To broaden the scope of the investigation, the search criteria of the arguments are relaxed. In the following subsection, all statements in the examined works are noted, which are either written in terms of

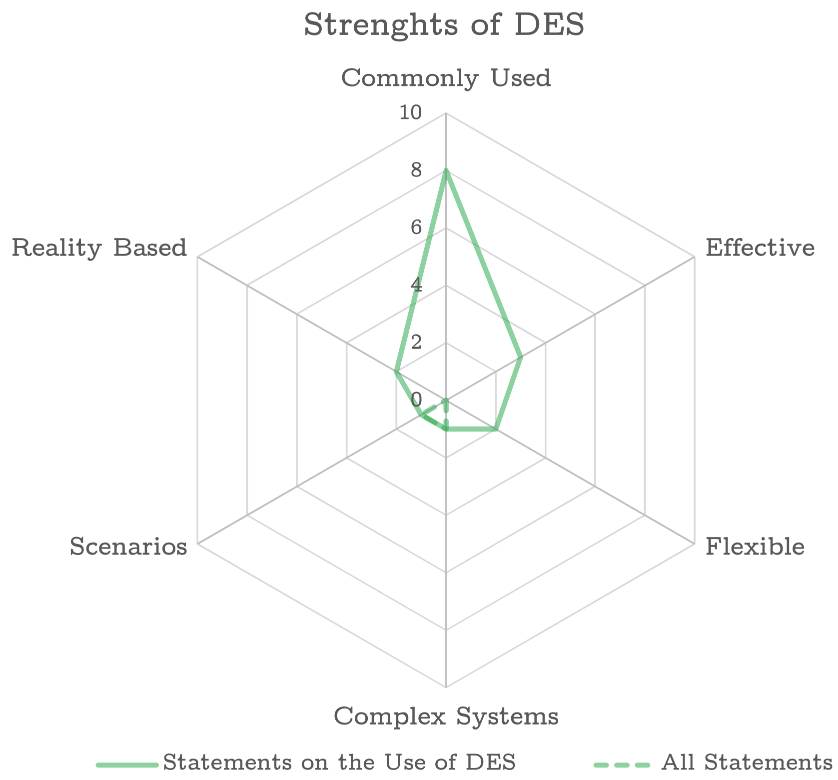

Figure 4.4: DES most named Strenghts

a strength or weakness of the paradigm, even if they only have a descriptive character and are not related to the direct line of argumentation for the selection of this paradigm. Nevertheless, this observation allows us to draw conclusions about the authors' attitude towards the paradigm, since they have written or quoted it in their works, which in a way reflects their view and opinion of the paradigm.

Altogether, a list of 10 benefits were found in the scientific papers. A list of all arguments found can be found in Appendix A, Table A.4.

In order to find the six most-mentioned arguments, a so-called spider diagram is used (see Figure 4.4). The axis to the outside indicates the frequency of occurrence of an argument, which is summarized under a key statement at the outer edge.

The solid line shows the absolute frequency of all arguments, while the inner dashed form shows whether such an argument was also used as a direct basis of argumentation for the use of DES as a paradigm and if so, how often. That the number of vertices of both figures do not match means that that not all of the advantages mentioned were ultimately used to justify the use of the paradigm with a corresponding argument.

The fact that, compared to agent-based modeling (see Figure 4.3), the most cited advantages of the paradigm do not coincide with the arguments used to justify its application make it necessary to revisit the arguments and explain them in more detail in order to gain a deeper insight. Only the arguments regarding the possibility of testing different scenarios and the ability to map complex systems were also used as arguments for the use of the paradigm. Their definition is not discussed again here and can be looked up on page 4.4.2

of this thesis.

- Commonly Used: The universal applicability of DES and the resulting usability in many areas is the most frequently mentioned advantages of Discrete Event Simulation. Abolhasani et al. [7]points out that in the context of supply chain simulation, DES is the most used paradigm besides system dynamics (SD). Mittal and Krejci [122] refer to various simulation studies and the successful implementation of the paradigm contained therein. They conclude from this the broad applicability of the paradigm.
- Effective: Pinho Pinho et al. [140] presents DES as an efficient tool to illustrate the complex stochastic nature of supply chain issues. Rabe et al. [141] also advocates the efficiency of DES, but only if events occur only at discrete points in time. In contrast, Wang and Takakuwa [180] consider the efficiency of DES to be more that the paradigm can be quickly combined with other modules, allowing a first solution to be found quickly.
- Flexible: Allen [10] refers to the flexibility that DES enables, addressing the dynamic field of modeling aircraft manufacturing supply chains. A similar argument applies to standard production systems, according to Garcia-Herreros et al. [68].
- Reality Based: Rasnick and Chatfield [143] as well as Rehman and Ryan [145] refer to the natural representability of reality that can be achieved using DES. Rasnick and Chatfield [143] explain their assumption by saying that the material and information flows of one of associated interactions can be represented as a set of events that can be modeled to discrete points, thus corresponding to the actual nature of discrete event simulation.

There may be several reasons why the arguments in favor of using DES do not coincide with the benefits most often mentioned. One possible argument would be that because DES is so well established and anchored in simulations, argumentation for its use is unusual because developers do not deal with it in detail.

When they emphasize the advantages of DES, authors mostly refer to their experiences in another or even the same field, including supply chain modeling and simulation. The argument of the natural and realistic representability of a system, alongside the scenario depictability of and testing of complex systems that DES enables, is rarely used in comparison. It appears that arguments in favor of discrete event simulation are aimed towards ease of use, which is also because in many fields, a lot of use cases wit the paradigm are available.

Identical to the processing of the advantages of DES mentioned in this scientific work, the challenges mentioned are also highlighted. Due to the lack of quantity of arguments to be found, in contrast to the advantages, a spider diagram is not used. Instead a table, which shows the key statement and its frequency and assigns the terms to the corresponding works (see Table 4.5). This can be identified by the bibliography entry number. In addition to naming the arguments, the elements are also described and explained and defined.

Table 4.5: DES named Weaknesses

		Papers		
Argument	**freq.[#]**	[183]	[10]	[122]
CAS	1	o		
Effort	1		o	
Human Involvement	1			o

- CAS: According to Wen-li and Yao-wen [183], DES cannot map the dynamic complexity prevailing in supply chains, which makes the method unsuitable for interacting supply chain networks.
- Effort: Allen et al. [10] attributes the disadvantage of the simulation paradigm, despite its advantages in terms of flexibility, to the fact that it requires a lot of time and data for implementation, and accordingly cites this point as a weakness.
- Human Involvement: Real Decision making and the autonomy associated with it is neither the object nor the core of DES, and thus cannot be reproduced according to Mittal and Krejci [122]. The integration of humans and human behavior can be better reproduced with ABM [122].

If one summarizes the mentioned weaknesses in relation to the topic, it seems that authors do not refer too much to theory in relation to this paradigm, at least not in case studies. In comparison to the arguments mentioned in relation to agent-based simulation, only two valid arguments have been found here, which objectively and descriptively deal with the weaknesses of DES, if not directly in relation to supply chain management.

Nevertheless, it is possible to transfer the lack of representation of autonomy and the challenges of mapping CAS with DES to the topic of supply chain. If one focuses on these two arguments, it can be deduced that supply chains in which human behavior has to be taken into account, and also the dynamics of the system triggered by the behavior and development of individuals and groups that contribute significantly to the simulation outcome, are difficult to map using DES. It lacks the agent structure that ABM provides to provide the autonomy and the required basic dynamic structure.

To be able to argue this conclusion more soundly, however, several statements from modelers are missing.

4.4.3. Comparison ABM and DES

The number of arguments regarding the paradigm selection of agent-based modeling greatly exceeds the number of arguments that can be found in the DES-based papers and accordingly deal with the applicability of this paradigm. Even under extended consideration and including the non-use case relevant descriptions of the paradigm, the situation doesn't change.

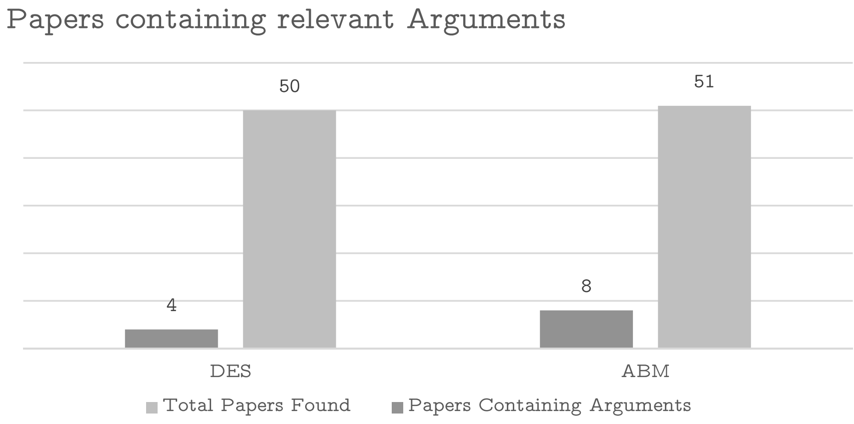

Figure 4.5: Argument Count.

The difference in number not due to the unequal distribution of papers and the paradigms assigned to them. As Figure 4.5 shows, the number of papers considered in terms of the distribution of paradigms used is almost the same, but there are twice as much papers in which arguments and objective theoretical statements were found regarding ABM. It has to be noted, that hybrid approaches were not taken into account in this count.

One possible theory regarding this finding is that the use of agent-based modeling in the field of supply chain simulation and other areas of industry has only become popular in recent years.

With this upswing, the paradigm is gaining ever more interest in the community, and more people are looking into it as an option. This shift in the paradigm itself has caused modelers examine the paradigm in more detail, to determine whether or not it is appropriate for their problem. This would imply that the choice of ABM in those cases was not a habitual one, but that through their research, the modelers concluded that ABM fits or could fit their problem. This theory is supported by the fact that the novelty argument of agent-based modeling and the associated curiosity have been used as argument for the usage of ABM.

Unlike agent-based modeling, there are few arguments as to why DES was used. One of them is that DES has been successfully applied in many areas of industry, and was therefore chosen as the basic paradigm for the case study. This line of argumentation is different from that for ABM. While ABM was examined for its applicability, DES was assumed to be applicable, which was reflected in this investigation by the few arguments presented. It can, therefore, be assumed that DES is already well established in the field of supply chain modeling, and that ABM has yet to establish itself.

In addition to the different frequencies with which descriptive arguments and explanations regarding the use of a specific of a paradigm are used, there are also differences between DES and ABM in terms of the strengths and weaknesses they have expressed, which, based on the papers examined, distinguish them and make them suitable for modeling, or especially for different topics of supply chain simulation.

If the arguments, including the advantages and disadvantages of the paradigms are compared, it is striking that the applicability and interpretation of the paradigms differ in four areas. The points mentioned here compare the advantages of one paradigm with the disadvantages of the other and vice versa, which brings out the biggest differences.

- Applicability to CAS
- Human Centered Development
- Available Resources and Effort
- Structural design of the system to be mapped

While the modeling of complex adaptive systems is mentioned as one of the strengths of agent-based modeling, the mapping of such a system is perceived as difficult when using discrete event simulation. Even though human-centered design is involved, and human activities and traits such as authority play an essential role in modeling and simulation output, ABM appears better suited for this purpose, based on the evaluation of the arguments, as the agent-based structure that constitutes ABM allows for the modeling of individuals, and the enabling of learning curves can be integrated into a dynamic environment.

On the other hand, ABM requires some resources that must be provided or can be provided to set up a simulation. DES seems to be more manageable due to its broad usability in many areas, flexibility and applicability, and with few resources, simple simulations can be performed. This is supported by the integration of many data sources, which can be networked in the simulation model.

The last difference regarding the applicability of a paradigm is the ability to map the structure of a system. ABM appears more suitable to map distributed nodes that communicate with each other, as it is the case in a modern supply chain network. Such a distributed simulation can be modeled as a social simulation, and the loosely coupled commands and interactions make it possible to model such a system. In contrast, DES is used to model centrally stored processes, such as those found in machine production scenarios.

A decision matrix is derived from the above statements. Based on questions and the statements made therein, decisions can be made as to which paradigm is suitable for the problem at hand, considering the underlying system, available resources and the human factors. Table 4.6 shows the output. On the left are the core questions, while on the right are the possible answers, assigned to a paradigm. Depending on priority, this can be a first indication for the selection.

The paradigm that is best suited for a supply chain analysis depends on various factors and cannot be generalized. One aspect that should never be overlooked is the experience already gained by developers. ABM-experienced and interested people will tend to deal with this paradigm and not with DES, and vice versa. This aspect cannot be depicted here, and it is up to individuals to decide to what extent this is included in the weighting.

Table 4.6: Decision Matrix Paradigms

Quetions	ABM	DES
What is the structure of the system to be created?	de-centralized	centralized
Is a dynamically emerging system behavior necessary?	yes	no
Are human interactions, decisions and autonomy core elements?	yes	no
Which resources and data are available?	many	few

Although the chains of argumentation found in scientific papers are mainly identical and can give a good picture to derive the advantages and disadvantages of the opposing paradigms, several different areas would have to be investigated and analyzed concerning paradigm selection, not only concerning the supply chain. Furthermore, it would help to interview developers actively, to follow their motives, and not only to interpret their choice of paradigm based on their statements.

4.5. Shared References

In Section 4.2, conclusions are drawn based on the statements made in the scientific papers as to the reasons for choosing one of the modeling paradigms addressed here. In addition, an objective analysis of the weaknesses and strengths of the paradigms will be quantified and compared in order to test the fields of application and especially the applicability of the paradigm in relation to Supply Chain Simulation.

As difficult as it is to find a uniform definition of each paradigm, it is also difficult to differentiate which opinions originate in the minds of the modelers and which were formed based on other works.

It can be assumed that cited works that deal with the paradigm have at least a moderate impact when it comes to forming opinions, ultimately influencing the choice of paradigm. Furthermore, it can be assumed that works that are repeatedly used as references in various papers are the basic building blocks learning for supply chain modeling, agent based modeling, and discrete event simulation, upon which definitions and theses are based.

The aim of this section of the thesis is to examine the works filtered out in Section 4.2, which deal with supply chains and their simulation, focusing on their common references. The objective is to find out which papers and authors are deeply rooted in these topics, to what exactly these papers refer, and which statements and definitions are formative in the branch of paradigms in the context of supply chain simulation.

In addition, it is to be found out to what extent representatives of one paradigm deal with the other, which is also to show how strict the dividing line between the two ways of thinking and modeling is, or whether scientific works refer to both paradigms, compare, and, based on this comparison, make a judgment on the use of a specific paradigm.

First the generation and processing of the data is explained. After revealing the works most frequently cited in the papers examined, they are grouped by topic. The topics ABM, DES, and framework will be further explored by describing the content of the most cited work in each topic. This should provide insight into which works are relevant for their disciplines due to their frequent use in other papers.

Finally, we will examine to what extent authors who have addressed supply chain topics based on agent-based modeling also refer to DES-oriented works and vice versa, in order to find out how strict the line of these paradigms and their representatives is.

4.5.1. Proceeding of References

In order to be able to analyze the reference lists of single papers in terms of commonalities, digital computer-aided processing is used. The source of the reference lists is Scopus [4], which is the world's largest database for abstracts and quotations of literature [6]. For each paper, the corresponding reference list is downloaded as BibTeX file and imported to Microsoft Excel. A BibTeX file is a special formatted text file holding references for specific literature [3]. The uniform formatting makes it easier to automatically analyze the sources without having to go through all citations manually. For papers that were not listed in the Scopus database, BibTeX entries are prepared manually and entered into the database for further research.

An example of a single reference of a paper is shown in Fig 4.6. In addition to title, year, and author(s), the BibTeX file often contains other information that is not processed in this paper. Only these attributes are important and of interest.

```
@article{
    author={Bhargava,Hemant K. and Sridhar,Suresh and Herrick,Craig},
    year={1999},
    title={Beyond spreadsheets: Tools for building decision support systems},
    journal={Computer},
    volume={32},
    number={3},
    pages={31-39},
    note={Cited By :42},
    language={English},
    url={www.scopus.com},
}
```

Figure 4.6: BibTeX entry example

By using various coded algorithms, all the information in the BibTeX files is extracted and brought into an Excel-exploitable form to filter out the most cited literature from the considered papers. The information about from which works the quote originates must not be lost. This information is needed to understand the thematic cross-links. The result of this step is a list of about 2000 citation entries.

Table 4.7 shows works that have been cited in at least four different scientific papers. In addition to the author and the name of the work, the table also indicates the year of publication and the bibliographical number with which the literature in this work can be clearly identified.

Regarding the year of publication, it should be noted that when different versions of a work appear in the quotations, the year of publication that appears most frequently is used. If there was no clear decision, the list refers to the oldest version to which reference was made.

To achieve a classification true to the theme, the works are additionally divided into five thematic blocks, which are described as follows:

- *ABM (Agent-Based-Modeling)*: Some works deal (almost) exclusively with Agent Based Modeling. These range from use cases to theory books that explain the entire topic of ABM from the ground up.
- *DES (Discrete Event Simulation)*: As with ABM, this category includes all those works that focus on and deal with DES.
- *FW (Framework)*: The work listed here is less concerned with either paradigm or its theory per se, but rather moves a framework to the center of the discussion. For this reason, this section has been considered separately.
- *SCS (Supply Chain Simulation)*: All the works grouped under this sub-item have a central theme of supply chain simulation. The scientific works were listed here if they could not be specifically assigned to a paradigm or if they generally deal with the symbiosis of supply chain analysis and simulation.
- *SIM (Simulation)*: Detached from the paradigms and the topic of supply chain analysis and simulation, this category includes literature that deals with the topic of simulation itself. Starting with a book, which is a simulation program, up to general preparation for the topic of simulation, this category covers simulation topics that cannot be accommodated in previous categories.
- *THEO (Theory)*: Even though the present work is mainly concerned with computer aided simulation, especially in the supply chain environment, this category includes those works that deal with theoretical foundations, such as the bullwhip effect or economic topics that serve as a basis for later simulations. These works will not be examined in detail.

