



D 2.1

Supply Chain Models for the identified ecosystems

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Abstract	This deliverable describes the entire development process of the quantitative supply chain models for the EU ecosystems under consideration. This concerns both the methodological approach, the criteria-based selection of specific supply chains per ecosystem and the actual modelling. The modelling of the models is based on expert assessments, practical workshops and basic scientific research. With the help of various modelling methods and tools, quantitative models for further investigation of the supply chains, the influences of disruptions and technologies are made possible. The initial validation described above ensures the fit of these models and provides a basis for the subsequent tasks and work packages.

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Executive summary

This Deliverable D2.1 describes quantitative supply chain models that were developed as part of the project RISE-SME in the four focused industrial ecosystems. The deliverable includes both the development of a comprehensive methodology for the delimitation, selection, development, and further use of the SC models, as well as the actual development of the models and the implementation of detailed information in quantitative models.

Building on the description of the textile, agri-food, mobility, and digital ecosystems in Deliverable D1.1 of this project [1], as well as the research on SC models in Deliverable D1.2 [2], this deliverable describes the results from Tasks T2.1 and T2.2. Specific supply chain focus areas were identified for each ecosystem using a multi-criteria narrowing down methodology. This narrowing down is necessary to create complete and sufficiently detailed quantitative models. This focussing is the chosen process to develop models that can be quantified in detail in subsequent tasks regarding the impact of disruptions and the use of technology. Each specification of the ecosystems to individual supply chains was made in such a way that simple adaptation to other areas within the ecosystem is easy to implement. At the same time, a representative supply chain with as many aspects of the ecosystem as possible was created.

A shoe supply chain was modelled for the textile ecosystem, which describes a geographical core in Italy and includes many SMEs. This supply chain is characterized by many sourced raw materials and intermediate products and compact production. Already planned extensions refer to the consideration of clothing-specific supply chains in this ecosystem.

In the agri-food ecosystem, an exploratory wine supply chain is described, which has a geographical focus in Spain and is characterized above all by the seasonal grape harvests and ripening processes.

As part of the mobility ecosystem, the electrified automotive supply chain is modelled, which, with final assembly in Germany, contains both European SCM clusters and international raw material and intermediate product stages and represents the most complex and globally interlinked supply chain overall.

For the digital sector, a value chain was analysed with a view to the digitally driven mobility as a service business within a European city. Due to the characterization of the ecosystem, an analysis less focused on material flows was carried out using a system dynamics approach.

Each of these developed models have been individually validated and analysed for functionality. As basic models, KPI measurements can be carried out in the following task packages of the project in the basic scenarios as well as in modified disruption environments. As described in the supply chain resilience fit model (see Deliverable D1.1 of the RISE-SME project [1]), the moderating influence of modern technologies on resilience reactions to disruptions can also be analysed. In the future, the models can also be transferred to other use cases within the ecosystems with little effort to carry out pilots and specific investigations.

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List of Abbreviations and Acronyms	
CLD	Causal Loop Diagram
DES	Discrete event simulation
EU	European Union
FEM	Finite element method
MaaS	Mobility as a Service
MBS	multi-body simulation
MC	Monte Carlo simulation
MCDM	Multi-Criteria decision-making
OM	Optimisation model
OTD	Order to Delivery Network (event-discrete simulation tool)
pCAM	Precursor cathode active material
SC	Supply Chain
SD	System Dynamics
SFD	Stock and flow diagram
SME	Small and medium sized enterprises

1 Introduction

The RISE-SME project aims to enhance the resilience of European industrial ecosystems through the development of technology-driven supply chains. This approach is designed especially to enable small and medium-sized enterprises (SMEs) to effectively detect and anticipate disruptions within their supply chains and to react to given changes through novel technologies. In a context where supply chains are increasingly vulnerable to a range of global challenges—including pandemics, geopolitical conflicts, and environmental crises—the integration of advanced technologies that can augment operational flexibility and agility is an important development for SMEs. The RISE-SME project seeks to promote the integration of modern technologies that focus on enhancing resilience as well as facilitating the formation of strategic alliances among SMEs and technology providers.

Central to this overall objective is Work Package 2 (WP2), which plays a crucial role in establishing the methodological foundation necessary for the evaluation and optimization of supply chain resilience through the integration of modern technologies. The overarching approach of this work package is to develop supply chain models that quantify the impact of occurring disruptions and the benefits resulting from the implementation of technologies. WP2 encompasses several key tasks, including the conceptualization of the methodology, the development of the quantitative models, the mapping and scouting of relevant technologies, and the formulation of an impact assessment methodology. The quantitative models and technology overviews developed here form the basis for the transfer-oriented activities in the following Work Package 3.

1.1 Purpose and Scope of the Deliverable

Deliverable D2.1 serves as the first report of Work Package 2, summarizing and integrating results from Tasks T2.1 and T2.2. The primary objective of D2.1 is to describe and visualize the development of quantitative supply chain models. These models are specifically designed to facilitate the impacts of technology usage for increased resilience within the four key ecosystems under consideration: textile, agri-food, digital, and mobility. By providing exemplary supply chain models for each of these ecosystems, D2.1 aims to serve as a foundational element for subsequent analyses and industrial applications within the broader framework of the RISE-SME project. In the second work package, the quantitative models are used to evaluate the implications of the technologies for the supply chains. In WP2.3 (and D2.2), the relevant technologies are identified, while in WP2.4 (and D2.3) an assessment is carried out using suitable resilience indicators.

