1 Introduction

Logistics distribution networks are complex systems. These systems are formed from entities, such as sites, suppliers, and customers (Christopher 2016). The sites present facilities, such as warehouses and distribution centres. They store materials as stock keeping units (SKUs) that are supplied from suppliers and distributed to customers based on their placed orders. Thus, transportation relations connect sites, suppliers, and customers and form a network of links between them. The size of the network increases when the number of links and entities increases, such as adding a site or an SKU to the network.

In the logistics distribution network, decision-makers select actions, such as "centralise an SKU in a site", to decrease costs and increase service levels (Benh 2003; Rushton et al. 2017). However, the impact of the actions might be conflicting (Rushton et al. 2017). For example, centralising an SKU in a site might reduce the costs, but it might decrease the service level. Centralising an SKU in a site cuts inventory costs associated with storing the SKU in the other sites in a network, but centralising the SKU might increase the delivery time to customers, and hence, might decrease the service level. The number of possible actions is influenced by the size of the network. Decision-makers are encountered by a large number of actions in large logistics distribution networks. They select actions and form action plans, in which the order of the actions influences their impact on the network. Additionally, decision-makers have to consider uncertainty in the lead time and the number of orders. Thus, the decision-makers face a challenging task in constructing action plans.

The selection of actions, forming action plans, and optimising a logistics distribution network is a challenging combinatorial optimisation problem (COP) (Dross and Rabe 2014). In this COP, an optimal action plan is formed from a finite space of actions. In large logistics distribution networks, the finite space of actions becomes large and, hence, selecting actions to form action plans becomes an *NP-hard* COP. Metaheuristic algorithms are used to solve these problems, such as evolutionary algorithms (Datta et al. 2019). The metaheuristic algorithms cannot guarantee that they will find the action plan that optimises the objective functions of the optimisation problem, but they can typically find a promising action plan (Talbi 2009).

In order to optimise logistics distribution networks, the complex networks are simplified and modelled using simple mathematical equations. However, the simplification includes assumptions that cut off valuable parts of the network dynamics. Thus, complex logistics distribution networks are modelled using simulation, such as discrete event simulation (Law 2015), and the simulation is combined with metaheuristics in a simheuristic approach to optimise these networks (Juan and Rabe 2013). In the simheuristics, the simulation is used to evaluate the objective function of an optimisation problem, and the metaheuristic algorithm constructs solutions. The simheuristics, therefore, combines the power of metaheuristics and simulation (Juan et al. 2018).

Decision-makers in logistics distribution networks can utilise logistics assistance systems (LASs) (Liebler et al. 2013). A LAS is a decision support system designed specifically for logistics distribution networks. Dross and Rabe (2014) have developed a LAS to recommend the most promising action plans. This LAS is based on a simheuristic approach and combines a discrete event simulation to evaluate the impact of action plans on the network and metaheuristics to construct these action plans. The performance of the LAS can be evaluated based on its response time. The response time presents the time needed to recommend an action plan. It is affected by the metaheuristics' computational time and the simulation run time. The metaheuristics' computational time includes constructing action plans, comparing them, and exploring new action plans. The simulation run time is affected by the number of simulation runs and the simulation model's size that is affected by the size of the logistics distribution network. Despite the benefit of simulation in modelling complex networks, it is a computationally expensive tool to evaluate the objective functions in an optimisation problem (Law 2015). Large logistics distribution networks have a large space of action plans to be explored by the metaheuristics, and the simulation run time is, therefore, long.

This research aims to improve the performance of the LAS, and hence, reduce its response time. The simplification of logistics distribution networks reduces their complexity and the size of simulation models, and hence, reduces the simulation run time, such as model simplification by assuming deterministic variables values. This simplification reduces computational demand, but might not present the network correctly. A fast simulation tool and parallel processing reduce the response time by reducing the computational time and distributing it. However, the research in this thesis investigates the simheuristic approach to improve the performance of the LAS. The performance of the LAS depends on the performance of the metaheuristics in the simheuristic approach. The metaheuristic algorithm is evaluated by the number of objective function evaluations and the quality of solutions (Talbi 2009). Thus, this research focuses on defining approaches to reduce the number of objective function evaluations and to increase the quality of recommended action plans.