Table 4.7: Most Cited Literature

	authors	year	Title of Paper
ABM			
[109]	Macal and North	2014	Introductory tutorial: Agent-based modeling and simulation
[106]	Li et al.	2010	The evolutionary complexity of complex adaptive supply networks: A simulation and case study
[135]	North and Macal	2007	Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation
[111]	Macal and North	2005	Tutorial on agent-based modeling and simulation
[26]	Bonabeau	2002	Agent-based modeling: Methods and techniques for simulating human systems
DES			
[123]	Mobini et al.	2011	Forest biomass supply logistics for a power plant using the discrete-event simulation approach
[14]	Asikainen	2010	Simulation of stump crushing and truck transport of chips
[18]	Banks et al.	1996	Discrete-Event System Simulation
SD			
[166]	Sterman	2000	Business Dynamics: Systems Thinking and Modeling for a Complex World
[165]	Sterman	1989	Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment
FW			
[69]	Giannakis and Louis	2011	A multi-agent based framework for supply chain risk management
[168]	Swaminathan et al.	1998	Modeling supply chain dynamics: A multiagent approach

Table 4.7 continued from previous page

	authors	year	Title of Paper
SCS			
[113]	Mahmoudi et al.	2009	Logistics of supplying biomass from a mountain pine beetle-infested forest to a power plant in British Columbia
[121]	Min and Zhou	2002	Supply chain modeling: Past, present and future
[195]	Zhao and Xie	2002	Forecasting errors and the value of information sharing in a supply chain
[33]	Cachon and Fisher	2000	Supply chain inventory management and the value of shared information
[103]	Lee et al.	2000	Value of information sharing in a two-level supply chain
SIM			
[159]	Sargent	2009	Verification and validation of simulation models
[87]	Kelton	2002	Simulation with Arena
[98]	Law et al.	1991	Simulation Modeling and Analysis
[52]	DONNELLY	1984	Design and Analysis of Experiments
THEO			
[172]	Tang	2006	Perspectives in supply chain risk management
[79]	Holweg et al.	2005	Supply chain collaboration: Making sense of the strategy continuum
[174]	Terzi and Cavalieri	2004	Simulation in the supply chain context: A survey
[74]	Gruen et al.	2002	Retail Out-of-Stocks: A Worldwide Examination of Extent, Causes and Consumer Responses
[41]	Choi et al.	2001	Supply networks and complex adaptive systems: Control versus emergence
[38]	Chen et al.	2000	Quantifying the bullwhip effect in a simple supply chain: the impact of forecasting, lead times, and information
[21]	Beamon	1999	Measuring supply chain performance

Table 4.7 continued from previous page

	authors	year	Title of Paper
[102]	Lee et al.	1997	Information distortion in a supply chain: The bullwhip effect
[101]	Lee et al.	1997	The bullwhip effect in supply chains
[42]	Christopher	1992	Logistics and Supply Chain Management

4.5.2. Most cited ABM literature

The work *Agent-based modeling: Methods and techniques for simulating human systems* written by Bonabeau [26], was cited most frequently in the specialized literature regarding agent-based modeling. In total, it has been mentioned in 10 of the papers that were examined.

This article, published by Bonabeau in 2002, deals with agent-based modeling in general. After a short introduction, the usage of the paradigm in four different areas is discussed. The application areas under discussion included flow simulation, organizational simulation, market simulation and diffusion simulation.

The definition of the paradigm, which finds application and room in the work definition of regulated processes and definitions, states that agent-based modeling is thinking in terms of building blocks that make up a system, which can also be described as microscopic modeling. In addition to this definition, which emphasizes ABM more than mindset, which modelers adopt to represent reality, the author also highlights three advantages that the paradigm enables and, when used correctly, sets it apart from others in a positive way. These three statements are listed below.

1. ABM can map emergent behavior
2. ABM is a natural representation of the system to be mapped
3. Flexibility

According to Bonabeau [26], the enabling of an Emerging Dynamic System results from the ability to map the interactions of single individuals embedded in the simulation. This opens the possibility to conclude on group behavior based on the behavior of individuals. If rationality or the ability to learn is imparted and these characteristics are anchored in the individual agents by means of rules, it is also possible that the dynamics of the simulation will develop on the basis of the behavior of individual actors. According to Bonabeau [26], it is precisely this mapping of the reality by means of individually acting entities that makes it possible to easily convert a given environment of the task under investigation into a model, since in both real-world and agent-based modeling, individuals act independently, thus establishing similarity. This is the second point that the author emphasizes as a strength of the paradigm. The third point of flexibility is a result of the dynamic adaptability of the simulated environment and the adaptation of the individual agents, which react to the changes accordingly.

Among the three points cited, the author mentions the ability to track emergent behavior as the dominant criterion that provides the greatest advantage. Although Bonabeau [26] does not go into detail in his work about the influence of Agent-Based-Modeling on supply chain issues, two out of the three advantages mentioned are used as arguments in the papers examined in this thesis to justify the use of this paradigm (see Table 4.2).

In his work, Bonabau [26] not only emphasizes the strengths of agent-based modeling, but also highlights the challenges he sees in connection with this paradigm. According to Bonabeau [26], the biggest challenge is resource-intensive implementation. The effort, the degree of difficulty and the resulting costs can be a hurdle when implementing a complex model, and much depends on how real the world to be recreated in the simulation must be. This is also consistent with the statements that were found in the investigation into the negative aspects of ABM (see Table 4.3).

The consistency between the arguments found in the works studied and those documented in the most cited work suggests that these statements are based on a universal view of the paradigm and reflect the characteristics of the paradigm. ABM seems to have precisely the weaknesses and strengths that authors allude to in their works, whereby the strengths exceed the effort required to extract them, at least in the works studied, but do not prevent the authors from using the paradigm.

At the same time, this work can be considered a fundamental contributor to the definition of Agent-Based-Modeling, carried forward in works by its renewed appeal.

4.5.3. Most cited DES Literature

The most cited work in connection with DES is a book written by Jerry Banks [18], *Discrete-Event System Simulation*. 16 % of the DES-focused papers studied referred to this work.

The book covers much more than the core of discrete-event simulation. Besides a general introduction to the term simulation, it describes the advantages and disadvantages of various simulations. The work does not focus on DES specifically, but evaluates the usefulness of using a simulation depending on certain boundary conditions.

Besides the general introduction to simulations and their associated process steps proposed by Banks et al. [18], which are frequently cited in the literature, he also deals with the principle of discrete event simulation. This starts with basic assumptions and progresses to run-throughs of individual examples, where the principle is explained.

Banks does not comment on the strengths and weaknesses of the paradigm. Neither is the topic of supply chain modeling specifically addressed in this work. As a result, arguments in favor of or against the paradigm cannot be crosschecked.

Due to the frequency with which this work is cited and the associated anchoring of Banks' thought processes in those who wrote works after him and referred to him, Banks' definition and viewpoint certainly had a considerable influence on themes written afterward. For this reason, the definition provided in his book is applied here once again.

"Discrete-event systems simulation is the modeling of systems in which the state variable changes only at a discrete set of points in time" - Jerry Banks [18]

4.5.4. Most cited Framework Literature

While this section of the thesis covers the paradigms ABM and DES to a far greater extent than the frameworks that are applied, the topic of frameworks occurs in this thesis, in the context of examining the applicability of a new framework to SCS, so the topic is also considered here.

The work that was most often cited as a reference concerning frameworks for simulation and modeling, and thus the work that seems to have a strong influence on the modeling approach of developers, is *Modeling supply chain dynamics: A multiagent approach*, written by Swaminathan et al. [168].

In 1998, when the paper was published in the journal Decision Sciences by Jayashankar Swaminathan, the increasingly central role of a well-functioning supply chain was well known. Only a well-performing supply chain network could enable the success of a networked company in the already competitive market. The resulting need to develop a time-efficient and resource-saving methodology that enabled correct decisions to be made in supply chain dynamics was correspondingly significant.

For this purpose, a developed framework is presented in this scientific work, which intended to make it possible to quickly and easily generate comprehensible models that help to make strategic decisions based on the simulation results.

The core idea is to identify individual elements of the supply chain that have the ability to interact with a subset of controls [168]. The individual agents belong to a grouping within the supply chain and accordingly have unique abilities and characteristics in how they interact with their environment. Furthermore, agents are divided into two groups according to their function.

These are structural elements, which include all agents that are directly involved in operational activities and the associated material flow in a supply chain, and control elements, which are responsible for the coordination of activities based on predefined policies [168].

These elements, drawn in Figure 4.7, form a simulation library, which, unlike other approaches, makes it possible to create and reuse a simulation model based on the prefabricated modules in modular design without extensive programming effort. This re-usability is the biggest advantage of the approach.

4.5.5. Interaction of the Subject Areas

To illustrate the relationships between the papers and their referencing articles graphically, a diagram graphically uniting the origin of the source and referenced articles with a 1:1 connection is used (see Figure 4.8).

The paper titles are arranged around the perimeter, indicated by their bibliography number, by which they can be clearly identified throughout this work, and can be referenced in the attached bibliography. The works studied and the works cited therein are graphically separated in Figure 4.8. Papers that have been examined are identified by the term Referential Literature at the outermost edge of the figure. The resulting most frequently cited works are graphically separated from the others by the term Reference. A granular consideration and classification of the scientific works takes place at the inner perimeter.

The works examined for their statements are distinguished between ABM, DES and hy-

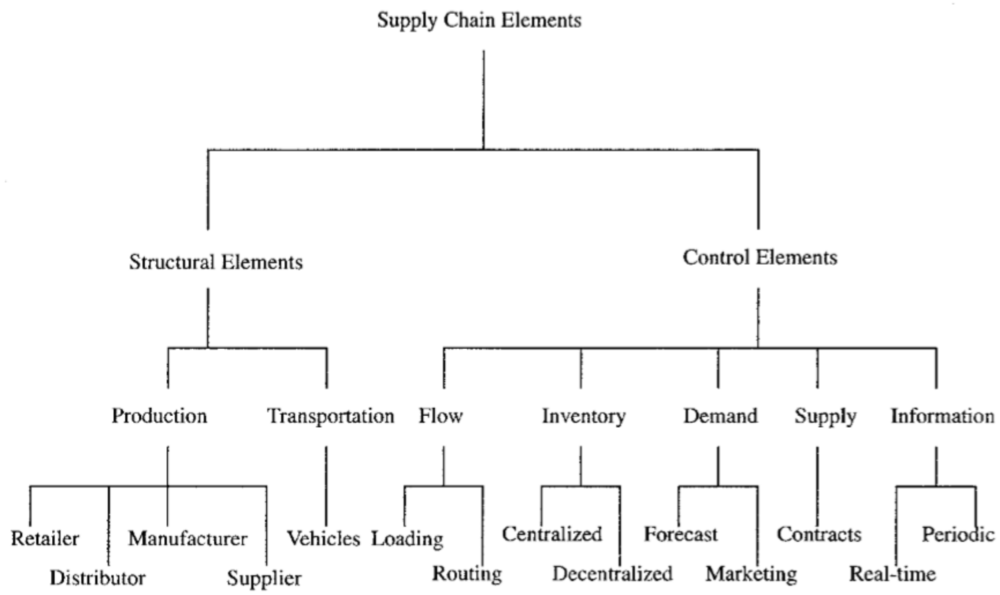

Figure 4.7: Library Supply Chain Simulation (Swaminathan et al. [168])

brid paradigms, which represent a combination of the two mentioned. It is important to note that only those works that have also quoted one of the most frequently referenced works are graphically illustrated, in order to preserve the clarity of the illustration.

As explained in Section 4.5.1, a distinction is made between the following six subject areas for the works cited.

- ABM (Agent-Based Modeling)
- DES (Discrete Event Simulation)
- FW (Framework)
- SCS (Supply Chain Simulation)
- SIM (Simulation)
- THEO (Theory)

Again, only those works are shown to which at least four different papers are referenced.

The coloring of the individual lines emphasizes additional information about which works refer to which subject area, and how strict the individual paradigms are with regard to their citation of other paradigms.

A tabular presentation of this graphic can be found in Appendix A, Table A.6.

It is noticeable that the colors in the graphic 4.8 do not mix strongly in the area of paradigms, which means that developers and authors who deal with a paradigm also predominantly refer to it. To elaborate on this fact, Figure 4.9 shows a flow diagram, which graphically illustrates the relationships without going into the level of detail of the individual papers.

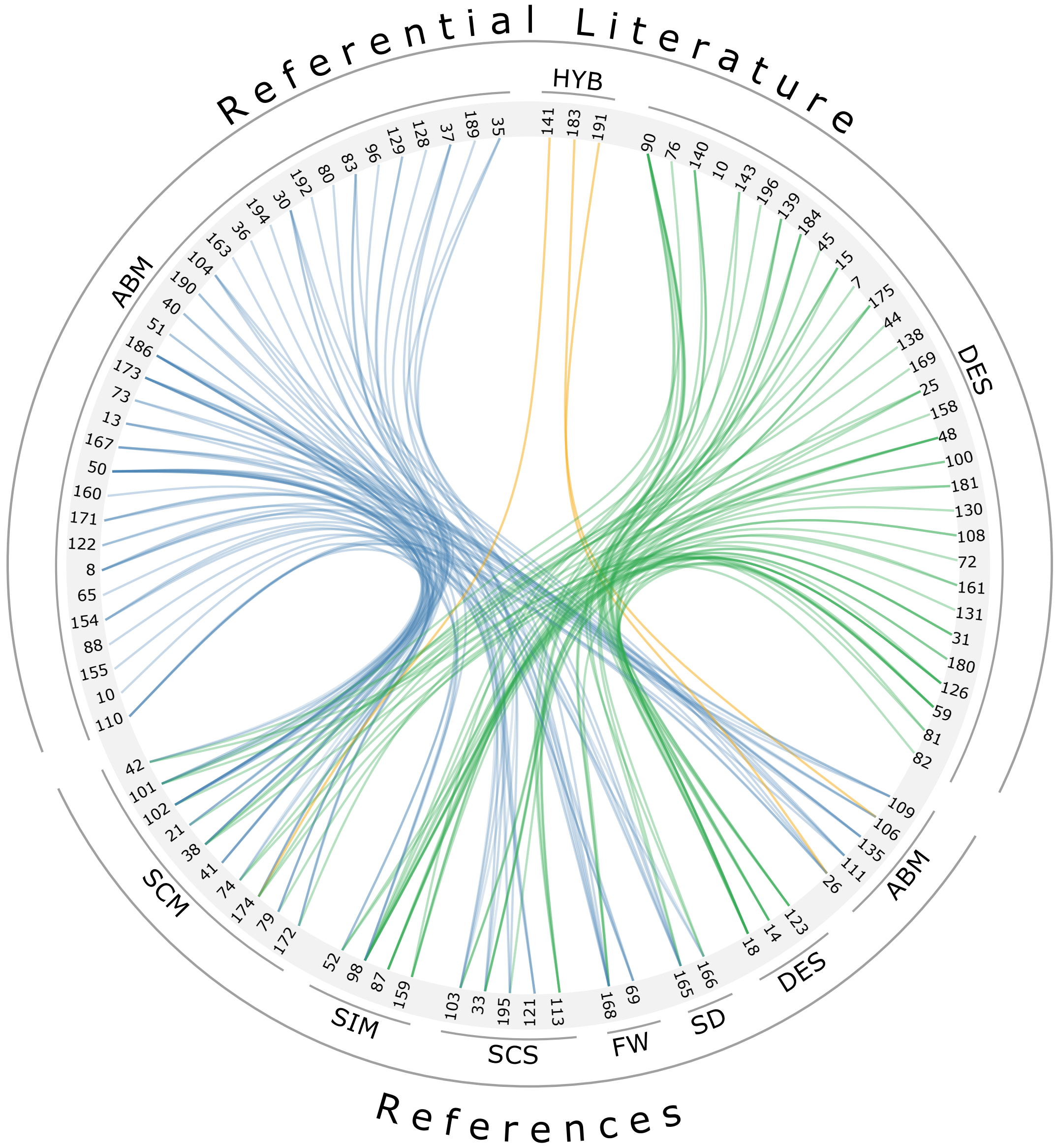

Figure 4.8: Citation dependencies

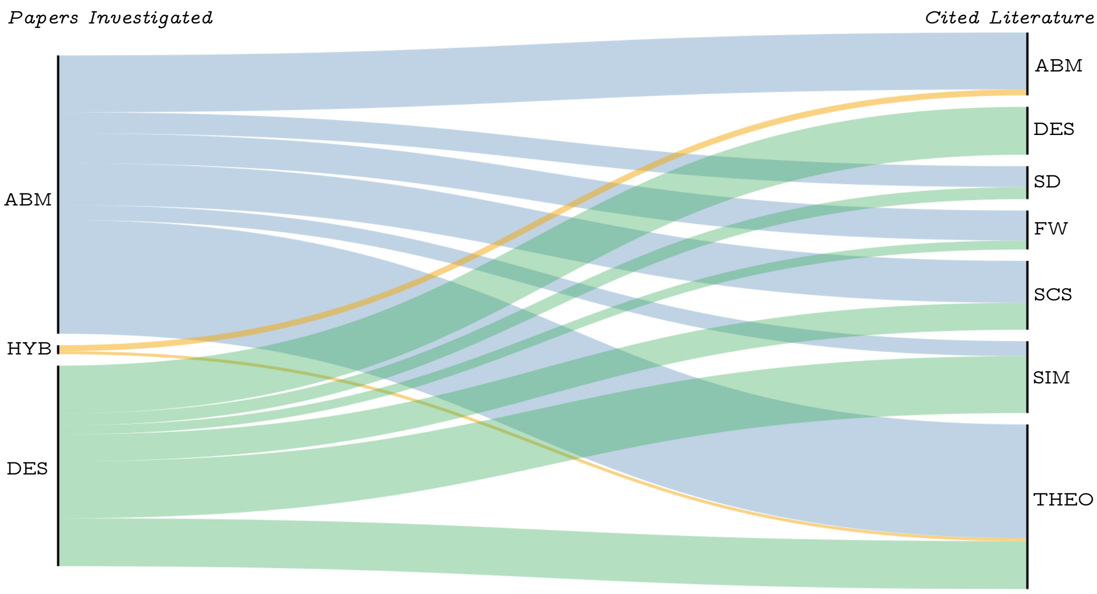

Figure 4.9: Interactions between different paradigms

Figure 4.9 confirms what was indicated in Figure 4.8. Authors who deal with a paradigm usually only refer to those works that originate from this paradigm or deal with it directly. There are a few cross-references. However, this can have several causes and is not necessarily related to the fact that they do not scientifically deal with other paradigms and approaches outside of their written work. This may be the case, for example, if they have already decided on a paradigm with which they want to approach the problem in advance of the work, and only treat and write the treatise in their work.