Through the utilization of knowledge and networks of all project partners and the exchange with sector and technical experts, central products and supply chains were identified, analysed, and modelled in representative exemplary supply chains models for each ecosystem. These quantitative models can be adapted to specific industry use cases with little effort in the following tasks and used in each iteration to analyse the effects of technology implementations. Another important part of the deliverable is the development of an end-to-end process model for the approach in Work Package 2 and the identification of key disruptions in the various models.

1.2 Deliverable structure

To effectively achieve the objectives outlined, a comprehensive and systematic methodology is employed for the creation of quantitative supply chain models, as well as for the simulation of various scenarios and impacts of disruptions and technology usage. This methodology is structured to ensure that the models are both accurate and representative of real-world complexities. Central to this approach is the use of event-based discrete simulation, which has proven to be a powerful technique for modelling material flow and supply chain networks. Additionally, system dynamics methods are utilized to capture the intricate interactions and dependencies that exist within these networks, allowing for a more nuanced understanding of supply chain behaviour. The supply chains illustrated are representative examples within the overall ecosystems, which can be easily transferred to similar real-world applications.

The structure of this report is organized into three main chapters. The first part (Chapter 2) provides the theoretical and methodological foundations necessary for choosing a suitable simulation method and developing simulation models. This includes an exploration of the process models employed, as well as a detailed explanation of the simulation tools and methods used throughout the project, such as discrete-event simulation and system dynamics modelling.

Following the foundational chapter, the second contextual chapter (Chapter 3) focuses on model development. It contains four parallel sub-chapters, each dedicated to the selection of a specific supply chain per ecosystem and the development of the associated quantitative simulation model. This structured approach allows for a comprehensive examination of each ecosystem's unique characteristics and challenges. These models can be used in subsequent tasks to quantify impacts via KPIs and to identify complex relationships between disruptions and technology potential.

Chapter 4 summarizes the results of the simulations, critically evaluating their validity and demonstrating that the reference models for normal supply chain operations have been successfully established. Based on these models, the chapter outlines the subsequent steps for implementing the disruptions addressed in future work packages, thereby paving the way for further research and development aimed at enhancing supply chain resilience.

The contents and interconnections of these three chapters in this deliverable are depicted in Figure 1-1.

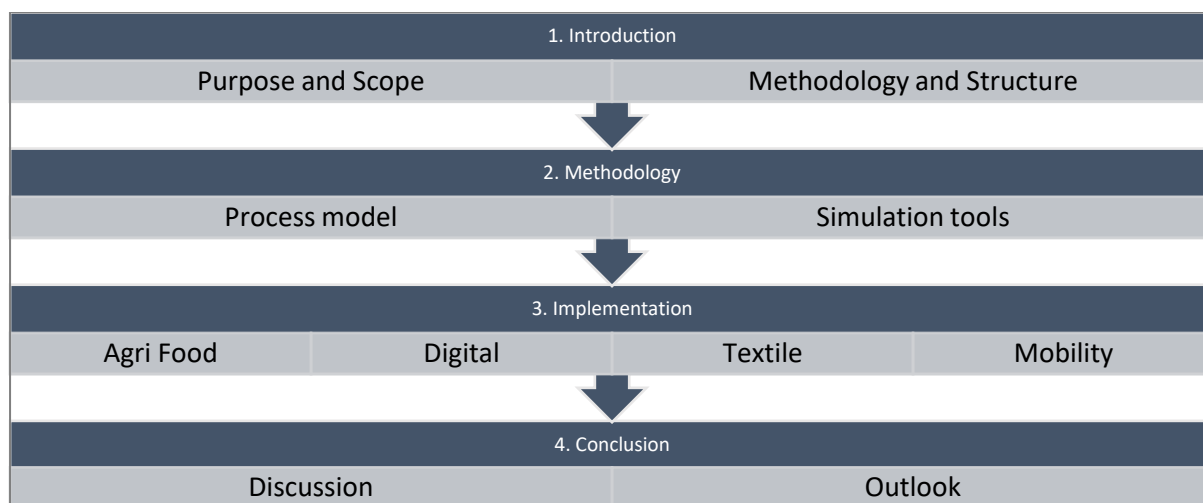


Figure 1-1: Structure of the Deliverable D2.1

2 Conceptualization of the methodology

In this chapter, the conceptualization of the methodology takes place. Starting with a literature review, the different steps are elaborated in detail to be able to build validated models and use them to increase resilience through scenario-based approaches.

2.1 Literature Review

The literature review was based on the analysis of relevant academic papers on supply chain models, risk management, and the use of digital technologies to manage disruptions. The research focused primarily on quantitative modelling methods for supply chains and thus represents a detailed investigation with a different focus than the research in D1.1. These articles were selected for their relevance to modelling supply chain disruptions and classified under various criteria, including the type of supply chain (such as manufacturing or retail), the nature of disruption events (such as natural disasters, health crises or political conflicts), and the model used (simulation, analytical or empirical models).

The searching criteria for these papers included the keywords "risk disruptions," "uncertainty," "vulnerability," "disruption resilience," "supply chain," "value chain," "supply network," "model strategy," "digital technology model," "blockchain," "interactions," "collaboration," and "network interactions."