Researchers have investigated several approaches to improve the performance of metaheuristics. Beiranvand et al. (2017) stated that the tuning of metaheuristics' parameters plays a significant role in finding promising solutions in a search space. Amaran et al. (2016) and Blenk et al. (2017) recommended utilising problem information to guide the search for promising solutions. Other researchers investigated approaches to reduce the number of objective function evaluations. Some approaches focused on reducing the size of the search space. For example, Bode et al. (2019) and Sheri and Corne (2009) defined constraints to screen solutions and reduced the size of the search space. Their approaches utilise the coefficients of the objective function and constraints to screen the solutions in the search space. Other researchers filtered solutions before their evaluation. For example, Alsheddy et al. (2018) and Cai et al. (2017) clustered neighbour solutions of a solution to be explored or not. Most of the approaches focused on the mathematical formulation of optimisation problems and the coefficients of the objective function and constraints. In simheuristics, researchers recommended reducing the number of simulation runs to improve the performance of the simheuristics (Ding et al. 2009; Alsheddy et al. 2018).

In order to improve the quality of the found solutions presented as action plans in the LAS, this research analyses the impact of actions on logistics distribution networks (Rabe et al. 2018a). The impact of an action on a network is affected by other actions in the action plan. Thus, the relationship between actions is investigated. These relations present particular information called domain-specific information (DSI) (Rabe et al. 2017a), such as the type of changes applied by an action, the success of an action, and the correlation between actions. This research utilises the DSI to alter the selection probability of actions to explore promising action plans. As a result, promising action plans in a smaller number of simulation runs might be recommended.

In order to reduce the number of simulation runs, this research investigated two approaches. The first approach reduces the space of actions (Rabe et al. 2018b). The space of actions is replaced by a smaller number of actions to select from. These actions are grouped to form complex actions based on the entities' attributes, such as grouping actions based on SKU attributes or site attributes.

The second approach that reduces the number of simulation runs investigates the action plans (Rabe et al. 2018b). Different action plans can be equivalent regarding their impact on the performance of the network. This research identifies the equivalent action plans by defining interchangeable actions and redundant actions in action plans. The equivalent action plans might have the same actions in a rearranged order. An action plan is evaluated based on its equivalent action plan, and the evaluation of action plans using simulation is skipped to reduce the number of simulation runs.

Finally, the approaches are prototypically implemented, and a real-world logistics distribution network is used to evaluate the impact of the approaches on the performance of the LAS. The performance is evaluated by the number of simulation runs and the impact of the recommended action plan.

This thesis is organised as follows: Chapter 2 describes logistics distribution networks and assisting tools for the management of the networks. Chapter 3 presents methods to solve optimisation problems. The LAS and the research problem are described, as well as the research questions are derived in Chapter 3. Chapter 4 discusses the utilisation of DSI to enhance to the performance of the LAS. Chapter 5 presents approaches to reduce the number of simulation runs in the LAS. The proposed approaches are evaluated in Chapter 6. Finally, Chapter 7 closes the thesis with a summary.

2 Management of Logistics Distribution Networks

This research studies approaches to enhance the performance of simheuristics applied to optimise logistics distribution networks and tests these approaches on a distribution network's case study. The application domain of this research, a multi-echelon logistics distribution network, is presented in Section 2.1. Distribution networks are complex systems. Hence, decision making is a challenging task, and several tools have been developed to support decision-makers. Assistance tools for the management of distribution networks are presented in Section 2.2.