Of the 48 papers that provide arguments for ABM and the 18 that fulfil the same function for papers dealing with supply chain simulations concerning DES, only two papers provide arguments for both paradigms, meaning that only two authors had demonstrably dealt with both paradigms at the time they wrote the paper. These two works are listed below.

- *A Hybrid Simulation Model of Inbound Logistics Operations in Regional Food Supply Chains* by Mittal and Krejci [122]
- *Procedures to accommodate system fluctuations that result in buffer compromised systems governed by the theory of constraints* by Reddy and Telukdarie [144]

Both are hybrid simulations, which combine Agent-Based-Modeling and Discrete Event Simulation, and therefore had to deal with both paradigms. The reason why the cross-linkage from HYB to DES is not shown in Figure 4.9 is that the cited DES papers were cited fewer than four times, which means that they fall out of the grid in the visualizations.

All other simulation approaches are separated from each other in their chain of argumentation, and based on the statements made in these works, do not deal with the other paradigm in terms of advantages and disadvantages. This supports the theory that the authors, at least in writing, do not deal with advantages and disadvantages, and that this can lead to a one-sided view of the paradigm.

4.6. Conclusion

The examination of scientific works published throughout the last few years in connection with supply chain theory based on the paradigms ABM or DES has provided an insight into the chains of argumentation that modelers, developers, and authors use to argue the use of the paradigm in a specific problem. Their view is also consistent with the statements and theses found in literature, which are further substantiated by statements in papers.

Concerning ABM, one of the main arguments used is the specificity, human based structures, systems, and interaction required due to the agent-based modeling knowledge and structure of the model. This, combined with the possible human-centered modeling approach, which is in line with the real world view, makes ABM appear to be a suitable paradigm for supply chain issues where humans play a central role. The learning ability of the individual agents, their autonomy, and freedom of decision is based on stored rules and boundaries that loosen the rigid structures when the model is initialized and adapt to the behavior of the system during the simulation. This is also the main argument by Bonabeau [26], the author of most cited paper examined in this scope, *Agent-based modeling: Methods and techniques for simulating human systems*. This explains why ABM differs from other paradigms, and why it is a viable modeling tool in system studies in which interactions of individuals contribute to system dynamics. The areas of application proposed by Bonabeau [26], for which ABM is well suited, are dynamic sectors with predominant flows, such as traffic and customer flow management, market insured industries, simulations in which orations with their risks and strategic interpretations are taken into account, and finally diffusion in terms of innovation and adoption dynamics. Even if Supply Chain Simulation is not explicitly mentioned, these are all partial areas of investigation that are relevant to a supply chain and from which the use of ABM can be argued. However, this paradigm must consider that it often involves a lot of effort and data to function, which may negate the application of the paradigm in small research environments.

In contrast to ABM, DES is better suited, based on the evaluation of the argumentation of the modelers and developers, to carry out a scenario investigations with relatively few resources. Thus, DES is particularly suitable for simulation studies that investigate a rigid structure and do not consider emerging systems.

With regard to common user references, even with this smaller number of underscored works, tendencies can be seen that are representative of these works and must therefore be taken into account in the prevailing themes. In the framework under investigation, Bonabeau [26] for ABM and Banks et al. [18] for DES stand out, as they are increasingly being referenced and are thus thematically influential in newly written works.

Furthermore, the examination of references has shown that authors only refer to thematic focuses that are directly related to their work. Thus, ABM-based scientific papers do not cite any works that focus on DES, and vice versa, at least if one determines this by looking at the most frequently referenced papers. this would mean that the two paradigms and their representatives interact little with each other, and thus the examination of which paradigm is best suited to a specific application is often lacking. An exception is in hybrid approaches, which try to present the strengths and weaknesses of both paradigms transparently and derive their approach from this.

It should be noted that this study and discussion of the use of ABM and DES is based only on the works found in a limited period that address a supply chain issue through a case study. A broad statement is, therefore, not possible. A further fact to be considered here is that the authors and groups of authors within their works only deal with the paradigm that is in use. This limitation further complicates cross-referencing and comparing the two paradigms. To make a more granular statement, and to achieve a more in-depth insight into the use of the paradigm and the underlying chains of argumentation, a further step would be to interview authors, modelers of the works, and have their views on the paradigm explained.

In general, however, the literature research showed a clear picture of the arguments and main representatives developers and scientists use to connect the two different paradigms. Depending on the intended use and the structural design of the problem, one of the paradigms seems to be more suitable, although modeling is possible using both approaches.

In order to make the process of modeling more accessible and to support it along the way, frameworks have been developed which take over this role and support the modeling process by means of defined process steps and proposed tools and illustrations. Such a framework was developed by Furian et al. [64], known as Hierarchical Control Conceptual Modeling (HCCM) (see Section 3.4.3 for a more detailed description). To what extent the DES-based framework can be applied to the supply chain topic, especially with the background of the advantages and disadvantages of DES in this context, as disclosed in this chapter, will be discussed in the next chapter by a practical example of a simulation study.

5

Supply Chain Simulation Study Using HCCM

Frameworks serve as a guide and are intended to play a supporting role in the intended applications by providing appropriate guidelines, thus facilitating the work. In the context of a simulation study, conceptual modeling is possibly the biggest obstacle, which is essential for the general success of the study. A framework created to model DES simulation models conceptually is called Hierarchical Control Conceptual Modeling (HCCM) developed by Furian et al. [64].

In this chapter, this framework is placed in the center of the focus. Based on HCCM, a model of a simplified supply chain will be developed, with which a complete simulation study will be conducted. Thereby the applicability of the framework to the supply chain topic will be discussed as well as similarities to the results of the literature review on DES in chapter 4.

The structure of the model is based on the four phases proposed by Furian et al. [64] on which its framework is built. The theoretical treatment of this framework can be looked up in Section 3.4.3.

5.1. Problem Description and Identification of Goals

The focus of the study is a simplified supply chain, which is reproduced. As no real problem is transferred to the simulation, rather a simplified problem has been created. At the heart of the supply chain is a company that is the central node of the overall supply chain setup, receiving orders from customers and distributing them in the supply chain for fulfillment in the network. The model will investigate the influence of supplier relations on the overall performance of the supply chain.

The general goal of the modelled supply chain network is to accept customer orders and process them as efficiently as possible based on the available resources, considering certain

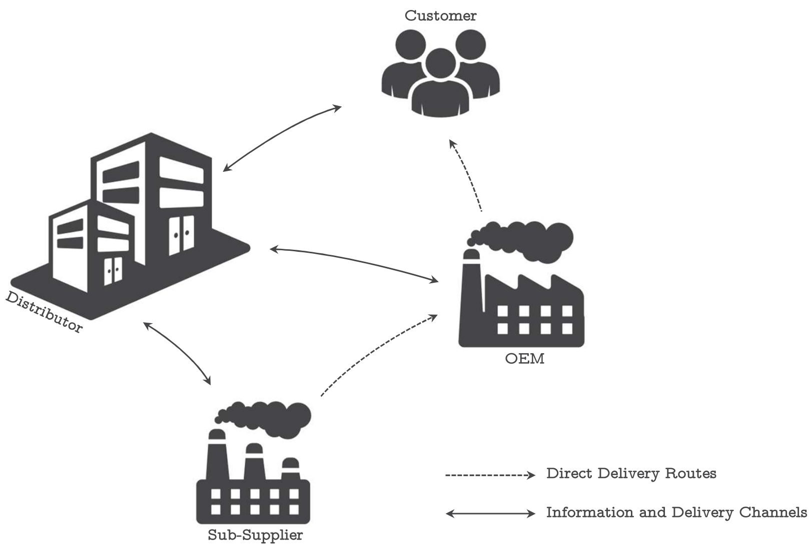

Figure 5.1: Supply Structure

constraints. The network available for this purpose consists of three basic entity types.

Figure 5.1 shows the model resulting from the iteration loops and how these different parties are networked, whereby for the benefit of clarity the number of suppliers is limited to one per level, i.e. one OEM and one sub-supplier. The rules of how the connections in the supply chain are organized remain the same, irrespective of the number of suppliers, which is why a simplified representation is permissible here.

The arrows in Figure 5.1, between the entity icons, symbolize a possible flow of material or information that can take place. The dotted lines indicate a material flow, enabled or prevented, depending on the simulation scenario. The effects of precisely these alternative direct material flow paths on the performance of the supply chain, measured by the average delivery time, are to be examined more closely by the simulation study.

The exact consideration and understanding of the problem, as well as how the different suppliers and entities of the supply chain are connected to each other, is addressed in the following sections within the framework of conceptual modeling.

5.2. The Conceptual Model

The following section documents the conceptual modeling of the system to be investigated, describing the result of an iterative process designed for finding the right approach to the topic given. The overall section is based on the HCCM framework. Thus, the four main phases of the HCCM described in Section 3.4.3 are also addressed and used to structure the content. A complete execution of the conceptual model including tables can be found in Appendix B.

5.2.1. Phase 1: Understanding the Problem

The goal of this phase of the framework is to understand the given system and background processes as well as the given boundary so far that the question of the simulation goal can be solved under consideration of these aspects in the simulation study.

A very first step was to identify the individual entities involved in the entire supply chain process. The aim was to identify involved stakeholders and entities from order placement to order fulfillment. This process of investigation spans the process from the customer, who places the order, to the supplier, who ultimately delivers the finished goods. These 4 parties span the entire ordering process and thus cover the entire supply chain.

- Customer
  Is a company or private person who is authorized to place orders which are then distributed in the supply chain network.

- Distributor
  The central control unit of the supply chain, which distributes and forwards received orders to suppliers and, upon receipt of the goods, carries out quality checks before the products are forwarded to customers. However, the distributor is not a manufacturing unit.

- Original Equipment Manufacturer (OEM)
  These are suppliers who manufacture end products. They have production lines (facilities) at their disposal on which the goods are manufactured.

- Sub-Supplier
  Similar to the OEM, these suppliers have production facilities at their disposal, where goods can be manufactured. They are responsible for providing the components to the OEMs so that the supply chain can manufacture final products in a closed loop.

Table 5.1 provides an overview of entities that were identified in this step. At the same time, the table also shows the attributes assigned to the individual entities and required for the ordering process. These include, for example, production facilities, warehouses or workforces, which complement the view of the entire supply chain.

The next step is to identify how the system of entities is constructed and how they interact with each other. There are two cases to distinguish, from which the corresponding transport routes can be derived. The decisive factor is the relationship between supplier and distributor, referred to as Trust Level (TL).

- Trust Level 0: Suppliers are not allowed to deliver the products to the clients directly. Both sub-components and end products must be shipped via the central supply chain node, where they undergo a final quality check to evaluate and ensure the quality of manufactured products before they are finally forwarded to the customer. Suppliers and

Table 5.1: Entities and their associated attribute within the Supply Chain

Entities	
Entity (→ Attribute)	**Explanation**
Customer	Physical person or company that can place an order
Distributor	Central point of accumulation of information, from which orders are distributed and quality checks are performed
→ (Un)Loading Area	Area where trucks can dock, where they are unloaded and loaded
→ Warehouse	Area with storage capacity, where products can be temporarily stored
→ Inspection Area	Area where quality checks of the final products are carried out
→ Workforce	Workers who belong to the structures to be depicted
OEM	Supply chain partner who provides finished products
→ (Un)Loading Area	Area where trucks can dock, where they are unloaded and loaded
→ Warehouse	Area with storage capacity, where products can be temporarily stored
→ Assembly Lines	Assembly Lines, where end products are assembled from sub-components, and finally packed
→ Workforce	Workers who belong to the structures to be depicted
Sub-Supplier	Supply chain partner, which provides semi-finished products and components
→ (Un)Loading Area	Area where trucks can dock, where they are unloaded and loaded
→ Warehouse	Area with storage capacity, where products can be temporarily stored
→ Production Lines	Production line, where sub-components are manufactured from raw materials
→ Workforce	Workers who belong to the structures to be depicted
Product	Physical products that are manufactured and shipped
Order	Purchase order, which is issued to the distributor or the supplier
Trucks	Service that transports products between two entities

customers are never in contact in this case, due to a missing material or information flow between the two parties.

- Trust Level 1: Consistent, stable product quality, as well as the resulting good relationship, allow a direct product shipment between producer and customer. The distributor simply forwards the order request and thus gives up his responsibility. The supplier sends the product directly to the sold-to party after production has been completed, regardless of whether it is a finished product or a partial component. Although all parties involved in the production process communicate exclusively via the distributor, good are sent directly to the customer without an intermediate stop at the quality check.

Furian et al. [64] recommends the graphical illustration of the connections between involved entities, so dependencies and processes can be better interpreted and understood.

Figure 5.2 shows different trust levels, more precisely which path a material flow takes, depending on the trust level of the supplier. Black lines are identical, regardless of the trust level of the suppliers. When splitting the graphs into red and green, a route is chosen on a case specific basis. The red lines show the route of the products if the supplying entity has Trust Level 0. In case of full trust, i.e. Trust Level 1, the green colored route is chosen.

Placed orders and their corresponding return to the entity are graphically grouped by the dashed boxes.

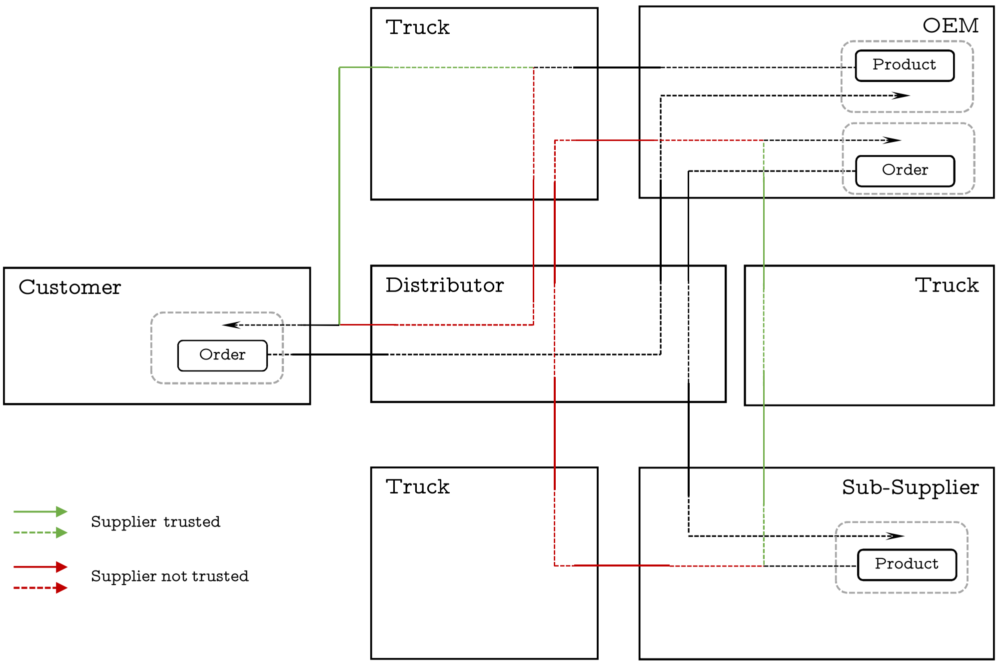

Figure 5.2: Supply Chain Structures

Regardless of the trust level of a supplier, the process of order fulfillment starts the same way, no matter whether the ordering unit is an OEM, which reorders sub-components, or a customer, which places orders for end products.

The purchase order arrives at the distributor, who distributes the purchase order in the network based on the workload and capabilities of the supplier base. At this point in time, the differentiation between different trust levels takes place.

If the supplier chosen by the distributor becomes trusted, i.e. Trust Level 1, the distributor transfers the entire order including customer information to the supplier and relieves himself of any responsibility. The supplier is then responsible for procuring the product and having it delivered directly to the customer. In this variant, there is no interaction between the physical product ordered and the distributor. Once at the supplier side, orders waiting to be produced are performed in a first-in-first-out (FIFO) fashion. For the handling of production, suppliers have production lines on which a specific product can be manufactured. Raw materials can be temporarily stored in the warehouse.

If the commercial relationship does not allow the responsibility of fulfilling the order to be passed on to the supplier selected for the order, a new order is placed in the system and forwarded to the supplier. The number and type of products is identical to the outgoing purchase order, but the specified customer is the distributor. This ensures that there is no direct connection between the supplier and the ordering entity. Each supplier in the network must limit their activities within the restrictions of shift working hours, which is defined by the times 6 a.m. to 10 p.m., with weekends off.

Upon receipt of the goods, the distributor checks the quality of the delivered products and forwards them to the original source of the order. The delivery of products to customers and suppliers takes 3 working days, whereby these are always delivered in the course of the day before and in addition can only be sent before 1 pm.

5.2.2. Phase 2: Identification of Modeling and General Objectives

The iterative mapping of the fictitious supply chain and its structure within the framework of the simulation study enables actual objectives to be found in some cases already in previous phases of the framework.

In this phase, the objectives found are clearly written down, making them clearly visible and transparent. This generally creates a common basis for a common goal, which everyone can work towards in a uniform way.

The framework of Furian et al. [64] proposes the presentation of targets in tabular form, with which they can be illustrated in a structured way according to their type. Table 5.2 shows the objectives, divided into organizational aims, general, and modeling targets.

The overall organizational goal is to guarantee an overall performance of the supply chain, not leading to delivery delays, regardless of the supply chain configuration and the transport routes used. This performance is measured by the percentage of orders placed with less than four weeks of delivery time.

The study examines how trust policies in the supply chain network affect overall performance and which configurations can ensure the required efficiency and performance.

5.2.3. Phase 3: Defining Inputs and Output Responses

The next step of the HCCM Framework is to define input factors based on the objectives, then to identify the expected output in order to evaluate if the modeling objective was met.

Input Factors

Input values represent fundamental values that characterize the system itself, which are fixed for different scenarios to be compared. Such values make it possible to adapt the model to different setups in the real world in order to find out to what extent objectives can be met. The choice of these variables and the definition of their limits must be compatible with reality and the system to be depicted.