The selection of these keywords aimed to extract common themes and methodologies across different studies, facilitating a structured analysis of how supply chains respond to different disruptions. Table 21 is an excerpt from a longer table and was created to organize this information, including:

- Disruption Event
- Type of Model
- Model Description
- Steps to Build the Model
- Information Collected

Table 2-1: Literature Review – Paper classification examples

ID	Reference	Disruption Event	Type of Model	Model	Steps to develop the model	Information collected
D1	Ruiying et al., 2017	Lateness in the delivery to the customers	Quantitative	Monte Carlo Simulation New type of resilience measurement	Start defining a problem Make assumption Collecting Information Application of the model	Number of suppliers; manufacturers; Distribution centres; retailers Geographical Areas of nodes Amount of product delivered Delivery distance Cost of delivery
D2	Awudu & Zhang, 2017	Biomass supply uncertainties (sustainability, tax, governmental policies, and regulatory policies)	Mix	Analytical methods Monte Carlo simulation Discrete event simulation Method	Map the supply chain Map of the disruption events of the sector (uncertainties)	Mapping of a general Supply chain model Strategic/tactical/operational decisions

ID	Reference	Disruption Event	Type of Model	Model	Steps to develop the model	Information collected
					Map of the simulation methods applied in literature	
D4	Pettit et al., 2013	Turbulence External Pressures Resource Limits	Mix	SCRAM Mixed Methods (Theoretical Linkages; Correlation of survey responses; pattern matching of focus group responses)	Define the scope Identify the team members of the project SCRAM survey to find the Capabilities to be evaluated in the model (8 different companies) Analysis to prioritize and finding the resilience gaps	Market position Recovery Financial strength Security Organization Dispersion Efficiency Anticipation Visibility Flexibility in Sourcing Adaptability Capacity Collaboration

The goal is to identify the most important steps in building a model, the necessary information, and the types of disruption events that are considered.

2.2 Steps of the methodology

From the analysis of the papers mentioned in the previous paragraph, we identified and categorized the steps necessary for developing supply chain models, focusing on commonalities across literature:

1. **Mapping disruptions and scope definition:** The first step is based on the analysis of the critical factors of the supply chain under consideration and related disruptions that can affect it. Based on this analysis, it is necessary to define the scope for which the model needs to be built. In this phase, it is important to establish the boundaries of the supply chain network to be analysed. This includes selecting key entities to map, such as suppliers, manufacturers, distributors, and retailers.
2. **Selecting The Method:** This step aims to analyse and list methods for assessing supply chain resilience, covering their characteristics, uses, advantages, and limitations. The main methods include the Monte Carlo simulation, discrete event simulation, multi-criteria decision models, optimization models, and system dynamics.
3. **Selecting variables and collection of information:** Recognizing key variables is essential for understanding the behaviour of the supply chain. This data encompasses different types of supply chain network information (such as Lead Time, Average Production Time, Number of workers, etc.).
4. **Supply chain mapping:** This step is based on network designs that represent the ecosystem. Key tasks include defining the mapping method, identifying supply chain structures and roles, determining supply chain levels, assessing actors at each level, and listing prioritized disruptions.
5. **Model Set-Up:** Model set-up involves building and running the supply chain model. The runtime and output of each model depend on its design, requirements, and data. Initial executions are used to verify parameter settings, uncovering potential

bottlenecks or errors. Several iterations might be necessary to optimize the settings. Selecting and configuring the correct model is essential.

6. **Scenario Building:** Scenario-based planning is necessary to examine how disruptions impact inventory, production costs, and service rates. Each scenario uses different inputs to evaluate the effects on profitability and resilience. Additionally, scenarios assess the role of technologies in enhancing economic (increase profit or decrease costs), environmental (reduce CO2 emissions or increase energy efficiency), and social sustainability (lower worker accidents and improve safety).

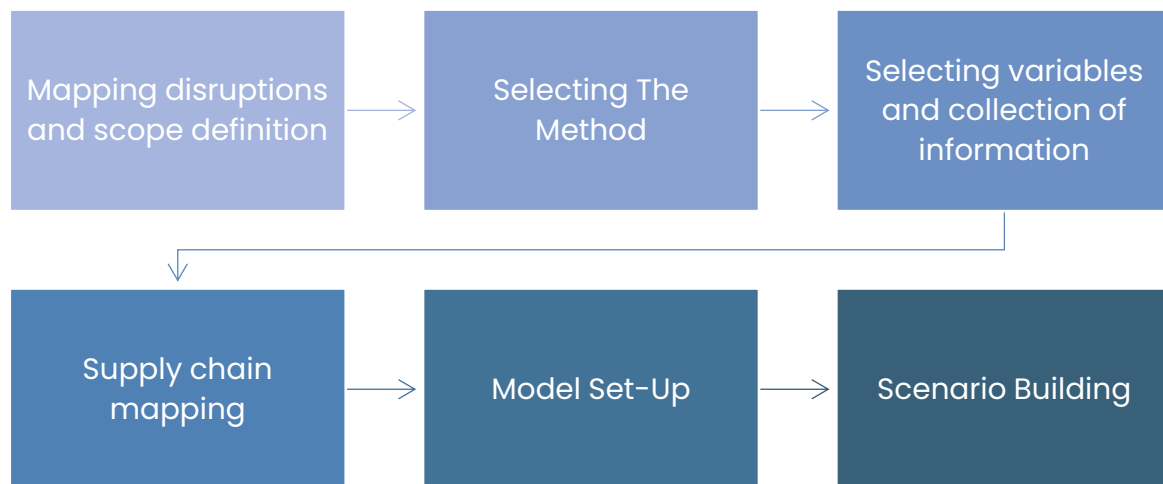


Figure 2-1: Conceptualization of the methodology

In the following chapters, each of these steps, reported in Figure 2-1, will be described in providing a guide to developing a generic supply chain model.