2.1 Logistics Distribution Networks

As a part of supply chains, in this section, distribution networks are presented. First, the relevant supply chain and logistics terms are described in Section 2.1.1. In Section 2.1.2, distribution networks and multi-echelon distribution networks are defined. In the management of distribution networks, decision-makers analyse the network and select decisions to improve the performance of the network. Decisions levels and performance measures are presented in Sections 2.1.3 and 2.1.4, respectively. Finally, the main challenges faced by the decision-makers are presented in Section 2.1.5.

2.1.1 Supply Chains and Logistics

Logistics and supply chains are two of many terms that refer to the distribution of products (Chiu 1995; Hesse and Rodrigue 2009; Rushton et al. 2017). Supply chains consist of a series of nodes that represent stages, physical entities, such as suppliers, manufacturers, distributors, retailers, and customers (Stadtler 2008; Ravindran 2016). Items are produced, packaged, and stored in these entities (Brandimarte and Zotteri 2007; Ravindran 2016). Stadtler (2008) stated that at least two organisations are connected in a supply chain where material, information, and financial flows take place. In addition to these physical entities, supply chains involve functions to achieve the customers' demands, such as procurement, production, and distribution (Portillo 2016; Ravindran 2016).

Huan et al. (2004) and Christopher (2016) described a supply chain as a network of links between the nodes. These nodes and links form the structure of the network (Cheng et al. 2014). Christopher (2016) argued that the term network could replace chain because of the multiple suppliers and customers in the supply chain. Figure 2.1 shows the network of connecting links between the nodes in a supply chain.

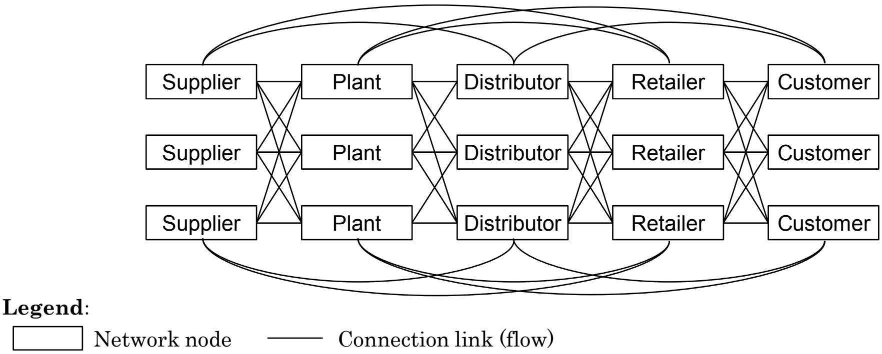

Figure 2.1: Supply chain network (after Chopra and Meindl 2016, p. 15)

In these networks, the two main flows are material flow and information flow (Riddalls et al. 2000; Steinrücke and Jahr 2012; Ghiani et al. 2013; Chopra and Meindl 2016). The material flow is associated with the flow of products from the suppliers' nodes to the customers' nodes; thus, it is a forward flow from the upstream to the downstream nodes. This flow can be between nodes in different stages or between peer nodes in the network (Brandimarte and Zotteri 2007). The latter presents the reallocation of products in case of overstocking or stockout. The material flow contributes to added costs and value to the products (Seppälä and Holmström 1995; Rushton et al. 2017).

The information flow is a backward flow, such as orders, promotions, plant capacity information, and inventory information (Riddalls et al. 2000; Steinrücke and Jahr 2012; Ghiani et al. 2013). It is a complementary flow to the material flow. Both flows are integrated to meet customer demand and efficient operations in the network (Steinrücke and Jahr 2012).

Another type of flow in the network is the financial flow (Sürie and Wagner 2008; Ravindran 2016). The financial flow includes credits and payments. The material flow is instantiated by order placement, which is one type of information flow. Then, the material flow is followed by a payment (a financial flow) and the information flow represented by an invoice (Sürie and Wagner 2008). Managing the material flow, the information flow, and the financial flow in an efficient matter in large networks is a "formidable task"

(Stadtler 2008). Chiu (1995) listed merchandise flow as another flow in the networks, which represents the flow of the material and the changes of its ownership.