In this example of a supply chain, this is the number of suppliers and the total production

Table 5.2: Simulation Study Objectives

Organizational Aim	
Lead-time should not exceed 4 weeks for 90% of the orders	
General Objectives	
Project Duration	5 months
Workload	1 developer for a total of 15 h per week
Visualization Requirements	No visualization of the model needed
Reusability Requirements	The model should be designed to enable the possibility of further expansion stages in the supply chain network
Documentation and usability	The simulation should be easy to handle and understand, even for untrained users. No detailed documentation is necessary.
Modeling Objectives	
Policy improvement	Evaluate different trust policies of suppliers including OEM and sub-suppliers

lines available to them. The main focus is on the distribution of trust levels and their impact on the supply chain network. Selected input factors are presented in Table 5.3 by designation and a brief definition.

Table 5.3: Input Factors

Input Factors	
# **of OEMs**	Number of available OEMs in the supply chain network
# **of Sub-Suppliers**	Number of available subcomponent suppliers in the supply chain network
# **of Production Lines**	Quantity of production facilities available to the supplier
Trust Levels	Trust Levels associated with the suppliers

Simulation Output

The Simulation output defined must match the targeted simulation objectives, defined in Table 5.2. They are used to test whether the set targets are achieved by selected input factors. In order to evaluate the performance of the supply chain under consideration of the four scenarios (see Section 5.3.1), the lead time is taken into account. Only orders from end customers will be considered. Delivery times for the orders between suppliers are not directly included in the calculation and visualization, as they indirectly affect the total lead time anyway. Table 5.4 shows the defined output values.

The following description shows how the output measures of the simulation are calculated and evaluated. The lead time (LD) is calculated as

$$LT = t_{OA,D} - t_{OA,C} \tag{5.1}$$

considering that

Table 5.4: Simulation Outputs

Aggregated Values	
Mean Lead Time	Average time from order arrival at distributor to delivery of the goods
90% Quantile Lead Time	Lead Time that is not exceeded by 90% of the orders placed and fulfilled
Mean capacity utilization	Average capacity utilization of suppliers in the supply network
Empirical Distributions	
Generation of empirical distributions of lead times in form of scatter charts or histograms	

$t_{OA,D}$:= time of order arrival at distributor
$t_{OA,C}$:= time of order arrival at customer

The smaller the lead time, the better the rated supply chain performance. If there are differences between the different scenarios and the formation of these scenarios, these are only manifested in the trust level scenario that is distributed in the network, as all other factors are identical.

The frequency of incoming orders is used to determine the capacity utilization of the entire supply chain. Each time an order is received by the distributor, the number of orders received in the last 45 days is recorded. The orders still arriving on that day are not taken into account and included in the calculation. The mathematical formulation stored in the evaluation looks as follows.

$$\mathrm{N}_O = \sum_{i=0}^{45} \mathrm{order}_{\mathrm{x-i}} \tag{5.2}$$

considering that

N_O ... amount of orders last 45 work days
order_x ... amount of incoming orders at day x

Accordingly, each order can be assigned to an order frequency. Since each order can also be assigned to a unique corresponding lead time, a correlation between lead time and order frequency can be established. This makes it possible to draw conclusions on how the utilization of the supply chain affects lead time. The capacity utilization is an average value calculated daily across all facilities of a supply chain level, i.e. across all assembly lines of the OEM, as well as all production lines of the sub-component suppliers. The calculation of the utilization rate is based on the following scheme.

$$\mathrm{UR} = \frac{\mathrm{t}_t - \mathrm{t}_w}{\mathrm{t}_t} \times 100 \tag{5.3}$$

considering that

t_t ... Total available production time per day
t_w ... Time during standstill during the day

On the basis of this information, which is calculated from the outputs, insights can be generated that provide information about the performance of the supply chain and clarify the reasons why lead times change.

On the basis of this information, insights can be generated that provide information about the performance of the supply chain and clarify the reasons why lead times change. These values will be picked out and presented graphically as part of the simulation evaluation.

5.2.4. Phase 4: Defining the Model Content (Scope / Level of Detail)

The next phase of the HCCM framework deals with the definition of the model contents. Thereby, entities are scanned, the structure is analyzed, and tasks essential for the modeling are described and prepared.

It must always be considered that an overly complex preparation and excessively comprehensive consideration of details leads to increased effort without contributing significantly to the improvement of the simulation model and its purpose.

Model Structure

Entities and their connections form the construct upon which the model to be simulated is ultimately based. This section is concerned with capturing this structure, together with the entities to be introduced.

The first step is to decide which entities contribute significantly to the simulation result and which can be neglected in the light of the simulation goals. Table 5.5 collates entities that have been collected and noted in table 5.1, page 59 in the first phase of the framework, and classifies them into two groups: those that are considered and modeled in the model, and those which are disregarded in this scope.

Once the entities are fixed, it is possible to capture the system graphically. Furian et al. [64] suggest making a blueprint that captures the model's behavior. Such an example has already been used in phase 1 of the framework to better understand the system (see Figure 5.2). This representation will be adapted to fit the specified entities to be modelled. The Result is shown in Figure 5.3. Both geographically fixed entities, as well as mobile entities, are shown in the blueprint diagram. Fixed objects outline the overall structure of the model, while moving bodies are illustrated with their possible flows.

The quantity of OEMs and suppliers shown is only an example. The process location does not change, regardless of how many suppliers are involved.

The green and red paths in Figure 5.3 represent the different paths of the orders, depending on the trust level of the individual suppliers. An exact description of the individual

Table 5.5: Entities and Attributes relevant to the Model

Entities		
Entity (→ Attribute)	**Included**	**Justification**
Customer	no	Can be mapped as an attribute of the orders
Distributor	yes	Central point for the accumulation of information, from which orders are distributed and quality checks are performed
→ (Un)Loading Area	no	Locality does not contribute significantly to the simulation output
→ Warehouse	no	No intermediate storage of products at the distributor
→ Inspection Area	no	Locality does not contribute significantly to the simulation output
→ Workforce	no	Activity of the quality check is only time-related and not personnel-dependent.
OEM	yes	Significant entity involved in order fulfillment
→ (Un)Loading Area	no	Locality does not contribute significantly to the simulation output
→ Warehouse	no	Handled as attribute of suppliers
→ Assembly Lines	yes	Important for capacity planning and lead time calculation
→ Workforce	no	Representable through assembly lines
Sub-Supplier	yes	Necessary for order fulfillment and roof structure for control of the production lines
→ (Un)Loading Area	no	Locality does not contribute significantly to the simulation output
→ Warehouse	no	Handled as an attribute of suppliers
→ Production Lines	yes	Important for capacity planning and lead time calculation
→ Workforce	no	Representable through production lines
Product	no	Can be represented as Order
Order	yes	Serves the general material and information flow
Trucks	no	Deliveries can be represented by time frames of the delivery duration

scenarios is given in Section 5.2.1.

Simplifications and Assumptions

The reality that not every detail of the real world can be represented in a simulation model leads to the necessity to simplify the system. In this section, elements are evaluated in terms of their impact on the outcome, as assessed by the modeler. The higher the effect, the more it must be assessed whether the element finds its place in the model and considers excluding an essential behavior. The confidence and influence of different assumptions and the assessment of their value is the responsibility of the modeler.

The result of this step is shown in Table 5.6, where assumptions and simplifications are listed in tabular form.

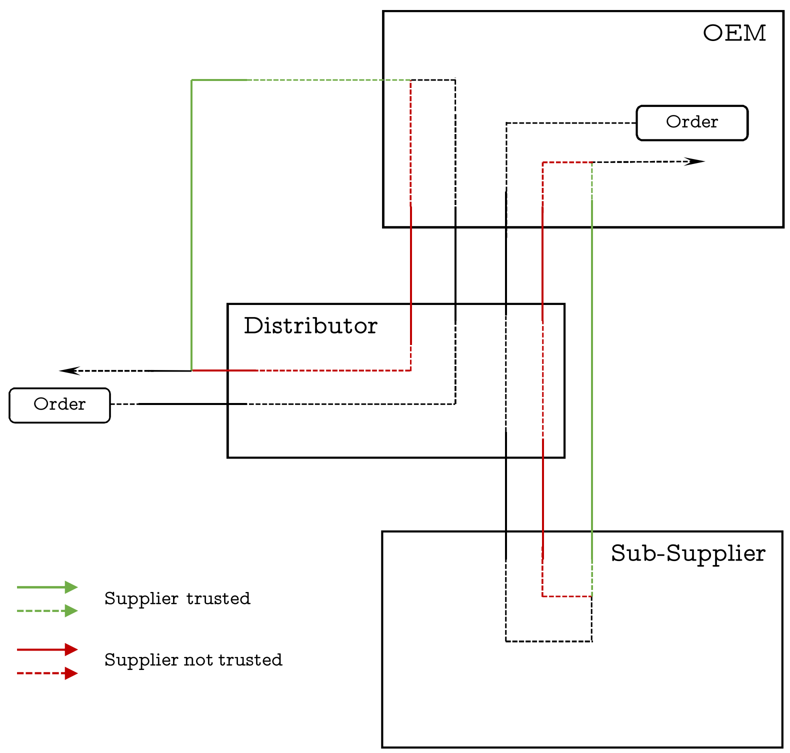

Figure 5.3: Blueprint of Final Entity Construct

Model Individual Behaviour

After setting out the objectives and defining tolerable assumptions and simplifications, the task is to outline processes and activities performed by involved entities within the network more closely. The individual behavior of each party and their activities in connection with the order fulfilment process is systematically analyzed, upon which the code modules to be implemented later are based.

The aim of this section is to provide a comprehensive definition of the activities that occur in the model. Based on this, diagrams are used to make the processes more descriptive and comprehensible. If the model itself is considered together with the formulation of the problem, it is noticeable that the central process is that of order fulfillment. All activities that are directly connected to it and thus contribute essentially to the simulation output must be considered and modeled accordingly.

It is important in understanding the following explanations and analyses that the term order covers both electronically incoming order requirements and physically produced components and products. This deceleration of the term will be interpreted and continued in the following chapters.

Due to the conceptual understanding and standardization of an order and physical product, a process of closed loop order processing, as shown in Figure 5.4 with its necessary

Table 5.6: Assumptions and Simplifications within the Model

Assumptions	**Confidence**	**Impact**
Sub-suppliers have enough raw-material in stock	Medium	High
No shortage of space and workforce	High	Medium
Simplifications	**Confidence**	**Impact**
Constant delivery times	Medium	Medium
No production breakdowns considered	High	Low
100 % good parts at quality check	Medium	Low
Simulation stops at the arrival of the last order at the distributor	Medium	Low
The supply chain is designed for one end product	Low	Low
Production lines can only produce one specific product	High	Medium
No parallelization of preparation activities on one production line	Medium	Low
No influence of different locations of the supplier and customer on delivery times	Low	Low
Constant cycle times in production lines	Medium	Low

activities, is facilitated. In terms of the entity order, it makes no difference whether the order for a product is placed by the end customer or by a supplier who orders a sub-component. Orders always run through the same processes, which differ only in the attribute of the customer and depend on the trust levels of the suppliers. This, thanks to the unification of the terms and entities grouped with the strict flow of information continuously via the distributor, makes background logic running simpler and reduces the programming effort required.

When an order arrives at the distributor, the distributor distributes it according to the free resources and workload in the system. The simplification made here is that the distributor can retrieve the required decision information on which the distribution is based in real time.

According to the distribution channels, the entity goes through various activities required for the order fulfillment process, as shown in Figure 5.4. A more detailed description can be found in phases 1 to 3 of the HCCM framework, where the exact processes are described and estimated with the help of a blueprint diagram.

These core activities form the basic building blocks of the model and help to identify which entities interact with these activities. The activities generated directly by the order fulfillment process must be covered, as well as those that are required indirectly, for example downtimes and waiting times, which do not contribute directly to the simulation result, but whose aggregation is necessary for the evaluation of the set target of the average capacity utilization of the suppliers, and at the same time contributes to the continuous timeline analysis.

Table 5.7 shows the result of this analysis showing the activities needed to be modeled to achieve and analyze the set goals. In addition to the activity, a description and the associated entity is also given.

By unifying the term order and not differentiating between ordering sub-components or end products, the activities can be further simplified. In the construct, production lines and

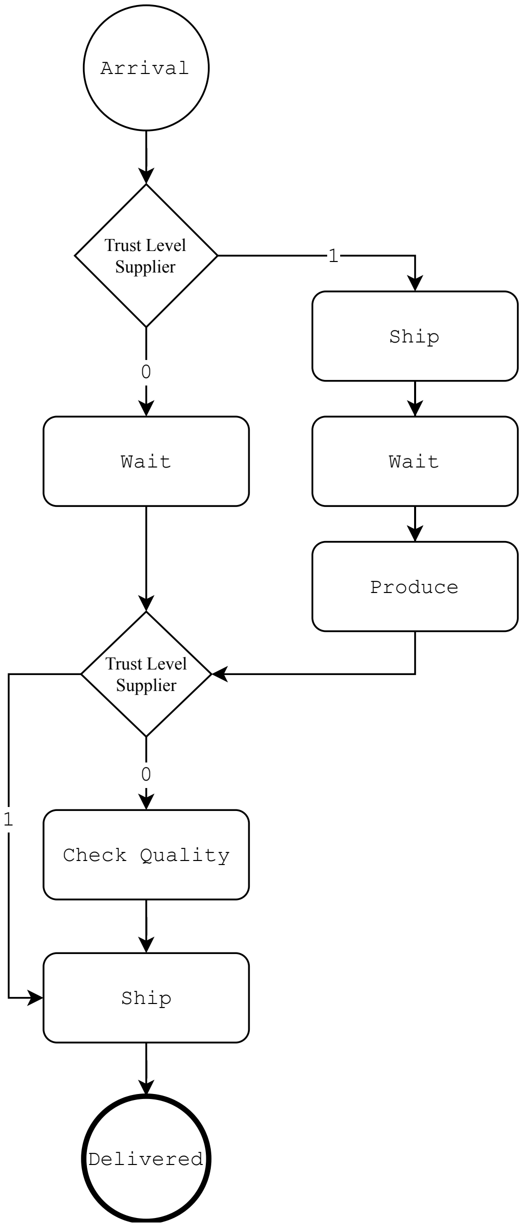

Figure 5.4: Behaviour View Entity Order

assembly lines have the same properties, and could be modeled as a single, universally applicable supplier unit. The only difference is the inventory policy: Sub-component suppliers always have enough components in stock under simplified conditions, OEMs order the required components from the incoming order.

Based on this thematic summary, production lines and assembly lines are summarized below under the term supplier facility, or facility for short. This classification of terms will be used in the following work. If it is necessary to differentiate between the facilities of OEMs and sub suppliers. This will be denoted explicitly. The terms assembling and producing are combined to the term production and no inconsistencies are generated. The individual behaviour of such a supplier facility is shown in Figure 5.5 in the form of a flow diagram.

Table 5.7: Activities to be Depicted

Activities		
Activity	**Entity**	**Description**
Quality Check	Order	Time-delayed activity of a random quality check for verification
Production	Order	Production of the ordered components
Assembly	Order	Production handling of the received order
Waiting	Order	Waiting on the order for further processing
Shipping	Order	Transfer of an order to the temporary, intermediate, or final destination
Production	Production Line	Production handling of the received order
Waiting	Production Line	Downtime of production lines between the production of individual products
Assembly	Assembly Line	Assembly of the items ordered
Waiting	Assembly Line	Rest periods between assembly of an entire order

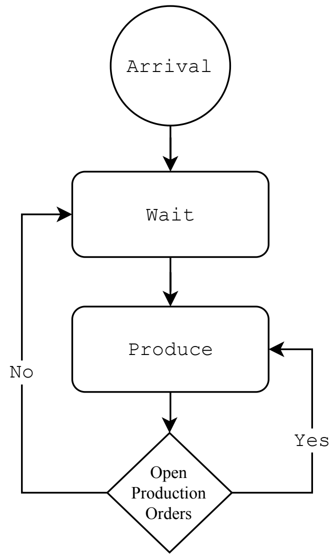

Figure 5.5: Behaviour View Entity Facility

Furian et al. [64] names the tabular processing of the individual activities with all their attributes and trigger mechanisms as adequate means to go into the individual sub-processes in more detail. Based on this, it should also be made easier for modelers and developers to convert the decisions and thoughts made in conceptual models into code that can be integrated by computers.

Such an example is shown in Table 5.8, based on the process step of production where both order and supplier facility are involved as entities. For a complete list of all activities required and modeled in the Conceptual Model, see Appendix B.

Table 5.8: Produce Activity Definition

Order Production	
Participating Entities	Order, Facility
Start Type	Requested
End Type	Scheduled
Start State Changes	Facility.IsReserved = FALSE Inventory -= Amount [BOMElement]
End State Changes	none
Attributes	**Description/Value**
Duration	Quantity dependent function
Request Attributes	**Description /Value**
Time Request	When was the request made from the Supplier Control Unit
Request Specification	Request filed after order arrival at Supplier

Model Control (System Behaviour)

These control units (CU) are a central collection of rules that control the units under their authority as well as the externally defined interfaces of their area of responsibility. They are therefore not only important for the thematic delimitation, which serves the purpose of clarity when it comes to mapping from the real world into the model, but are also able to influence the behavior of the model profoundly through their decisions and track the corresponding reaction of the system. Individual Control Units can also be subordinated to others, which automatically leads to a branch-like hierarchy-level structure. [64]

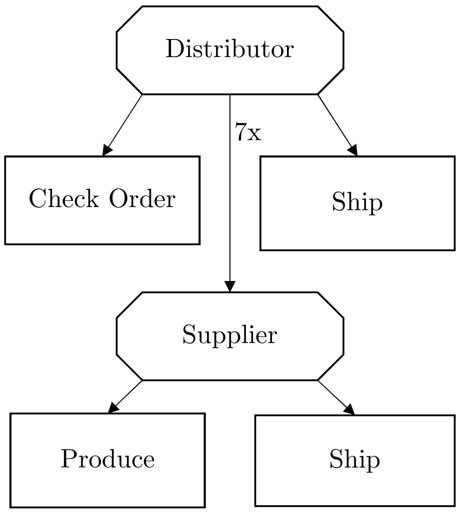

Figure 5.6: Structure Control Units

In the configuration under investigation, the distributor is the central CU, which mainly shares the task of distributing any orders received and checking them if necessary. Its subordinates are the so-called Child Control Units (CCU), the suppliers, responsible for synchronizing the production into one of their production lines upon receipt of an order. Together they form the basis of the supply network, also illustrated in Figure 5.6. Activities are drawn as rectangles, coordinated by CU presented as octagons.