2.3 Mapping disruptions and scope definition

The first step consists of recognising the crucial elements and associated disruptions in ecosystems, followed by defining the model's goals. Different publications emphasize the importance of crafting strategies for resilient and sustainable supply chains. For example, a digital supply chain twin is suggested to depict real-time network conditions, which can be leveraged to handle disruption risks [3].

This research aims to develop a decision support system that improves proactive and resilient supply chain designs and supports reactive, real-time risk management. In a similar approach, [4] introduce a hybrid approach for designing a sustainable supply network resistant to disruptions, using a stochastic objective optimisation model to assess suppliers' sustainability performance [4]. This method aims to inform outsourcing decisions and resilience strategies to reduce costs and improve sustainability during disruptions, as illustrated in a case study in the plastic pipe industry [4]. Another scientific review examines blockchain-based resilience strategies that help micro-, small- and medium-sized enterprises (MSMEs) recover from disruptions, employing a resource-based perspective to improve operational efficiency [5]. [6] explore how artificial intelligence can be applied to

foster resilience in supply chains, especially amid the challenges of an unpredictable business environment that requires balancing daily operations with preparation for adverse events. Other studies, such as [7], delve into the intricacies of setting up or moving distribution centers in global supply chains by considering costs, trade uncertainties, risks, environmental compromises, and the effects of disruptive technologies [7].

These examples of research underline the importance of defining the following parameters:

- **Disruption Event:** Identification of the disruption event to be monitored. A disruption event is an unexpected incident that significantly disrupts the normal operations of a system or supply chain with cascading effects, negatively impacting performance.
- **Scope Type:** Refers to the level at which the scope operates, such as Strategic-Long Term, Operational-Short Term, or Tactical-Medium Term.
- **Dimension:** It refers to the areas or aspects being considered, such as processes, horizontal and vertical networks, or organizational structures. It defines the specific elements involved in the scope.
- **Performance:** It specifies the key indicators to track, such as the implementation of a production process. It defines what will be measured.

Below is a brief classification of these types of scopes (Figure 2-2).

DISRUPTION EVENT	SCOPE TYPE	DIMENSION	PERFORMANCE
Global and complex supply chains Environmental crises and natural disasters Political conflicts and crises ...	Strategic - Long Term Tactical - Medium Term Operational - Short Term	Markets Network Department Operational Areas Process ...	(Examples) • Evaluate the profitability of a new process implemented • Facilitate the decision-making of establishing or moving the distribution facilities • Reduce time to market • Reduce CO2 emission • Design a new sustainability supply network • Define a model to manage the disruption events

Figure 2-2: Example of scope classification

As an example, based on the objectives outlined above, the specific scope can be divided into the following macro-categories (Table 2-2):

Table 2-2: Example taken from literature of definition of the scope

Reference	DISRUPTION EVENT	SCOPE TYPE	DIMENSION	PERFORMANCE
Singh et al., 2023	Health and pandemic disruptions; Environmental crises and natural disasters	Strategic Long Term	Network	Impact of the SC resilience strategies adopted against disruption events
Sundarakani et al., 2021	Technological disruptions and low digital maturity; Challenges in sustaining existing business model	Tactical Medium Term	Network	Establish or moving distribution facilities
Polonio et al., 2024	Global and complex supply chains (decentralization of supply and demand); Skill Gaps	Operational Short Term	Process	Evaluate the profitability of a new process for olive pomace gasification

For what concerns the identification of the disruption events in the SC, they are clustered according to the macro categories of critical factors defined in Task T 1.2 reported in the table below (Table 2-3).

Table 2-3: List of disruption types (T1.2)

ID	Main Critical Factor
T1	Health and pandemic disruptions
T2	Environmental crises and natural disasters
T3	Political conflicts and crises
T4	Technological disruptions and low digital maturity
T5	Challenges in sustaining existing business model
T6	Supplier and customer concentration (overdependencies)
T7	Global and complex Supply chains (decentralization of Supply and Demand)
T8	Skills gaps
T9	Waste
T10	Infrastructure and Logistics Disruptions

The objective is to associate each major category of critical factors with the disruption event identified in the literature concerning the Supply Chain. Table 2-4 provides an example of two disruption events analysed within the Textile ecosystem.

Table 2-4: Example of disruption event analysis for the textile sector

ID	Main Critical Factor	Critical Factors description	Disruption Event
T.1	Health and pandemic disruptions	Possible closure of frontiers and lockdowns can impact this ecosystem given its highly interconnected supply chain and significant employment and GDP contributions	Staff availability issues (Illness)
			Interruption along the Supply Network
T.2	Environmental crises and natural disasters	The global economic crisis, currency devaluation, and concerns about natural disasters impact the development of the supply chain.	Damaged materials /final products
			Interruption along the Supply Network

This analysis was carried out for all four ecosystems to pinpoint the potential effects and identify the specific elements they impact.

2.4 Selecting the modelling Method

The goal of this phase is to analyse the methods and techniques to generate a pool of potential tools that can be used to assess or measure the resilience of a specific supply chain. For each model, the general characteristics, applications, advantages, and limitations have been identified within the literature and technology review. The main models analysed are:

- Monte Carlo simulation
- Discrete event simulation
- Multi-criteria decision model
- Optimisation model
- System Dynamics

Most of these methods are characterized by the generation of different scenarios to select the best option. Each of them requires a detailed mapping of the system to be analysed and a specific set of data to run the model effectively.