In order to coordinate the links, the entities, and the flows in the network, effective planning is required presented as supply chain management (Svensson 2008). The concept of supply chain management became known since the 1980s (Svensson 2008), and the term supply chain management was used by Oliver and Webber (1992) to refer to an approach that facilitates the trade-off between the conflicting objectives in supply chains. In their approach, the supply chain is represented as a single entity, its functions have a supply as an objective, and decision making is required to balance the conflicting objectives of the functions.

The Council of Supply Chain Management Professionals defines the supply chain management as in Definition 2.1. It includes supply and demand management within the supply chain (Zijm et al. 2019); forecasting, order processing, transportation, and inventory management (Bowersox et al. 1992); a collaboration between all the organisations (Christopher 2016); and relationships between suppliers in the upstream and customers in the downstream of the supply chain (Hesse and Rodrigue 2009).

> **Definition 2.1 Supply Chain Management:** "Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies" (Council of Supply Chain Management Professionals 2020). "Effective supply chain management involves the management of supply chain assets and products, information, and fund flows to grow the total supply chain surplus" (Chopra and Meindl 2016, p. 16).

Logistics refers to the supply of materials, their management, their distribution, and the management of the information flow associated with it (Rushton et al. 2017; Zijm et al. 2019). Christopher (2016, p. 2) viewed logistics as "the process of strategically managing the procurement, movement, and storage of materials, parts, and finished inventory, and the related information flows through the organization and its marketing channels in such a way that current and future profitability are maximised through the cost-effective fulfilment of orders".

The Council of Supply Management Professionals differentiates in its definition between logistics management and supply chain management

(Definition 2.2). Logistics is a framework for planning the flow of material and information (Langley 1992; Stadtler 2008; Rushton et al. 2017; Zijm et al. 2019). On the other hand, supply chain management is concerned with the cooperation between processes of the partners in the supply chain (Christopher 2016).

> **Definition 2.2 Logistics Management:** "Logistics management is that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements" (Council of Supply Chain Management Professionals 2020).

2.1.2 Multi-echelon Logistics Distribution Networks

Networks are converging from suppliers through production and assembly activities; products from different suppliers meet at production and assembly nodes. (Brandimarte and Zotteri 2007). On the other hand, diverging networks represent the distribution side. Products flow from their production node to different warehouses (different nodes in the network). Distribution refers to the movement from suppliers' nodes to customers' nodes and storing items within the distribution network (Rushton et al. 2017). Items are transferred through distribution channels from a storage node to a customer node (Rushton et al. 2017). The items can be distributed directly to retailers, can pass through a warehouse and then to a retailer, or even pass other stages until they reach the retailer, such as a wholesaler.

A logistics distribution network is a system that consists of several entities, such as facilities, suppliers, stored items, and distributors (Chiu 1995; Seppälä and Holmström 1995). The system is defined in Definition 2.3.

> **Definition 2.3 System:** "A system is defined as a collection of entities which act and interact together toward the accomplishment of some logical end" (Schmidt and Taylor 1970, p. 4). These entities could be, e.g., people, or machines (Law 2015, p. 3).

Facilities represent critical structural entities in a logistics distribution network, and they are based on strategic decisions (Ravindran 2016) – strategic decisions are described in Section 2.1.3. The facilities are presented as distribution centres and warehouses. Hesse and Rodrigue (2009, p. 277) defined a distribution centre as "a facility or a group of facilities that perform consolidation, warehousing, packaging, decomposition, and other functions linked with handling freight". Thus, it provides essential value-added services in the distribution of items. It receives items, stores them, prepares the orders, performs some of the processing or the assembling, schedules vehicle routing, and handles the items (Chiu 1995). In this thesis, the term "site" will be used to represent facilities used to stock items in a distribution network. The relation between sites is described by structural attributes, such as their location and the major constraints (Meyr and Stadtler 2008). The site locations are determined, and items are allocated to the sites (Reza Nasiri et al. 2010). In a trading distribution network, a variety of products are supplied and stored in sites. Then, they are distributed to a variety of customers.