For the sake of clarity, only one supplier control unit is shown here. In the model, there are seven of these (one OEM and six sub-component suppliers). However, since they do not differ in their tasks, Figure 5.6 a can be reduced to the form shown with this reference.

A central task of the control units, the definition of the rules, must be performed in the next step. Furian et al. [64] refer to different approaches that can be considered. In addition to pseudo-coding and writing in text form, he also mentions flow diagrams as a suitable tool for representing policies. The latter is also used here to illustrate the policy of trust level dependent order distribution in the network performed by the distributor (see Figure 5.7).

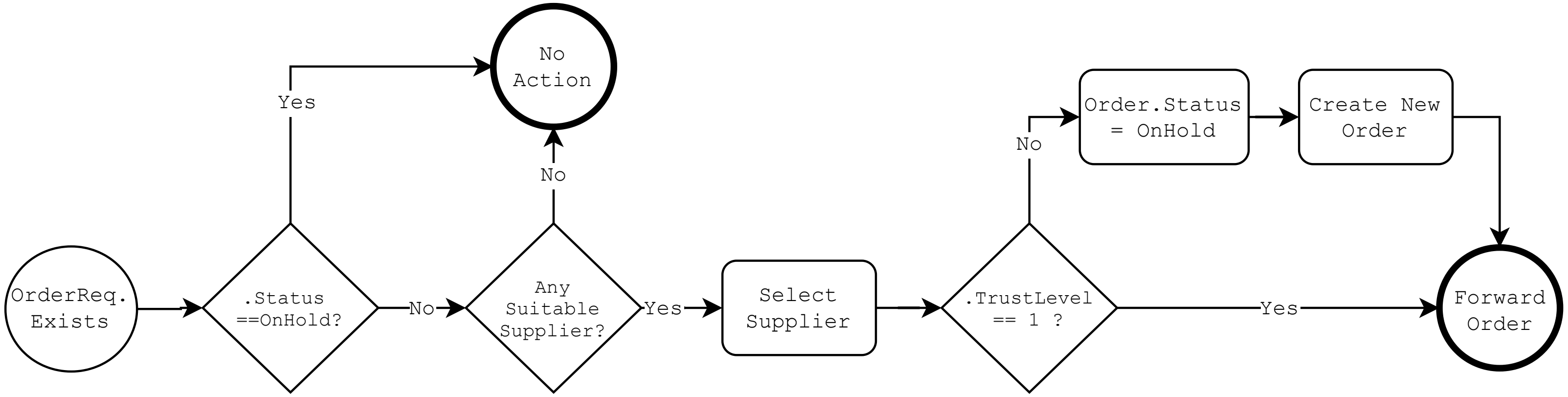

Figure 5.7: Control Policy CU Distributor: Order Request

5.3. Simulation

This chapter deals with the elaboration of the computer simulation, based on the developed conceptual model and including the processing of the results. The simulation outputs of the different scenarios are graphically prepared, compared and conclusions are drawn about the lead time and how it depends on the scenario conditions. Based on these lead time evaluations, conclusions are drawn about the utilization rate of the supply chain.

5.3.1. Simulation Variants

The goal of implementing a supply chain network with the HCCM and its output is tested through various scenarios. The central focus is to examine the impact of different trust levels of the suppliers on the general performance of the supply chain, measured in terms of delivery times and order fulfillment.

In order to test all scenarios for the trust levels of the given supply chain structure and to compare their output, whereby a supply chain hierarchy always has the same trust level, four simulation scenarios are required. These are listed in Table 5.9.

Despite the introduced nomenclature of the unified term Supplier, the distinction between sub-component suppliers and OEMs is important and must be considered. Thus, in the following and in the evaluation, OEMs are summarized under the same term, and sub-component suppliers under the term supplier.

Table 5.9: Simulation Scenarios

		Trust Level	
Scenario	Naming	OEM	Supplier
1	All Trusted	1	1
2	OEM Trusted	1	0
3	Supplier Trusted	0	1
4	No Trust	0	0

The four different scenarios are also described below.

1. All Trusted: Goods are not sent via the distributor and therefore do not have to undergo a quality check. OEMs supply directly to end customers, subcomponents directly to OEMs.

2. OEM Trusted: All OEMs can deliver directly to the end customer. Sub-components find their way to the OEM via the distributor. Thus, there is no contact between the OEM and sub-component supplier. The end customer, however, can find out who the producer of the end product is.

3. Supplier Trusted: No end product may go to the end customer without being checked. However, OEMs and sub-component suppliers are in direct contact, which enables uninterrupted material flow between the two supply chain partners.

4. No Trust: This is precisely the opposite of the first simulation variant. Any material flow runs via the distributor, checking the quality of the products. In this model, only the distributor knows which parties are involved in the supply chain.

The simulation results are available as text files for each scenario and can be processed with suitable programs to visualize them.

5.3.2. Results and Interpretations

This section deals with the results of the simulation study and its evaluation. The deactivation of stochastic variables in connection with the simulation, coupled with the precisely defined arrival of the orders, had two effects. On the one hand, one simulation run was sufficient to generate the final simulation outputs, and on the other hand, the inactive stochastic variables made it easier to compare the simulation outputs with respect to the impact on trust level distribution.

For a quantitative comparison of the lead times, a box plot diagram has been created for the scenarios (See Figure 5.8).

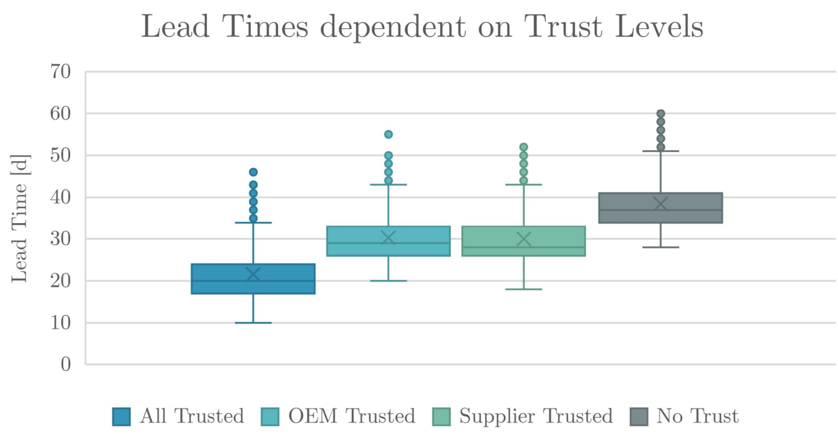

Figure 5.8: Boxlot Diagram Lead Times over 4 scenarios

Figure 5.9 shows that according to all assumptions, a supply chain in which all suppliers have Trust Level 1 performs significantly better than the other scenarios examined. The additionally required transport routes and quality checks mean that lead times almost double in the worst case, which has a correspondingly negative effect on the impression of the end customer.

Scenarios 2 (OEM Trusted) and 3 (Supplier Trust), in which only either OEMs or sub-component suppliers are allowed to send the ordering unit goods directly, are similar in performance. Only in the case of the outliers is there a fluctuation between the two scenarios. However, this may be because weekends unfavourably extend the delivery time.

The primary objective of the effects of the policy in regulating the performance of the supply chain can be better illustrated quantitatively by the key figures defined in the target review. All key figures are based on delivery times, by which the performance of the supply chain is measured.

The 90% quantile indicates the time, measured in days, within which 90% of placed orders can be delivered. The 90% quantile of orders as well as the average delivery time of orders is shown in Table 5.10 for the different scenarios.

Table 5.10: Lead Time Performance Indicators

Scenario	All Trusted	OEM Trusted	Supplier Trusted	No Trust
90% Quantile [d]	32	41	40	49
Mean Delivery Time [d]	21,5	30,2	30,0	38,5

The result of this study shows that the trust the distributor has in the supplier base and the freedom they enjoy in terms of direct customer contact has a significant impact. In addition to the required transport routes, which are unavoidable, delivery times are also delayed by quality checks. Weekends, which are additionally involved, delay deliveries even further.

The key figures show a striking difference between the 90% quantile and mean delivery time, which cannot only be explained through the impact of intervening weekends. This behavior can also be seen in Figure 5.8 through the mathematical data outliers.

To get to the bottom of this, the frequency of incoming orders in the last 45 days is used to to draw conclusions about the utilization rate influencing the lead time. Figure 5.9 shows the illustration and result of this thought. It shows lead times of all four scenarios in dependence of frequency.

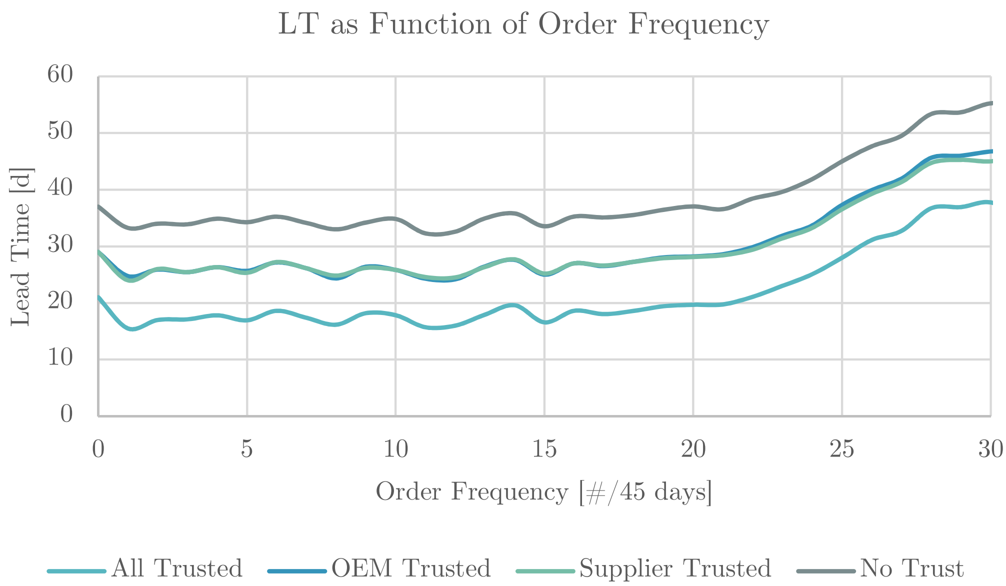

Figure 5.9: Leadtime dependent on Order Frequency

The evaluation shows that all scenarios behave in the same way. There is an offset in the lead time, which is caused by the different setups of the trust levels. The analysis demonstrates two findings.

Firstly, the data at the left end of the horizontal axis of the chart, illustrated by Figure 5.9, showed a decrease in lead time with increasing order frequency. This is due to the fact that in the start-up phase, OEMs do not have any components in stock and therefore have to wait for them. This behavior always occurs when orders appear without the required components in stock. This can be counteracted by an order policy that is implemented differently, which would have to be implemented by the OEMs to compensate for order bottlenecks.

Furthermore, the consistency of the lead time is striking, which can be seen up to point 20 on the x-axis in Diagram 5.9. The curve fluctuates above this point and rises steadily. Conversely, this means that the average supply chain for orders of this size arriving every two days is on average (for a larger quantity the resources on the supplier side would have to be increased) coupled with adjusted inventory policies.

In order to gain a better understanding of the Utilization Rates (UR) of the suppliers as a function of their capacity utilization, which allows the design and maximum possible performance of the entire supply chain to be revealed, the dependence of these values is compared in Chart 5.10.

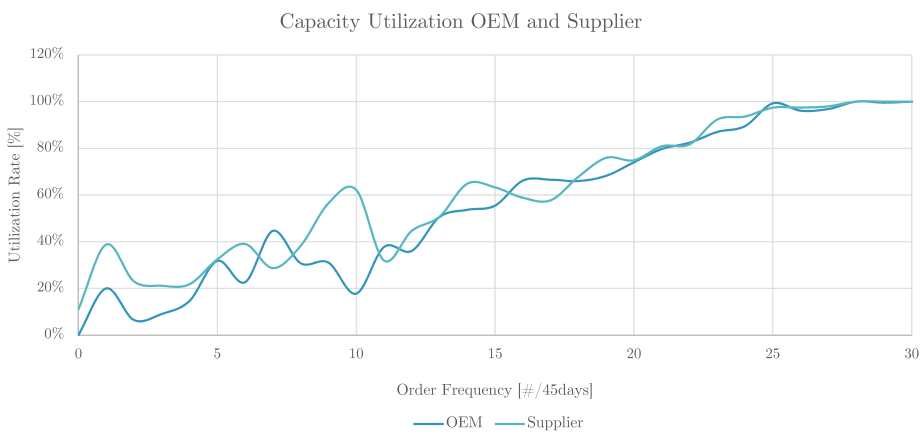

Figure 5.10: Capacity Utilization dependent on Order Frequency

A constantly growing workload with an increasing number of orders, which are integrated into the system per time unit, can be seen. However, a comparison with Figure 5.10 shows that the average capacity is only exhausted at 25 orders per 45 days. The increase in lead times can be seen in Figure 5.9, however, at approximately at 20 orders. Conversely, this means that the supply chain is performing worse than its design would allow.

To get to the bottom of this phenomenon, the workloads in Figures 5.11 and 5.12 are broken down to individual suppliers. The first shows the utilization rate of the two assembly lines of the OEM in comparison, while the second compares the utilization of two subcomponent suppliers, who are responsible for the same product, and thus a valid comparison is permissible.

It seems that the distribution of production orders works well within the company. Both

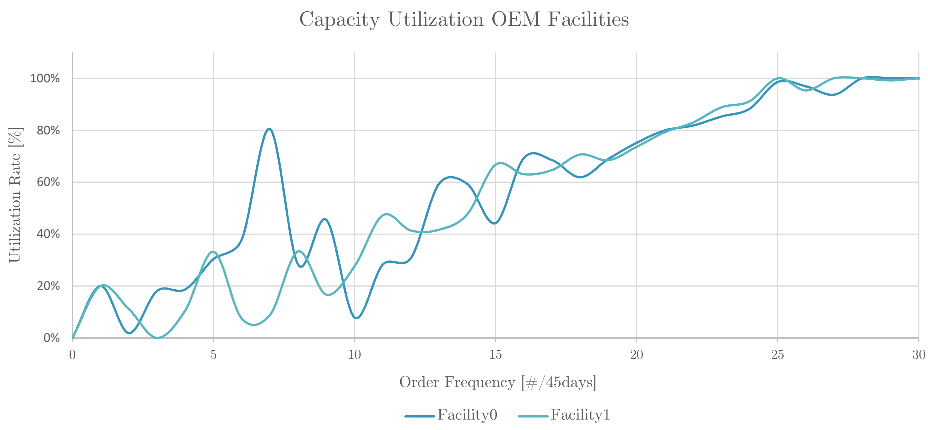

Figure 5.11: Capacity Utilization Assembly Lines

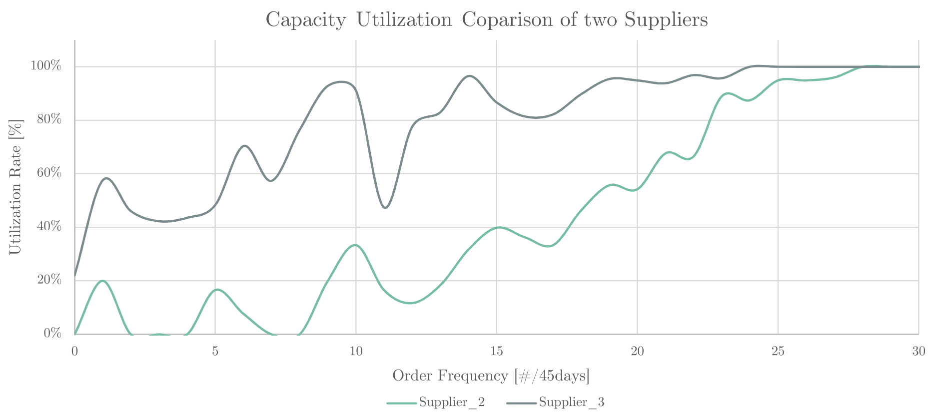

Figure 5.12: Capacity Utilization two different Suppliers

curves of the utilization rate in Figure 5.11 are synchronous except for some peaks.

This is different when comparing different companies. Orders and their corresponding workloads are distributed differently, especially when the order situation is low. In conclusion, it can be deduced that control structures in the model are insufficiently developed, or adapted from reality, and are a significant point of improvement in order to save resources. By working out these findings, it would be possible to keep the lead times of high-frequency incoming orders constant without having to use additional resources. In addition, a dynamic adaptability of supply chain resources would help to keep the performance of the supply chain constant without wasting or overloading resources.

In general, however, the different trust level scenarios have no influence on the system's capacity utilization and capacity planning, only an impact on the lead time. This is also the reason why only individual suppliers and facilities are compared graphically, without taking into account the various scenarios.

5.4. Resume on the Implementation

This section of the thesis aims to reflect the insights and impressions generated by the implementation of the supply chain simulation. It should be clarified, how the applicability of the Discrete Event Simulation (DES) based framework to this topic was felt and which conclusions can be drawn from it of the applicability of DES in general to such problems. In particular, the findings from the literature review in chapter 4 will be taken up, and the statements and conclusions will be cross-checked and compared with the impressions generated. The study of scientific papers describing the practical application of simulation to supply chain issues, written and published in recent years, has provided an insight into the chains of argumentation that modelers, developers, and authors use to argue the use of a specific paradigm. Depending on the problem definition and the given constraints, as well as the structural conditions and the design of the system to be depicted, one of the paradigms seemed to be more suitable for the conditions given. In the following section, the focus is on those arguments from the theory part, which were either most represented or where the difference between the paradigms, ABM, and DES, was most noticeable. Since the used HCCM framework is based on DES, the focus is also put on the following: which disadvantages of DES remain, which can be eliminated, or which strengths of DES are preserved by the framework. The focus will therefore be on the following three points:

- Representability of Autonomous Entities
- Modelability of Complex Adaptive Systems (CAS)
- Suitability of the paradigm for Scenario Simulation

Representability of Autonomous Entities One of the main arguments for the use of Agent-Based-Modeling (ABM), in this context, is the human-based structures that can be mapped with it. The enabled representations of learning abilities of individual agents and their autonomy and freedom of decision allow modeling of a dynamic environment with a human component. The result is, according to literature references, a suitable medium for the simulation of a supply chain that exhibit these conditions. Mittal and Krejci [122] goes beyond this and compares DES and ABM about the representability of the human component. Mittal and Krejci [122] states that ABM has an advantage in this aspect and that the sequence and mapping of autonomous decisions is difficult to represent with DES and is not a core competence of the paradigm mentioned. In the context of the investigation of the published simulation studies, the not well representable human component argued most against DES.