Monte Carlo simulation

Monte Carlo simulation is a computational technique that uses random sampling and statistical models to predict and analyse the potential outcomes of an uncertain process. By generating random inputs for the probability distributions of different variables, this method allows simulation of real-world situations and estimation of the likelihood of various scenarios [8]. In business, the Monte Carlo method can be used in decision-making processes, enabling efficient management of uncertainty and data-driven decision making [9]. Monte Carlo simulation is an effective tool to tackle complex scenarios, providing crucial support for supply chain optimisation and performance analysis [10]. On

the downside it is not possible to model agent-based, event-discrete or time-discrete processes.

Discrete event simulation

Discrete event simulation (DES) is widely used in different sectors, including production, logistics, and supply chain management. In the context of modelling time behaviour and time updating in simulation models, a distinction is made between continuous and discrete simulation. Continuous simulation, for example applied by the finite element method (FEM), multi-body simulation (MBS) or flow analyses (computational fluid dynamics, CFD), uses a continuous time and state set, whereby continuous state transitions and a uniform time course are represented[11].

In contrast, discrete simulation involves state changes that take place at specific, discrete points in time. For example, in production and logistics models that represent discrete goods with discrete states, the states of the model elements are only changed when an event occurs, which corresponds to real processes [12].

Continuous simulators are rarely used in the context of logistics systems. For this reason, the discrete event simulation methodology will be examined in more detail. In discrete event simulation, only the points in time at which the state of the system changes are represented. The system is therefore modelled as a sequence of events, i.e., as points in time at which a change of state occurs. Events can be, for example, the arrival of a parcel or the repair of a conveyor belt. Each event takes place at a specific point in time [13, 14].

Multi-criteria decision model

Multi-Criteria decision-making (MCDM) models can assist decision-makers in selecting or ranking alternatives by qualitatively or quantitatively evaluating a finite set of criteria. An MCDM framework consists of four key elements [15]:

- Alternatives (options or choices)
- criteria (attributes or decision factors)
- weights assigned to criteria (indicating their relative importance)
- performance ratings of the alternatives with respect to each criterion

For a given MCDM problem, alternatives and criteria are organised into index sets, with criteria further divided into benefit and cost types. Criteria that do not differentiate between alternatives are excluded to ensure meaningful decision-making.

A decision matrix is then constructed, where each element represents the performance of an alternative to a criterion.

This matrix allows decision-makers to rank the alternatives and select the most appropriate one. Most MCDM methods require normalisation of the decision matrix and the identification of positive and negative ideal solutions as part of their calculation process [15].

Optimisation models

Optimisation models are used to find the best possible solution for a problem under a defined set of constraints. Optimization methods employ different mechanisms to find the optimal solution, depending on factors such as the modelling approach, problem complexity, and the objectives of decision-makers. The optimal solution is a vector that provides the global optimum (maximum or minimum) of the objective function while avoiding local optima. Based on the literature, optimization methods can be categorized as local search methods, global search methods, or guaranteed optimal methods. These methods are applied in many areas, including inventory management, production planning and scheduling, transportation and logistics management, and supply chain design, integration, and collaboration [16].

System Dynamics

System Dynamics is a modelling method designed for analysing long-term decision-making in complex systems. It effectively simulates changes in subsystems and their interactions using causal loop diagrams, which represent feedback mechanisms. Positive feedback loops indicate reinforcing behaviours, while negative loops suggest balancing or goal-seeking behaviours. Modelling with System Dynamics offers a structured approach to capture and analyse dynamics. By modelling stocks, flows, and feedback loops, the effects of changes within the system can be investigated, and potential future developments can be simulated. This methodology is particularly useful for assessing the long-term effects of interventions or changes in a network or ecosystem [17]. The System Dynamics approach is particularly suitable for modelling continuous systems, as opposed to discrete event-based simulation. This is particularly relevant when the focus is on strategic issues rather than individual processes or movements. System dynamics strives to integrate all relevant aspects of a system into a closed model to create a comprehensive picture. Confidence in an SD model is strengthened by continuous testing of the model structure and its behaviour [17, 18].

A procedure consisting of five steps is proposed for modelling with System Dynamics:

1. Identification and definition of the problem, including the description of the historical pattern to be described by the mathematical equations, what the boundaries of the analysis are, the time horizon of the analysis, and the expected behaviour of the system over time.
2. Construction of the Causal Loop Diagram (CLD), which makes it possible to represent the mental models in the system analysis, generate hypotheses about the causes of the system dynamics, and communicate the feedback responsible for the problem to be analysed.
3. Building the simulation model to test the dynamic hypothesis, create the stock and flow diagram (SFD), and perform validation tests.
4. Analysis of the experiments.
5. Formulating and evaluating strategies to better understand the role and relative importance of model parameters in generating historical trends by developing entirely new strategies, structures, and decision rules.

System dynamics models are built using variables like stocks, flows, converters, and connectors are mathematically represented by differential equations solved through simulation. This methodology has been widely applied across various fields, including business, ecological, social-economic, and environmental systems [18]. SD models have been successfully used to analyse supply chain performance in cases of disruption. The fields of application of SD include the pharmaceutical industry. [19]

For the development of the models, the VenSim software is used in the context of this study, which can be used to develop system dynamics models as well as Monte Carlo simulations and help to solve optimization problems.