Transport means and their selection influence the distribution (Meyr and Stadtler 2008). They are presented by the fleet used for the transportation of items. Third-party logistics can contribute to the distribution of items in the networks and can provide other activities, such as storage (Hesse and Rodrigue 2009; Seyed-Alagheband 2011). Further integration of services can be achieved by the cooperation with a fourth-party logistics partner that provides services for managing the complex networks (Christopher 2016).

Another element in distribution networks is an inventory. It is formed as a result of an imbalance between inflows and outflows from the nodes in the network (Rushton et al. 2017). Inventory is often presented as an average level since the inventory level varies over time (Sürie and Wagner 2008). It is used to protect against uncertainties in the demand and the lead time (Sürie and Wagner 2008; Ravindran 2016). Safety stock is a term used in association with an inventory that is held to compensate for the uncertainties. The inventories are in the form of raw material, work in process, or finished goods. In this research, the stored items are assumed to be stored as stock-keeping units (SKUs). Every SKU presents a different item that differs in its weight, size, identification number, assortment, and other attributes (Rushton et al. 2017).

In addition to the sites and stocks in the distribution network, the network includes human resources and information technology (Ravindran 2016). The human resources are presented as technical staff that designs effective networks, the managerial staff, and operators. The information technology interferes with the activities and the exchange of information.

Logistics distribution networks include all the activities related to the movement of SKUs from one node to another in the network, such as transportation (Hesse and Rodrigue 2009). Transportation has a vital role in the success of distribution networks (Rushton et al. 2017). Other activities are procurement of SKUs, receiving the supplied products, storing, and packaging (Ghiani et al. 2013).

During the material flow, some of the SKUs' characteristics may change (Ghiani et al. 2013). Value-added activities contribute to the change in the value as a form-value, while distribution activities add value as time- and place-value (Bowersox et al. 1992; Christopher 2016; Rushton et al. 2017). Time- and place-values are associated with storage and transportation, respectively. The value is defined from the customer's perspective (Christopher 2016). This value affects the costs associated with SKUs (Rushton et al. 2017).

A term used in the description of networks is "echelon", which refers to the number of stages in a network. Brandimarte and Zotteri (2007) started numbering from downstream; thus, the first echelon is the one that stores and distributes products to customers. The customers' stage in the network is not considered as an echelon by most of the researchers. The second echelon is the stage that supplies these stores. Based on Riddalls et al. (2000), the echelon is presented in a distinct generic procedure in the system. One echelon can be considered as a group of sites performing a similar process in the network, such as procurement, distribution, and sales (Steinrücke and Jahr 2012). Thus, Figure 2.1 presents a four-echelon network.

2.1.3 Decisions in Distribution Networks

The management of logistics distribution networks includes planning, organising, and controlling (Schmidt and Taylor 1970). Planning involves making decisions regarding forecasting, site location, SKU allocation to sites, and distribution means based on predefined objectives. Organising is related to the arrangement of resources to meet the objectives efficiently and effectively. Controlling is based on assessing performance measures and selecting decisions to take corrective actions when the performance deviates from predefined objectives (Ghiani et al. 2013). These actions change the state of the network, like an operator as described by Ku and Arthanari (2016).

Decisions can be used to solve tasks that arise in distribution networks, such as locating sites, selecting suppliers, designing sites, selecting transport means, dealing with seasonal trends, and scheduling vehicles (Ghiani et al. 2013). As a result, decisions influence the configuration of the distribution network and its performance (Onstein et al. 2019).

The decisions can be classified based on the entities that are affected, such as decisions regarding inventory, sites, and transportation (Ravindran 2016; Rushton et al. 2017). For example, decisions concerning inventory define the stock level of the SKUs and their allocation to the sites. Transportation decisions define transportation means to use and distribution channels, and