At the level at which the simulation study was conducted, the focus was not on the simulation of single individuals. Despite this, the integrated facilities, to a certain extent, depict entities that function both as a resource-binding unit for task fulfillment during the simulation and as customers in the ordering process of new goods and raw materials. Due to this change of state and change of the associated task area, regulated by given boundary conditions and environmental impacts, entities can be attributed a certain autonomy, even if the core of the framework (the so-called control units and advance control mechanisms) are responsible for regulation and control. Thus, the simulation study has shown that the appropriate identification of control mechanisms and control structures using the framework can, to a degree, represent the autonomous behavior of individual entities and entity groups.

About the argument of Mittal and Krejci [122] that ABM would be more suitable to represent autonomous decisions and decision-makers, a differentiation must be made based on the findings of the simulation study. By using HCCM, such dynamic environments can be represented by the use of control structures, and the subject area is thus not only deprived of ABM, but can therefore be covered to a certain degree by DES. The more structures and hierarchies are already present in the real system (with central points of contact) and the more entity groups have the same tasks and roles, the more the use of the HCCM framework pays off in the implementation. This is because core processes are controlled in a bundled way, and the challenges created by queue-based DES simulations are reduced and eliminated.

The more autonomous individuals are represented in a simulation, which cannot be assigned to an existing control structure and for which a separate control center must be set up, the more complicated the modeling using the HCCM framework becomes because of the growing and increasingly complicated control structures and control mechanisms to be implemented. It is important to note that too many control structures complicate the simulation model to be implemented and too few control structures lead to tremendously complex control mechanisms that need to be implemented. With a high number of autonomous agents, both would be the case, so in this context, the Agent-Based-Modeling (ABM) might be more appropriate. It should be noted, that this estimation is based on the findings of the theoretical investigations and the simulation study. No practical comparison was made based on a simulation study.

Modelability of Complex Adaptive Systems (CAS) In contrast to ABM, DES is better suited, based on the evaluation of the argumentation of the modelers and developers, to carry out a scenario investigation with only a few resources. Thus, DES is particularly suitable for simulation studies that investigate a rigid structure and do not consider emerging systems. An argument, which was made regarding the use of DES in connection with the simulation of the supply chain, is the one made by Wen-li and Yao-wen [183], which is the representability of complex, emerging systems and the examination of these using different influence factors. Wen-li and Yao-wen [183] opposed the use of DES in adaptive problems of complex nature, because, according to them, DES cannot capture the dynamic complexity of supply chains. So, the method is not suitable for interactive supply chain networks. Pfeiffer et al. [138] spoke out for the use of DES in this context. In the literature, there is no consensus in this context on which the representatives of the respective paradigms agree.

In this context, the impressions gained from the simulation study, the control structures of the HCCM seem to contribute positively to the usability of DES in supply chain issues. Choice of control structures, including their number and complexity, interrelationships within supply chain networks, or in general interrelationships in a network of entities, can be represented very well. Changing boundary conditions, circumstances or events are distributed in the network by the stored structures and trigger associated follow-up reactions, can be used to control the merger in the network and the network behavior in general. This is done by efficiently setting up control structures and with relatively little programming effort. This was shown in the simulation, especially when orders were placed, which were distributed individually in the network according to the capacity utilization of the individual facilities and order situation. Based on the impressions generated during the execution of the supply chain simulation it should be noted, that emergent behavior is limited for DES, even when using the HCCM framework. Entities can migrate between different control structures, but the underlying construct of control centers remains constant. Agent-based modeling should reveal further freedom in how individual entities and entity groups evolve.

Suitability of the paradigm for Scenario Simulation In contrast to ABM, DES seems, according to the study of the use cases, to be as good, if not better suited, to test different scenarios using fewer resources. The execution of the simulation study showed that HCCM served as a framework and guideline, inviting to think about inputs and outputs. Since different scenarios were investigated, suitable basic conditions had to be researched and the results compared. It was a strong advantage that the definition of input and output factors was seen as a separate phase of the framework and thus attention was paid to this topic. Thus, the simulation is given a certain degree of flexibility in advance and different scenarios can be investigated. Yet, this advantage is independent of the topic and is reflected in all areas, not only in the simulation of a supply chain. It can be mentioned as a general advantage of the framework, especially for inexperienced developers. The short simulation time required to complete the simulation, enabled by using DES, also had a positive effect in this context. This has the advantage that adaptations of input factors can be implemented and their effect on the output evaluated quickly.

In summary, the core idea of the control units and their integrated structure, which are brought to life by the HCCM framework, mitigates or even eliminates disadvantages of the usual DES. The structures allow a flexible orientation of the model and extend the network idea. Roles integrated into the system become more flexible and are more autonomous, without weakening the advantages of the Discrete Event Simulation (DES) like representability of scenarios in away. In general, it can be said that the findings of literary research only correspond to the experiences made. Personal experience value cannot be disregarded here. A direct comparison of an agent-based simulation and one based on the HCCM framework could provide more information on the results of the literature review and the mentioned arguments as well as an an insight into the potential of the framework.

6 Conclusion

In conclusion, this work consists of two parts. Firstly, the literature research investigating used modules and simulation paradigms to model a supply chain, which is summarized retrospectively in section 4.6. The second part was about the use of a framework, called HCCM, based on which a conceptual model of a supply chain was created, which became the subject of a simulation study.

The following conclusion wants to clarify how the applicability of the framework to this topic was felt, what the results of the simulation were, and to identify, if the applied framework helps to design a suitable conceptual model for a supply chain simulation. Thereafter, it should be disclosed to what extent there are parallels between these findings and the findings of the applicability of the individual paradigms to supply chain issues, which were disclosed in the literature review.

The subject of the investigation of the simulation study was a simplified supply chain structure, whose performance is measured using various performance indicators. Thereby, different configurations of the supply chain structure and their cooperation regarding the trust placed in them formed the cornerstones of the various scenarios that were examined. The core objective of the simulation study was to examine the impact of different trust levels on performance, which, according to their distribution in the network, have a significant influence on the material flows in the system itself.

As can be assumed, the scenario with the fewest routes, induced by trust, showed the best performance with regard to lead time. In addition to shorter lead times, resources can also be saved by reducing the amount of transport required, and costs can be reduced in the overall view of the supply chain. In addition to this insight, the model was also able to provide an outlook regarding the design of the supply chain and its capacity limits, numerically delimited and indicated by manageable numbers of orders per period. A closer look showed that trust levels have no influence on these key figures, but that optimized control and order distribution structures could significantly improve resource utilization.

The general outcome of investigating the supply chain network problem was that the more direct transport routes are found in a network, the timelier ordered goods can be delivered. Conversely, this means that suppliers should expand their system in a qualified manner, and OEM and sub-suppliers should be in direct contact with each other, ideally by integrating them into an Enterprise Resource Planning (ERP) system, so that orders can be distributed optimally through the network. Due to its dynamic structure, the model shown can be adapted to other scenarios with little effort. Inputs are designed in such a way that the supply chain size, its capacities represented by available resources and necessary attributes, can be adapted quickly. This simulation model can be used in the future as a basic model for further expansion stages, allowing capacity planning and lead time estimates to be made. The scope of application is not only limited to separated companies but can be applied to any cooperation construct that can be represented by control structures and the entities managed by them.

These control structures, which allow described extensions among other things, are the basic idea of the used HCCM framework. Furthermore, the control structures allow to mitigate a weakness of the traditional DES paradigm and allow the modeling of autonomy, dynamic and emergence to a certain degree. A conspicuous feature of that used framework, which cannot be directly attributed to the supply chain topic, is the valuable support as a guideline in the initial stage of conceptual modeling and throughout the entire model-finding phase. The framework and its range of proposed tools, anchored and divided into individual phases, provided useful instruction to develop an implementable model from the basic idea of a working framework.

The detailed phases of the framework to be implemented suggest that it can be applied not only to simplified topics like the presented supply chain but also to more complex structures. Based on the experience generated by the application, the framework opens a wide range of application possibilities, including supply chain issues, which can be addressed. The simplified example of the supply chain network, however, could probably not unmask the full potential of such a directional guide. This also applies to the core idea of this framework of non-queue-based control structures integrated into the model, steering the behavior of the entities and thus the behavior of the entire system through the stored rules and boundaries. For more complex systems with more complicated logics and rules, the structures created by the framework would show their advantages even more clearly. The control policies implemented in this study, however, were kept simple with rudimentary dispatching and ordering rules and entity roles that do not change over time.

The most challenging part of the simulation was to find all necessary production and lead time parameters to achieve a realistic result. Furthermore, order sequences, the duration of quality checks, transport routes, and production times had to be determined by iterative simulation processes and plausibility checks. This surely brought the greatest uncertainty into the designed model. As essential factors were set as parameters, the model could easily be adapted to new conditions. This initially entailed additional expenditure, but ultimately paid off, and made the model itself more open to future studies and scenarios.

Comparing the results of the literature research regarding the applicability of paradigms to supply chain issues with the findings of the simulation study, it is striking that there are parallels. The DES based HCCM framework allowed to generate a model that was very well suited for the investigation of various scenarios by using only a few resources. Thus, this aspect of simulation support knowledge coincides with the strengths attributed to DES in the papers. The literature research also led to the conclusion that DES is particularly suitable for rigid structures. In the case of emergent structures, modelers use agents to try to approximate the system to be modeled. However, despite the simplified representation of the supply chain, and the fact that this probably does not fully exploit the findings, this statement can be questioned. With the framework it was possible to describe all activities required for order fulfillment according to the control structure logic, allowing the supply chain network to be modularly expanded with little effort and potentially also to a certain extent dynamically and automatically in a simulation. The simple scalability showed its advantages, especially in the resource-saving iterative adjustments of the model.

One of the advantages of agent-based modeling, and one of the disadvantages of discrete event simulation, mentioned most frequently in the papers examined, was the lack of human centricity. While ABM shows its strengths in terms of human-based structures and the interaction of the parties involved, this seems to be one of the major disadvantages of DES. If the individual facilities of the supply chain simulation are associated with independent units, it can be said that the non-queue-based control description of the model shows a certain autonomy of the involved units. By attaching the requests, which are processed accordingly and trigger a reaction in the network, interactions and the resulting reactions can be modeled in the future by using the framework, shown exemplarily in a supply chain network. However, it is not possible at this point to say to what extent this will lead to the human level and whether the freedom of agent-based modeling can be reproduced. This can be investigated in future simulation studies in this area, preferably in the context of a direct comparison.

In summary, this simple model has made a wide range of findings possible. It has allowed to analyze statements regarding the choice of paradigm in supply chain issues and at the same time to counter-check them with a new framework. Furthermore, it has shown that important conclusions can be drawn by using simulation-based models and which impacts the data-driven decisions generated by the outputs can have. In times in which markets become more price-driven, requirements on products increase, but at the same time delivery times must decrease in order to maintain competitiveness. Supply chain structures must be developed for a company through vertical integration and the expansion of networks. Data-driven results that are understandable for all stakeholders and decisions based on these results are the first key to achieving it.

List of Figures

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A

Literature Review

Table A.1: Selected Papers

	Authors	Year	Title of Paper
ABM			
[95]	Lalbakhsh et al.	2018	Capacity analysis for aircrew training schools - Estimating optimal manpower flows under time varying policy and resource constraints
[10]	Allen et al.	2018	Simulating the impact of external demand and capacity constraints in aerospace supply chains
[155]	Rouzafzoon and Helo	2018	Developing Logistics and Supply Chain Management by Using Agent-Based Simulation
[88]	Kessentini et al.	2018	Agent-Based Modeling and Simulation of Inventory Disruption Management in Supply Chain
[154]	Rosales et al.	2018	The Impact of Distribution Channel Decisions and Repeated Stockouts on Manufacturer and Retailer Performance
[107]	Li et al.	2018	H8 Consensus for Multiagent-Based Supply Chain Systems under Switching Topology and Uncertain Amounts
[65]	Gallab et al.	2017	Risk analysis of maintenance activities in a LPG supply chain with a Multi-Agent approach
[8]	Achter et al.	2017	On Agent - based Modelling in Semiconductor supply Chain Planning
[137]	Ottemöller and Friedrich	2017	Modelling change in supply-chain-structures and its effects on freight transport demand
[115]	Malykhanov and Chernenko	2015	Strategic Planning of logistics for offshore arctic drilling platforms
[171]	Tan et al.	2015	Design of Supply Chain Topology to mitigate Demand and Supply Risks
[160]	Seck et al.	2015	A Simulation-based Approach to Risk Assessment and Mitigation in Supply Chain Networks
[57]	Fang and Puqing	2015	Simulating the Structural Evolution in Agri-food Supply Chain: An Agent-based Model

Table A.1 continued from previous page

	Authors	Year	Title of Paper
[50]	Dominguez et al.	2015	The impact of the supply chain structure on bullwhip effect
[167]	Sun et al.	2015	Complexity Analysis through the Modeling of Human Behavior in a Complex Supply Chain Planning Environment
[13]	Arvitrida et al.	2015	How do competition and collaboration affect supply chain performance? An agent based modeling approach
[32]	Cabral and Grilo	2015	Analyzing the impact of business interoperability on the performance of cooperative supply chain networks
[73]	Groves et al.	2014	Agent-assisted supply chain management: Analysis and lessons learned
[15]	Avegliano and Cardonha	2014	Investigating the Hidden Losses caused out-of-shelf Events: A Multi-Agent-Based Simulation
[173]	Tang and Pan	2014	Agent-based Supply Chain Management Modelling and Simulation
[51]	Dominguez et al.	2013	Using multi-agent systems to explore information sharing in arborescent supply chain networks
[186]	Wu et al.	2013	Supply Chain Risk Management: An Agent-Based Simulation to Study the Impact of Retail Stockouts
[197]	Zolfpour-Arokhlo et al.	2013	Route planning model of multi-Agent system for a supply chain management
[93]	Laarabi et al.	2013	An Overview of a Multiagent-Based Simulation System for Dynamic Management of Risk Related to Dangerous Goods Transport
[40]	Chinh et al.	2013	An Agent-Based Simulation to Quantify and Analyze Bullwhip Effects in Supply Chains
[105]	Li and Huang	2012	The impact of product category on pricing decision in a two-echelon dual-channel supply chain

Table A.1 continued from previous page

	Authors	Year	Title of Paper
[39]	Chen et al.	2011	Simulation on influence mechanism of environmental factors to producers' food security behavior in supply chain
[190]	Xu et al.	2010	Reducing the Probability of Bankruptcy through Supply Chain Coordination
[104]	Li	2010	Modeling and Simulation of Supply Network Evolution and Revolution: A Multi-Agent Approach
[163]	Sirivunnabood and Kumara	2009	Comparison of Mitigation Strategies for Supplier Risks: A Multi Agent-Based Simulation Approach
[36]	Chan	2009	Flexibility or adaptability? Which one is more suitable for distributed supply chain?
[84]	Junli	2009	Agent-based logistics simulation system design and implementation
[194]	Zhang and Xiao	2009	A Simulation Analysis on Evolutionary Game of Information Sharing in Supply Chain Based on Multi-agent
[30]	Bryceson and Slaughter	2009	Integrated Autonomy A Modeling-Based Investigation of Agrifood Supply Chain Performance
[187]	Wu-cheng and Xin-xing	2009	A Negotiation Model of Supply Chain Based on Multi-agent
[192]	Zhang et al.	2008	Agent-based Simulation of a Speciality Chemicals Supply Chain
[80]	Hou et al.	2008	Research of buyer-supplier relationship based on agent approach
[83]	Jirong et al.	2008	Simulation study on influences of information sharing to supply chain inventory system based on multi-agent system
[96]	Lao et al.	2007	Complexity Analysis and Modeling of Enterprise Information Resources Integration
[129]	Mujaj et al.	2007	A Reverse Pricing Model for Multi-Tier Supply Chains
[128]	Moyaux and McBurney	2006	Modeling a Supply Chain as Network of Markets

Table A.1 continued from previous page

	Authors	Year	Title of Paper
[37]	Chan and Chan	2006	Early order completion contract approach to minimize the impact of demand uncertainty on supply chains
[193]	Zhang et al.	2006	A model and dynamics for reticulated supply chain based on multi-agent system.
[67]	Gao et al.	2006	Design and simulation of multi-robot logistic system
[97]	Lau et al.	2006	Agent-Based Modeling of Supply Chains for distributed scheduling
[134]	Nilsson and Waidringer	2005	Toward Adaptive Logistics Management
[189]	Xie and Chen	2005	Studies on horizontal cooperation among homogenous retailers based on multi-agent simulation
[35]	Chan and Chan	2005	Comparative Analyisis of Negotiation Based Information Sharing in Agent-Based Supply Chains
[92]	Kong and Wu	2005	Collaboration attitude choice-based intelligent production control model in dynamic supply chain system
HYB			
[112]	Mahfouz and Allen	2018	Brexit: Preparing for the Worst Scenarios
[144]	Reddy and Telukdarie	2017	Procedures to accommodate system fluctuations that result in buffer compromised systems governed by the theory of constraints
[122]	Mittal and Krejci	2015	A Hybrid Simulation Model of Inbound Logistics Operations in Regional Food Supply Chains
[183]	Wen-li and Yao-wen	2010	Simulation of Supply Chain Network Based on Discrete-continuous Combined Modeling
[191]	Yutian et al.	2010	Emergency resources dynamic assignment problem statement and modelling