To facilitate the selection of the most suitable model, the summary table below (Table 2-5) presents a comparison of the identified pros and cons for each option.

Table 2-5: PROS and CONS of the method

METHOD	PRO'S	CON'S	References
Monte Carlo simulation (MC)	Handling uncertainty; Flexibility; Improve decision making; scenario analysis	Data requirements; Complexity in model building; Oversimplification risk; Interpretation challenges; Limited modelling possibilities for whole supply chains	[8–10]
Discrete event simulation (DES)	Extremely detailed system representation; Flexibility; Scenario analysis; management of queues; Resource allocation optimization	Complexity; Data requirements; Long time processing; User Expertise required	[11–13]
Multi-criteria decision model (MCDM)	Structured and transparent process; Flexibility; Quantitative and Qualitative data; Enhanced stakeholder involvement in the decision process	Data requirements; difficulty in criteria comparison; Limited modelling possibilities for whole supply chains	[15]
Optimisation model (OM)	Scalability; Improve decision making; management of constraints	Complexity; Data requirements; sensitive to assumption; hard to solve problems and need to relax constraints	[16]
System dynamics (SD)	Scenario analysis; Improved decision making; long term evaluation	Model complexity; Oversimplification; User Expertise required	[17–20]

For our objectives, it is essential to select a flexible model that enables the creation of different scenarios. This flexibility is crucial for effectively evaluating and understanding the resilience of the supply chain under different conditions. The comparison of methods in the

table shows that different methods are better suited to certain situations and systems than others. Based on the previous findings, this provides an initial framework for a justified model selection

2.5 Selecting variables and collection of information

The goal of this phase is to determine and gather the key variables that need to be observed and quantified in the supply chain model being developed. According to the literature review, it is essential to specify the independent (input) and dependent (output) variables, as well as the function that connects them. In Figure 2–3, some examples are reported [10, 20–23].

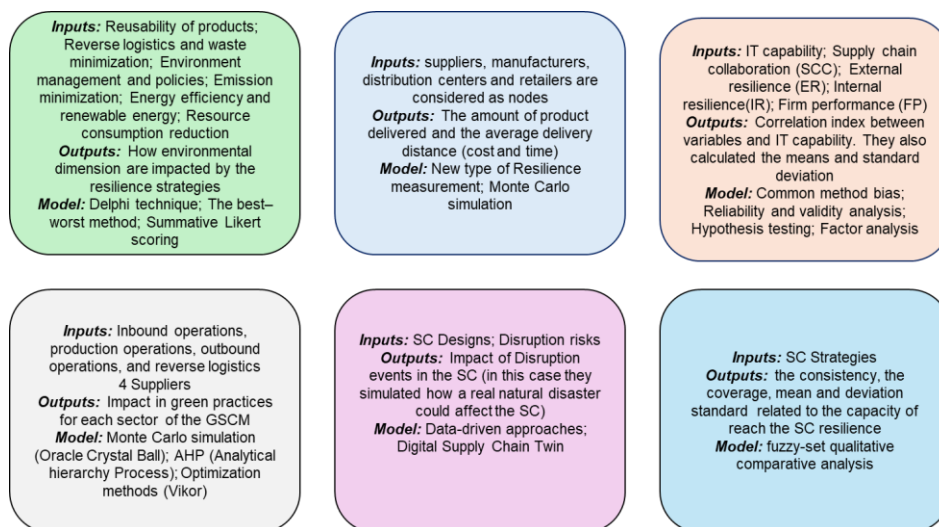


Figure 2–3: Selecting variables to monitor (Examples)

After defining the variables to monitor, it is important to collect all the information related to:

- The structure of the supply chain
- The disruptions and their impact on the supply chain interconnections.

The collection of data regards the supply chain's structure of the network. This category encompasses data concerning the supply chain's framework, including the count of nodes (such as suppliers, manufacturers, distribution centres) and edges (such as transportation routes, information flows). As a result, a table structure according to Table 2–6 has been created.

Table 2-6: Collecting information (Examples)

Specific Network Data	
Main Company	Production Unit ID
	Product
	Production Capacity
	Lead Time
	Average Production Time
	Batch Size
	Loss
	Number of workers
Supplier	Supplier-ID
	Material
	Stock
	Lead times (Days)
	Transport bundling
	Amount of workers
	Location
	Bill of material
	Batch sizes (per day)
	Minimum order quantity
	Country of origin of raw materials
	Replenishment strategy
Sales Market	Sales Market
	Markets (Macro & Countries/ Regions)
	Demand specifics (Description)
	Demand(pieces a year)
	Pieces per order
	Frequency of orders (weeks)
	Distribution (month)
Cross Dock	Cross Dock Identifier
	Capacity Min
	Capacity Min
	Capacity Average
	Location
	Handling time
Distribution Center	Distribution Center-ID
	Distributed Products
	Capacity Min
	Capacity Max
	Capacity Average
	Location
	Handling Time
...	...

The collection of information on the disruptions and their impact on the supply chain interconnections is based on:

- Impacted Nodes of the Network
- Impacted operational areas related to the main company: for main company and for supplier nodes, it is possible to consider also operational areas like Sales Department, Finance Department, HR etc.
- Impacted interconnection with examples of impact on operations. This can be based on information from past disruption events, including their causes, duration, and impact on supply chain performance.

For each ecosystem, all relevant information has been gathered and presented in a table. This allows the association of key critical factors, disruption events, and the resulting effects on the supply chain network. Table 2 7 provides examples from the Textile ecosystem. Understanding and mapping these types of interactions are crucial for effectively designing supply chain models that can withstand disruptions.

Table 2-7: Collecting Information about Disruption (Example from Textile Ecosystem)

ID	Main Critical Factor	Critical Factors description	Disruption event in SC	Impacted Nodes Network	Impacted Operational areas related to the main company	How (Examples – which impact)
T.1	Health and pandemic disruptions	Possible closure of frontiers and lockdowns can impact this ecosystem given its highly interconnected supply chain and significant employment and GDP contributions	Staff availability issues (Illness)	Main company; Distribution Centre; Sales Market; Customer; Cross dock; Main Company	Production unit; Sales Department; HR; Storage Unit; Intercompany transport; Finance Department	1.Main Company/ Production Unit: A shortage of production staff, due to illness, is causing delays in completing scheduled production. 2.Main Company/Storage Unit, Finance Dep.: High economic investment is required to bring the storage unit into compliance with new health and safety regulations, specifically in response to updated pandemic-related laws. 3.Main Company-Distribution Centre-Sales Market/Intercompany Transports: Delays or cancellations of customer orders are occurring due to a shortage of transport staff due to illness.
			Interruption along the Supply Network	Supplier; Distribution Centre; Sales Market; Customers; Main Company	Production Unit; Purchasing Department; Selling Department; HR; Storage Unit; Finance Department	1. Main Company-Supplier/ Purchasing Dep., Production unit: Production has been interrupted due to a shortage of raw materials, and it is impossible to purchase more because the supplier has closed due the pandemic. 2. Main Company-Customer/ Storage Unit, Finance Dep.: A decrease in product demand is leading to increased storage costs.

ID	Main Critical Factor	Critical Factors description	Disruption event in SC	Impacted Nodes Network	Impacted Operational areas related to the main company	How (Examples – which impact)
T.2	Environmental crises and natural disasters	The global economic crisis, currency devaluation, and concerns about natural disasters impact the development of the supply chain.	Damaged materials /final products	Distribution Centre; Sales Market; Customers; Cross dock; Main Company	Production Unit; Storage Unit; Intercompany Transport; Finance Department	1.Main Company/Storage Unit, Finance Dep.: A natural disaster has caused severe damage to the main company's storage unit, with many products being destroyed, resulting in a significant loss of profit.
			Interruption along the Supply Network	Supplier; Distribution Centre; Customers; Sales Market; Cross Dock; Main Company	Production Unit; Purchasing Department; Sales Department; HR; Storage Unit; Intercompany Transport	1.Distribution Centre-Customer: Inability to deliver goods to customers due to damage at the distribution centres caused by a fire in the storage unit. 2. Main Company-Cross Dock-Customer / Intercompany Transport: Delays in customer deliveries because intercompany transport is blocked due to adverse weather conditions.

2.6 Model Set-Up

The model setup is a phase in the modelling process, where the customised supply chain model is programmed and executed in task T2.2. Each model has its own specific mechanisms, which depend on its underlying design, computational requirements, and the nature of the data input. The runtime for these models can vary significantly depending on the complexity of the model, the level of detail in the data, and the scenarios that are analysed.

The outputs of these models also differ based on the specific objectives and settings of the simulation. The model is first run with the variables in the as-is situation to check that the parameters are set appropriately (validation of the model). Sometimes, results might include insights into potential supply chain bottlenecks, errors in balancing resources, or in planning operations. Several runs may be necessary to reach the appropriate setting of the model.

This setting will then be used to run the scenarios, i.e., forecasts of inventory levels under disruption scenarios and risk assessments, to reach recommendations for improving resilience and responsiveness. Variability in model runtime and output underscores the

importance of selecting the appropriate model and configuring it correctly to align with the goals of the analysis.

This phase involves an examination of the output to understand the implications of the model's findings in the context of supply chain dynamics and resilience. Theoretical frameworks and principles guide this analysis by providing a structured approach to interpreting results, such as identifying patterns and correlations of the data.

Example on how to set-up a model: Order-to-Delivery-Network OTD

OTD is a software developed at Fraunhofer IML and is used as a simulation environment for the supply chains in the textile, agriculture and mobility ecosystems. The simulation environment Order-to-Delivery-Network (OTD) is a discrete-event simulation for mapping supply chains. OTD covers the planning and material flow of a supply chain from incoming orders through production to delivery to the customer. Comprehensive planning processes are mapped in detail and evaluate the supply chain according to costs, performance and ecological parameters. OTD is adapted for the analysis of weak points, disruptions and bottleneck analyses. (Note in advance: The following explanation of OTD modelling is explained in more detail, as OTD is used multiple times in the development, and it therefore seems appropriate to describe the functionality in detail.)