Table A.1 continued from previous page

	Authors	Year	Title of Paper
DES			
[90]	Kogler	2018	A discrete-event simulation model to test multimodal strategies for a greener and more resilient wood supply
[76]	Hamed et al.	2018	Flexibility as an enabler for carbon dioxide reduction in a global supply chain: A case study from the semiconductor industry
[9]	Alfieri and Pastore	2018	Adding Urban Hubs in Supply Chains: An Italian Fast Fashion Case Study
[124]	Moore et al.	2018	Simulation-based evaluation on integrating additive manufacturing capability in a deployed military environment
[140]	Pinho et al.	2018	Soft Computing Optimization for the Biomass Supply Chain Operational Planning
[54]	Eddoug et al.	2018	Performance evaluation of complex multi-echelon distribution supply chain
[142]	Rabe et al.	2018	Evaluating the consolidation of distribution flows using a discrete event supply chain simulation tool: application to a case study in Greece
[145]	Rehman and Ryan	2018	Development of a Control Theoretic Based Simulation Model of a Supply and Distribution System with Reusable Items
[110]	Macal	2018	Tutorial on agent-based modeling and simulation: ABM design for the zombie apocalypse
[143]	Rasnick and Chatfield	2017	Information blackouts in a multi-echelon supply chain simulation
[139]	Pinho et al.	2016	Modelling a Bio Mass Supply Chain through discrete event simulation
[23]	Benzaman et al.	2016	Discrete Event Simulation of Green Supply Chain with Traffic Congestion Factor
[196]	Zhou et al.	2016	Improving supply chain performance through simulation

Table A.1 continued from previous page

	Authors	Year	Title of Paper
[156]	Sahoo and Mani	2015	GIS based discrete Event Modelling and Simulation of Biomass Supply Chain
[184]	Windisch et al.	2015	Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain
[56]	Eriksson and Eliasson	2015	Analyzing machine concepts and delivery strategies to cut delivery costs for forest fuels using a discrete-event simulation model
[175]	Thompson and Badizadegan	2015	Valuing Information in Complex Systems: An Integrated Analytical Approach to Achieve Optimal Performance in the Beer Distribution Game
[182]	Webb et al.	2014	Simulation as a Tool for evaluating Bioenergy Feedstock Supply Chains
[45]	Cooper et al.	2014	Evaluating Cost-to-Serve for a Retail Supply Chain
[94]	Lakshmanan	2014	Application of Discrete Event Simulation at Eastman Chemical Company
[68]	Garcia-Herreros et al.	2014	Empirical study of the behavior of capacitated production-inventory systems
[7]	Abolhasani et al.	2014	Optimization of Multi-commodities Consumer Supply Chains Part II: Simulation Modeling
[85]	Kabirian et al.	2013	Revenue and Production Management in a Multi-echolon Supply Chain
[44]	Cooper et al.	2013	Reducing Inventory Cost for a Medical Device Manufacturer using Simulation
[63]	Forstner and Mönch	2013	A Heuristic to Support Make-To-Stock, Assemble-To-Order, and Make-To-Order Decisions in Semiconductor Supply Chains
[138]	Pfeiffer et al.	2013	A Simulation Approach to Evaluate Supply Chain Flexibility
[169]	Taki and Kazemi	2013	A three echelon supply system: a discrete event simulation
[27]	Borodin et al.	2013	A discrete event simulation model for harvest operations under stochastic conditions

Table A.1 continued from previous page

	Authors	Year	Title of Paper
[141]	Rabe et al.	2012	An Approach for Increasing Flexibility in Green Supply Chains driven by Simulation
[53]	Dorsch and Hackel	2012	Integrating Business Partners on Demand: The Effect on Capacity Planning for Cost Driven Support Processes
[25]	Blanco et al.	2011	Using discrete-event simulation for evaluating non-linear supply chain phenomena
[188]	Xiang et al.	2011	Simulation on order allocation within multi-suppliers of industrial cluster
[158]	Samvedi and Jain	2011	Studying the impact of various inventory policies on a supply chain with intermittent supply disruptions
[70]	Gnoni et al.	2011	A simulation comparison analysis of effective pallet management scenarios
[58]	Finke et al.	2010	Modelling and Simulating Supply Chain Schedule Risks
[48]	de Assis Rangel et al.	2010	A simulation model to evaluate sugarcane supply systems
[75]	Hallam	2010	Lean Supply Chain Management Techniques for Complex Aerospace Systems: Using Discrete Event Simulation to Mitigate Programmatic Cost and Schedule Risk
[100]	Lee and Farahmand	2010	Simulation of a base stock inventory management system integrated with transportation strategies of a logistic network
[181]	Watanarawee and Baramichai	2010	The evaluation of information sharing and transshipment mechanisms on supply chain performance: The case study from Thailand' retail chain
[130]	Muller et al.	2009	A Simulation of the Pharmaceutical Supply Chain to Provide Realistic Test Data
[108]	Luo and Ji	2009	The Impact of Information Sharing on the Performance of Different-Echelon Supply Chain

Table A.1 continued from previous page

	Authors	Year	Title of Paper
[72]	Grewal et al.	2009	Performance effects of setup time reduction with and without decision variable re-optimization: A simulation-optimization study
[161]	Sharda and Vazquez	2009	Evaluating capacity and expansion opportunities at tank farm: A decision support system using discrete event simulation
[131]	Mustafee et al.	2006	Distributed Simulation with COTS Simulation Packages: A Case Study in Health Care supply
[31]	Byrne and Heavey	2006	The impact of information sharing and forecasting in capacitated industrial supply chains: A case study
[180]	Wang and Takakuwa	2006	Module-Based Modeling of Production-Distribution Systems Considering Shipment Consolidation
[157]	Saif et al.	2006	Simulation Optimization of a Four-Stage Supply Chain System
[126]	Morrice et al.	2005	Discrete Event Simulation I Supply Chain Planning and Inventory Control at Freescale Semiconductor, Inc.
[59]	Fleisch and Tellkamp	2005	Inventory inaccuracy and supply chain performance: a simulation study of a retail supply chain
[81]	Hwarng* et al.	2005	Modelling a complex supply chain: understanding the effect of simplified assumptions
[82]	Jain and Leong	2005	Stress testing a supply chain using simulation
[91]	Komoto et al.	2005	A Multi-Objective Reconfiguration Method of Supply Chains through Discrete Event Simulation

Table A.2: Statements about ABM found in literature

Strengths ABM	Statements	Paper
Autonomy	Agemts involved are able to make autonomous decisions	[32]
	Autonomous behaviour of modeled individuals	[67]
	Promising so model interacting autonomous agents	[88]
	Promising in SC investigation, due to autonomous behaviour	[186]
CAS	Suitable to model human based complex systems	[122]
	Applicable for complex business managing processes	[73]
	Combined with CAS, ABM can represent every kind of enterprise and its relations	[96]
	By combining ABM and CAS, deep insight into logistic management can be gained	[134]
	Powerful technique to analyze complex dynamic supply chain processes	[155]
	Gets used when complex emergent behaviour is prevelant	[171]
	Best approach when it comes to complex systems	[173]
	Shows its strength in modelling complex systems	[186]
	Suitable tool to solve complex systems	[197]
	Good approach to model complex adaptive systems	[8]
	Popular tool to model complex adaptive structures like Supply Chains	[40]
	Promising approach to model interactive complex systems	[88]
Commonly Used	finds a significant place in the supply chain literature	[80]
	Growing interest of ABM in combination with supply chain disruptions management	[88]
	Commonly Applied in Supply Chain Management	[167]
	ABM is a promising research area, applied in various supply chain case studies	[171]
	Recently applied to Supply Chain Management	[173]
	ABM has been used in a various fields	[186]
	Complex systems of various fields have been investigated using ABM	[189]
	ABM has been extensively used in supply chain modeling	[190]
	ABM is applied in various fields	[193]
	Popular paradigm due to its universal applicability	[13]
	ABM successfully used in various case studies	[163]
Decentralized Structures	Capable to represent distributed Networks	[8]
	Applicable to model structural decentralized supply chains	[35]
	ABM most popular distributed solving technique regarding supply chain problems	[37]
	Has gained a lot of attention handling decentralized plans	[36]

Table A.2 continued from previous page

Strengths ABM	Statements	Paper
	Suitable to model decentralized social systems	[88]
	Usable for dynamically distributed supply chain structures	[193]
	Suitable to model a distributed transportation environment	[197]
Dynamic	No static environment has to be assumed	[73]
	Allows you to display the dynamics of a supply chain	[173]
Effective	One of the most effective ways to model and analyze Supply Chain Nodes	[50]
	Effective approach predicting the behaviour of a system	[144]
	Effective way to model a Supply Chain	[163]
	Internal behaviours can be modeled effectively	[190]
	One of most effective ways to model dynamic route choice problems	[197]
Emerging	Possible to model emerging organizational structures	[8]
	Emerging behaviour possible to model based on individual written rules	[32]
	ABM enables modeling emerging dynamic systems like Supply Chains	[40]
	Low level decisions and the resulting system behaviour can be investigated	[73]
	System behaviour emerges based on low level decisions and interactions	[88]
	Single component decision rules form the system behaviour	[122]
	Emerging properties are suitable to model and analyze supply chains	[128]
	ABM gets used, when emerging behaviour is essential	[171]
	Effect of macro effects on the overall picture can be investigated	[173]
	Allows to reveal emerging system behaviours	[186]
	Natural way to represent a human based emerging system	[192]
Fault Tolerant	The architecture of ABM shows a good fault tolerance	[67]
	Robust to modelling errors	[73]
Flexible	More flexible than centralized strategies at high complexity systems	[73]
	Flexible behaviour of agents leads to the simple adaptability of these	[88]
Granularity	ABM allows the granular representation at different levels of complexity	[93]
	Structure enables the modeling on micro level	[186]
	Internal individual behaviours can be investigated	[190]
Heterogeneous Behaviour	Individuality in a heterogeneous system can be investigated	[40]

Table A.2 continued from previous page

Strengths ABM	Statements	Paper
	The non-mandatory homogeneity of a system represents a big advantage of ABM	[173]
	Heterogeneous Systems can be analyzed	[186]
	Modeling and analyzing and observing heterogeneous behaviour is possible	[8]
Human Behaviour	Gain knowledge of human behaviour	[8]
	Being able to model human reactions	[15]
	Intelligence and pro-activity of agents is an advantage	[190]
	Pro-activeness and human autonomy beneficial in dynamic simulation models	[92]
	Human like representation enables reality based modeling	[186]
	Good approach to model social networks	[167]
Interactions	Interaction processes can be designed more efficient	[8]
	Interactions between single agents can be analyzed	[13]
	Social networks and processes can be modeled by using ABM	[15]
	Agents can communicate with each other to share information	[32]
	ABM is most suitable for systems with involved information exchange routines	[35]
	Ability to share information is biggest advantage of ABM	[37]
	ABM is a promising approach to model interactions between individuals	[88]
	Enables the consideration of complex relationships	[96]
	Good approach when it comes to social interactions	[167]
	Promising for supply chain investigation due to possible interactions and negotiations	[186]
	Powerful tool to analyze competition and cooperation	[189]
	Most effective in route choice problems due to enabled communication among agents	[197]
Low Effort	ABM might be combined with existing DES libraries to lower the effort	[8]
Modularity	Modular structure of ABM enables cooperation among different developers	[8]
	Due to the modular structure, the ABM represents a scalable modeling approach	[144]
	ABM based models can be easily extended	[173]
New	Has not been carried out in a specific area and gains interest	[13]
	ABM is new and gets popular to investigate supply chains	[36]

Table A.2 continued from previous page

Strengths ABM	Statements	Paper
	New approach of ABM enables the integration of artificial intelligence and parallel computing	[155]
Reality Based	The acquisition of knowledge and development of agents is realistic	[32]
	By using agents it is more convenient representing the reality	[96]
	ABM is a natural way to describe a system	[104]
	Real world entities can be represented by agents	[155]
	Due ABM it is possible to represent a supply chain node realistically	[163]
	Agents act like real components to be investigated	[186]
	There is a natural correspondence between agents and supply chain nodes	[50]
	Characteristics of real life components can be adapted by agents	[88]
Understandable	ABM provides an understandable model	[73]
	ABM is an comprehensive modeling paradigm and simulation approach	[88]
	Results of ABM are interpretable by most of the stakeholders	[133]
	ABM allows to understand interactions on a operational level	[144]

Table A.3: Weaknesses of ABM found in literature

Weaknesses ABM	Statements	Paper
Framework Dependent	The success of ABM simulation studies strongly depends on Frameworks used	[8]
High Effort	Effort put in pays back in a late stage of the simulation study	[8]
New	Necessary psychological insights are not yet available	[8]
	Research an know-how in supply chain management is limited	[88]
	Not much used in the field of supply chain simulation	[171]
Objective not ensured	Achievement of System objective can't be ensured due low cooperative efficiency	[67]
Required Data	Agent-based modelling requires availability of much data	[144]

Table A.4: Strengths of DES found in literature

Strengths DES	Statements	Paper
Centric structures	DES appropriate if events are handled centrally	[144]
Commonly Used	Most used modeling approach when it comes to supply chain management at operational and tactical levels	[7]
	Commonly used to analyze manufacturing systems	[10]
	Intensively used in various fields in industry	[68]
	Many studies were carried out in the area of supply chain simulation with the help of DES	[122]
	DES is commonly used to capture the stochastic and complex nature of supply chains	[140]
	Several studies on supply chains have been conducted using DES	[143]
	DES models are becoming popular to investigate and evaluate supply chains	[157]
	DES models are widely accepted as appropriate approach to model real world problems	[196]
Complex Systems	DES usable to analyze complex systems	[139]
	Suitable to simulate complex behaviours of complex relationships of entire life cycles	[91]
	DES allows the representation of complex interdependencies	[138]
Different Data Sources	DES makes it possible to include different data sources	[68]
Easy to Use	Simple simulations manageable in spreadsheets	[85]
Effective	Effective approach to model and simulate supply chain processes	[140]
	Effective methodology when the system changes status at discrete times.	[141]
	DES is a module-based efficient modeling paradigm	[180]
Flexible	The flexibility of DES enables the generation of suitable system models	[141]
Large Nr. of Variables	DES can handle large amounts of variables	[161]
Reality Based	Supply chains can be modeled naturally by a set of events happening at discrete points in time	[143]
	Natural representation of the supply chain through the ability to include pure delays	[145]

Table A.4 continued from previous page

Strengths DES	Statements	Paper
Scenarios	DES is suited to model and investigate different scenarios	[138]
	Simplifies the analysis of various what if scenarios	[141]

Table A.5: Weaknesses of DES found in literature

Weaknesses DES	Statements	Paper
CAS	DES cannot reflect dynamic complexity	[10]
High Effort	Performing a DES requires many resources	[122]
Human Involvement	Autonomous decision making is difficult to depict	[183]

Table A.6: Most cited References

	Authors	Year	ABM	HYB	DES
ABM					
[109]	Macal and North	2015	[8] [110] [167] [13]		
[106]	Li et al.	2010	[8] [171] [50]	[183]	
[135]	North and Macal	2007	[73] [122] [173] [13]		
[111]	Macal and North	2005	[192] [186] [110] [104]		
[26]	Bonabeau	2002	[173] [110] [30] [155]	[191]	
[168]	Swaminathan et al.	1998	[186] [50] [110] [30] [104] [189]		[45] [15] [59]
DES					
[123]	Mobini et al.	2011			[184] [139] [90] [140]
[14]	Asikainen	2010			[184] [139] [90] [140]
[18]	Banks et al.	1996			[25] [169] [126] [48] [81] [90]
SD					
[166]	Sterman	2000	[65] [186]		[90] [175]
[165]	Sterman	1989	[190] [173] [83] [167] [37]		[175] [143]
FW					
[69]	Giannakis and Louis	2011	[173] [88] [154] [40]		
SCS					
[113]	Mahmoudi et al.	2009			[184] [139] [90] [140]
[121]	Min and Zhou	2002	[8] [186] [173] [50]		
[195]	Zhao and Xie	2002	[173] [50] [37]		[31]
[33]	Cachon and Fisher	2000	[50] [35] [194]		[59] [108] [181]
[103]	Lee et al.	2000	[80] [190] [173] [35]		[31] [108]

Table A.6 continued from previous page

	Authors	Year	ABM	HYB	DES
SIM					
[159]	Sargent	2007			[126] [90] [100] [48]
[87]	Kelton	1998			[126] [130] [48] [180] [72]
[98]	Law et al.	1991	[10] [36] [154]		[44] [25] [131] [126] [90] [180]
[52]	DONNELLY	1991	[186] [50]		[126] [48]
SCM					
[172]	Tang	2006	[186] [160] [163]		[158]
[79]	Holweg et al.	2005	[50] [13] [51]		[31]
[174]	Terzi and Cavalieri	2004	[8] [122] [186]	[141]	[82] [7]
[74]	Gruen et al.	2002	[186] [154]		[15] [59]
[41]	Choi et al.	2001	[50] [96] [30] [104]		
[38]	Chen et al.	2000	[173] [50] [129] [83] [51]		[15] [59] [143]
[21]	Beamon	1999	[73] [186] [30]		[138]
[102]	Lee et al.	1997	[171] [173] [50] [35] [129] [83] [40] [128] [37]		[181]
[101]	Lee et al.	1997	[8] [129] [83] [167]		[59] [76] [175]
[42]	Christopher	1992	[171] [167]		[25] [81]

B

Conceptual Model

In the following, the conceptual model on which the simulation study is based is presented.

Appendix B.1. Problem Description

As no real problem is transferred to the simulation, rather a simplified problem has been created. The general goal of the modelled supply chain network is to accept customer orders and process them as efficiently as possible based on the available resources. The network available for this purpose consists of three basic entity types.

- Distributor
  The central control unit of the supply chain, which distributes and forwards received orders to suppliers and, upon receipt of the goods, carries out quality checks before the products are forwarded to customers. However, the distributor is not a manufacturing unit.
- Original Equipment Manufacturer (OEM)
  These are suppliers who manufacture end products. They have production lines (facilities) at their disposal on which the goods are manufactured.
- Sub-Supplier
  Similar to the OEM, these suppliers have production facilities at their disposal, where goods can be manufactured. They are responsible for providing the components to the OEMs so that the supply chain can manufacture final products in a closed loop.

The effects of alternative material flow paths on the performance of the supply chain shall be investigated, measured by the average delivery time.

There are two cases to distinguish, from which the corresponding transport routes can be derived. The decisive factor is the relationship between supplier and distributor, referred to as Trust Level, illustrated by the different color scheme.

- Trust Level 0: Suppliers are not allowed to deliver the products to the clients directly. Both sub-components and end products must be shipped via the central supply chain node, where they undergo a final quality check to evaluate and ensure the quality of manufactured products before they are finally forwarded to the customer. Suppliers and customers are never in contact in this case, due to a missing material or information flow between the two parties.

- Trust Level 1: Consistent, stable product quality, as well as the resulting good relationship, allow a direct product shipment between producer and customer. The distributor simply forwards the order request and thus gives up his responsibility. The supplier sends the product directly to the sold-to party after production has been completed, regardless of whether it is a finished product or a partial component. Although all parties involved in the production process communicate exclusively via the distributor, good are sent directly to the customer without an intermediate stop at the quality check.

The individual elements of the conceptual model are listed in the following and referred to corresponding contents, which deal with the respective key points.

Appendix B.2. Objectives
Table B.1 shows the objectives, divided into organizational aims, general, and modeling targets.

Appendix B.3. Outputs
The defined modeling outputs to be generated by the simulation study are summarized in Table B.2

Appendix B.4. Input Factors
Selected input factors are presented in Table B.3 by designation and a brief definition.

Appendix B.5. The Model Structure
Structural View of the Supply Chain is presented in Figure B.1 as structural blueprint. Table B.4 provides an overview of the entities considered and entities neglected in the modelling process.

Appendix B.6. Individual Model Behaviour
The individual model behaviour is described by a tabular overview of the activities to be mapped (see Table B.5), the representation of processes of active entities in the form of flow diagrams (see Figure B.2) and detailed activity descriptions (see Tables B.6 to B.10)

Appendix B.7. System Behaviour
The control tree of the supply chain structure is given by Figure B.3, the detailed control unit specifications are described in Table B.11. The control policies of the two Control Unit types involved, Distributor and Supplier, are shown in Figures B.4 and B.5.

Appendix B.8. Simplifications and Assumptions
Simplifications and assumptions made are outlined in Table B.12.

Table B.1: Simulation Study Objectives

Organizational Aim	
Lead-time should not exceed 4 weeks for 90% of the orders	
General Objectives	
Project Duration	5 months
Workload	1 developer for a total of 15 h per week
Visualization Requirements	No visualization of the model needed
Re usability Requirements	The model should be designed to enable the possibility of further expansion stages in the supply chain network
Documentation and usability	The simulation should be easy to handle and understand, even for untrained users. No detailed documentation is necessary.
Modeling Objectives	
Policy improvement	Evaluate different trust policies of suppliers including OEM and sub-suppliers

Table B.2: Simulation Outputs

Aggregated Values	
Mean Lead Time	Average time from order arrival at distributor to delivery of the goods
90% Quantile Lead Time	Lead Time that is not exceeded by 90% of the orders placed and fulfilled
Mean capacity utilization	Average capacity utilization of suppliers in the supply network
Empirical Distributions	
Generation of empirical distributions of lead times in form of scatter charts or histograms	

Table B.3: Input Factors

Input Factors	
# **of OEMs**	Number of available OEMs in the supply chain network
# **of Sub-Suppliers**	Number of available subcomponent suppliers in the supply chain network
# **of Production Lines**	Quantity of production facilities available to the supplier
Trust Levels	Trust Levels associated with the suppliers

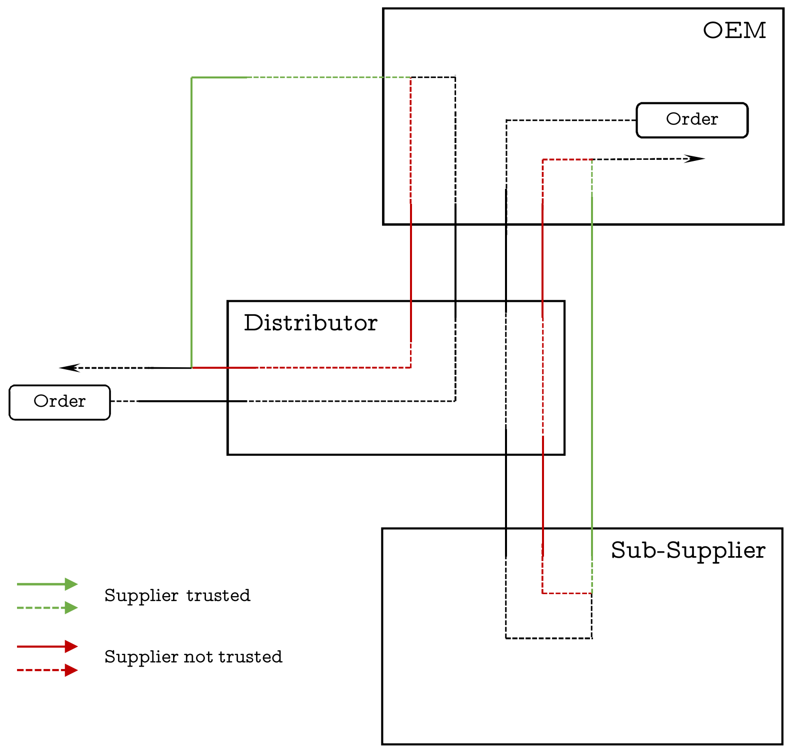

Figure B.1: Blueprint of Final Entity Construct

Note: The quantity of OEMs and suppliers shown is only an example. The process location does not change, regardless of how many suppliers are involved. Green and red paths represent the different paths of the orders, depending on the trust level of the individual suppliers.

Table B.4: Entities and Attributes relevant to the Model

Entities		
Entity (→ Attribute)	**Included**	**Description**
Customer	no	Physical person or company that can place an order
Distributor	yes	Central point of accumulation of information, from which orders are distributed and quality checks are performed
→ (Un)Loading Area	no	Area where trucks can dock, where they are unloaded and loaded
→ Warehouse	no	Area with storage capacity, where products can be temporarily stored
→ Inspection Area	no	Area where quality checks of the final products are carried out
→ Workforce	no	Workers who belong to the structures to be depicted
OEM	yes	Supply chain partner who provides finished products
→ (Un)Loading Area	no	Area where trucks can dock, where they are unloaded and loaded
→ Warehouse	no	Area with storage capacity, where products can be temporarily stored
→ Assembly Lines	yes	Assembly Lines, where end products are assembled from sub-components, and finally packed
→ Workforce	no	Workers who belong to the structures to be depicted
Sub-Supplier	yes	Supply chain partner, which provides semi-finished products and components
→ (Un)Loading Area	no	Area where trucks can dock, where they are unloaded and loaded
→ Warehouse	no	Area with storage capacity, where products can be temporarily stored
→ Production Lines	yes	Production Lines, where sub-components are manufactured from raw materials
→ Workforce	no	Workers who belong to the structures to be depicted
Product	no	Physical products that are manufactured and shipped
Order	yes	Purchase order, which is issued to the distributor or the supplier
Trucks	no	Service that transports products between two entities

Table B.5: Activities to be Depicted

Activities		
Activity	**Entity**	**Description**
Quality Check	Order	Time-delayed activity of a random quality check for verification
Production	Order	Production of the ordered components
Assembly	Order	Production handling of the received order
Waiting	Order	Waiting on the order for further processing
Shipping	Order	Transfer of an order to the temporary, intermediate, or final destination
Production	Production Line	Production handling of the received order
Waiting	Production Line	Downtime of production lines between the production of individual products
Assembly	Assembly Line	Assembly of the items ordered
Waiting	Assembly Line	Rest periods between assembly of an entire order

Table B.6: Produce/Assembly Activity Definition

Order Production	
Participating Entities	Order, Facility
Start Type	Requested
End Type	Scheduled
Start State Changes	Facility.IsReserved = FALSE Inventory -= Amount [BOMElement]
End State Changes	none
Attributes	**Description/Value**
Duration	Quantity dependent function
Request Attributes	**Description /Value**
Time Request	When was the request made from the Supplier Control Unit
Request Specification	Request filed after order arrival at Supplier

Note: Assembling of final products and production of sub-components have the same systematics, and are therefore summarized here.

Table B.7: Shipment Activity Definition

Order Shipment	
Participating Entities	Order
Start Type	Requested
End Type	Scheduled
Start State Changes	none
End State Changes	none
Attributes	**Description/Value**
Duration	3 working days
Request Attributes	**Description /Value**
Time Request	When was the request made
Request Specification	Request filed after production is finished

Table B.8: Activity Check Products Definition

Quality Check	
Participating Entities	Order
Start Type	Sequential
End Type	Scheduled
Start State Changes	none
End State Changes	none
Attributes	**Description/Value**
Duration	Function of items to be checked
Request Attributes	**Description /Value**
Time Request	When was the request made
Request Specification	Request filed after the products arrive at the distributor

Table B.9: Facility Waiting Activity Definition

Activity Wait Facility	
Participating Entities	Facility
Start Type	Sequential
End Type	System
Start State Changes	none
End State Changes	none
Attributes	**Description/Value**
Start Time	Time activity starts

Table B.10: Order Waiting Activity Definition

Activity Wait Order	
Participating Entities	Order
Start Type	Sequential
End Type	System
Start State Changes	none
End State Changes	none
Attributes	**Description/Value**
Start Time	Time activity starts

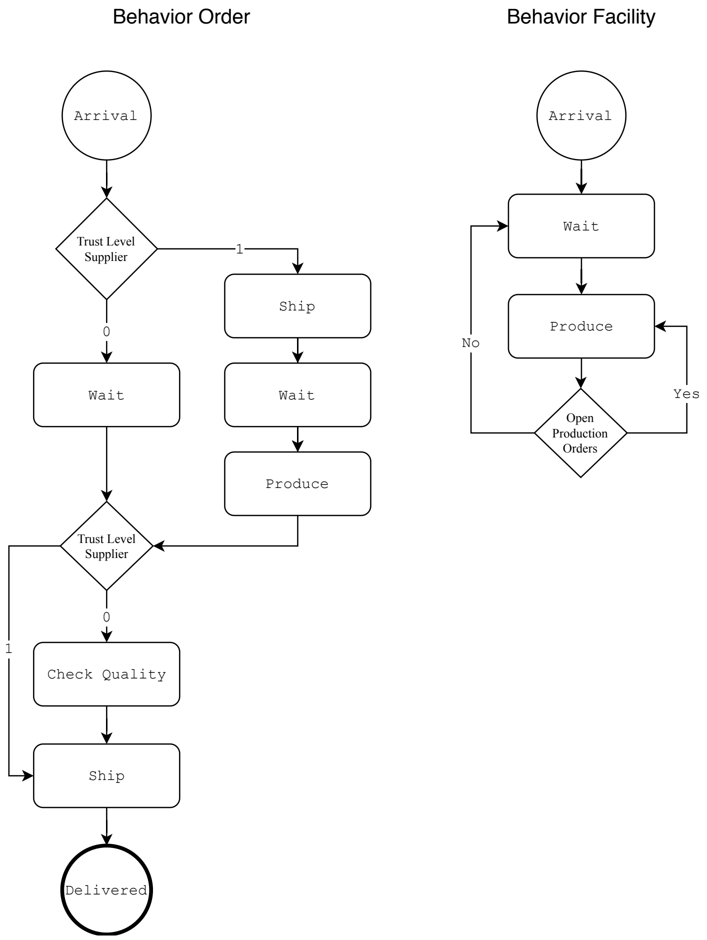

Figure B.2: Behavioral View of Entities

Table B.11: Control Units Definition

Control Units		
Name	**Entities**	**Attributes**
Distributor	Order	Order.Amount Order.Principal Order.Product Order.Status
Supplier	Facility	Facility.Inventory Facility.IsReserved Facility.Skill
	Order	Order.Amount Order.Principal Order.Product Order.Status

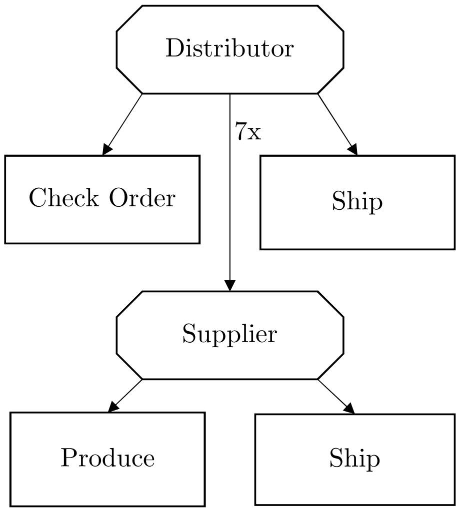

Figure B.3: Structure Control Units

Note: For the sake of clarity, only one supplier control unit is shown here. In the model,there are seven of these (one OEM and six sub-component suppliers). However,since they do not differ in their tasks,the representation can be reduced to the form shown with this reference.

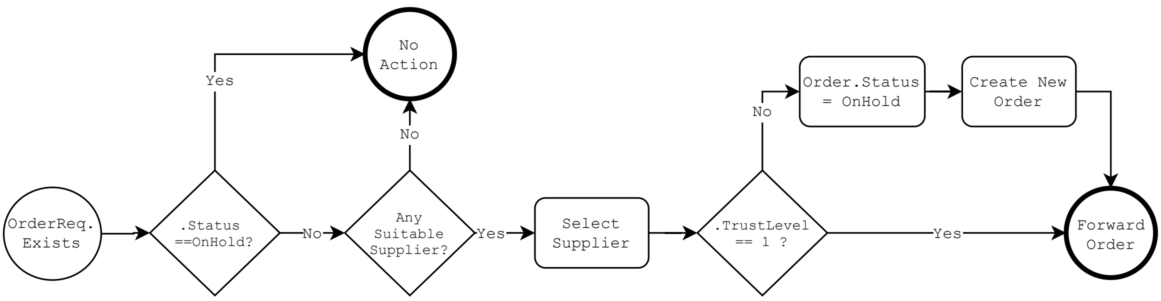

Figure B.4: Control Policy CU Distributor: Order Request

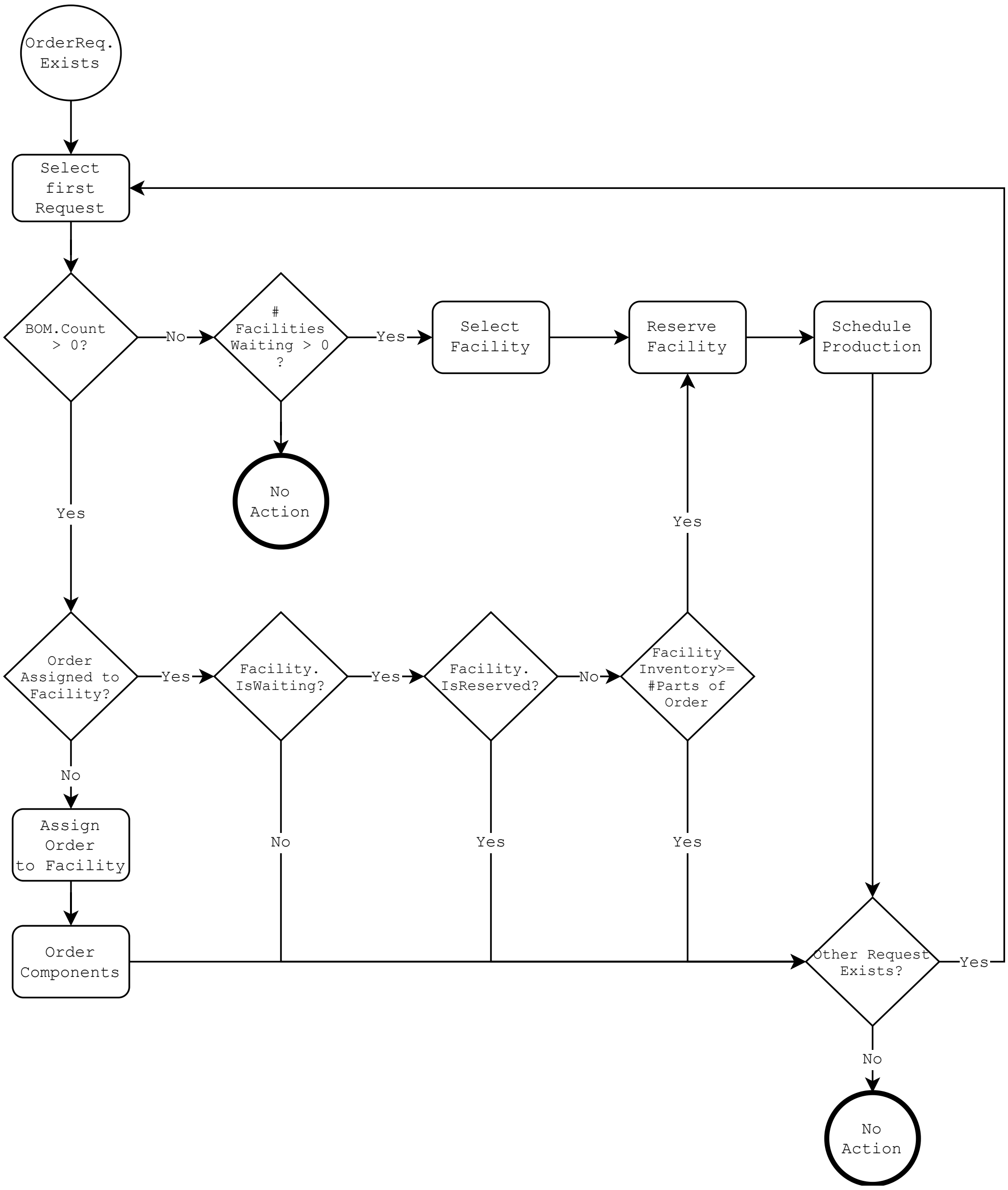

Figure B.5: Control Policy CU Supplier: Order Request

Table B.12: Assumptions and Simplifications within the Model

Assumptions	Confidence	Impact
Sub-suppliers have enough raw-material in stock	Medium	High
No shortage of space and workforce	High	Medium
Simplifications	**Confidence**	**Impact**
Constant delivery times	Medium	Medium
No production breakdowns considered	High	Low
100 % good parts at quality check	Medium	Low
Simulation stops at the arrival of the last order at the distributor	Medium	Low
The supply chain is designed for one end product	Low	Low
Production lines can only produce one specific product	High	Medium
No parallelization of preparation activities on one production line	Medium	Low
No influence of different locations of the supplier and customer on delivery times	Low	Low
Constant cycle times in production lines	Medium	Low

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