Supply chains are mapped by OTD using a series of predefined objects that represent the nodes of the supply chain. These can be parameterized individually depending on the object type. Figure 2-4 contains an illustration of possible object types that can be used in OTD. The object types presented and the associated representations are used in the following elaborations both in the conceptual models and in the implementation. The functionality of the most important of these object types is to be interpreted as follows:

- Source: This is the origin of the materials in the simulation model. The source supplies material without time delay. A distinction is made between two types of control, the demand-driven supply and the continuous (push) supply of material.
- Transport: The transport represents a transport relationship that is used to control and parameterize the material flow between nodes. The setting options of a transport relationship essentially describe the capacity, duration, and type of transport triggering.
- Production: A production city is used to manufacture products from one or more raw materials. Production also has internal upstream and downstream warehouses. By parameterizing the production, the capacity, the required input and output materials, the production time, and the operating times can be set.
- Warehouse: The warehouse has two main functions; on the one hand it is used to store material and on the other hand it acts as an internal customer of the supply chain that can trigger orders. The main features of the warehouse are the ordering policy, and the products stocked. In addition, lead times for shipping, lead times for ordering and storage capacity can be parameterized.
- Sink: The sink serves as the end point of the material flow. The sink represents a customer or seller to whom the product is sold and who leaves the simulation model.

The graphical representation of the elements presented is attached in Figure 2-4.

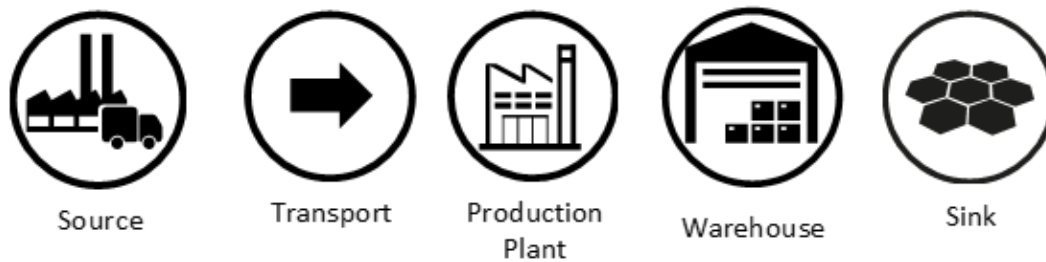


Figure 2-4: Excerpt of OTD Objects

2.7 Scenario Building

Scenario-based planning allows for exploring the effects of disruptions, such as geopolitical events or logistical bottlenecks, on critical factors like inventory levels, production costs, and service rates. Each scenario will include a unique set of input variations, helping to assess how these changes affect output metrics such as profitability and resilience.

By experimenting with different scenarios, companies can improve their decision-making process, creating a robust foundation for navigating disruptions while maximising their performance in terms of economic sustainability (i.e. increase profit, decrease costs), environmental sustainability (i.e. decrease CO2 emission, increase energy efficiency), social sustainability (i.e. decrease workers accidents, increase safety)).

For this specific project, the creation of the scenarios is based on the set of technologies that are identified in task T2.3 and that can be used to define how these technologies can have a positive impact on facing the disruptions considered.

The scenario-building phase is based on the definition of the impact expected of the technologies on the input variables and the definition of the range of variability to be assigned to each variable. Most of the time, a graphical representation of the variables to be analysed is based on representation with branches for an easy-to-use visualisation of the variables considered and their relations. The range of variability must be decided according to the forecast and expectation of the supply chain on the input and output variables. This will allow us to assess the impact of these changes (T2.4).

3 Development of quantitative models

Following the approach described in Chapter 2, a representative supply chain model is created for each ecosystem, providing a basis for future analyses and development in specific use cases. To begin this process, the supply chain that will be modelled is identified and clearly defined before model development starts. The entire modelling procedure follows the top-down approach outlined in Chapter 3.2.

3.1 Supply chain selection process

For selecting a suitable and representative supply chain in each ecosystem, criteria were extracted from D.1.1 that can be used to evaluate potential supply chains. These criteria include:

1. The **added value/turnover** of the supply chain in the EU
2. The **strategic relevance** of the supply chain for the European Union [21]
3. The **geographical significance** of the supply chain in relation to the project partners
4. The **representativeness** of the supply chain network for the ecosystem
5. The **importance of European SMEs** in the supply chain
6. The **availability of detailed information** on the supply chain
7. The role of the supply chain in the **digital and green twin transformation** in the EU
8. The compliance of the supply chain structure with the **SC fit model** from D.1.1
9. The **vulnerability** of the supply chain to disruption

The weighting of these criteria for the potential specific products and supply chain boundaries within the ecosystems ensures that a comprehensible and realistically easy-to-adapt model basis can be created for as many real cases as possible. On the one hand, this model must be general to gain broad acceptance, and, on the other hand, the detailed modelling must make assumptions to be able to quantify the evaluations of influences and changes caused by disruptions and the use of technology in a comprehensible manner.

Once the supply chain has been selected, data is gathered to create the value chain map. This map is divided into the key phases of the supply chain, which form the supply chain network map. As part of developing this network map, the supply chain is broken down into its sub-processes. This leads to a detailed representation of the supply chain, which is then implemented in the modelling tool. This detailed implementation involves defining the specific parameters that control the material flow.

The following sub-chapters describe the approaches, assumptions and results for the quantitative SC models in the agrifood ecosystem (Chapter 3.2), the mobility ecosystem (Chapter 3.4), the textile ecosystem (Chapter 3.5), and the digital ecosystem (Chapter 3.6). Each of these chapters describes for the respective ecosystem the collection of the data required for modelling, the concept model, which describes the basic structure of the supply chain model, the selection of the simulation tool, the implementation of the model in the modelling tool used in each case and the validation of the quantitative model through initial evaluations and comparisons with the real world.

3.2 Supply chain mapping

The detailed modelling after narrowing down the supply chains to be considered follows the methodology described in Figure 2-1. As shown in Figure 3-1, the steps of modelling, validation and initial interpretation of the basic experiments were iterated to create an optimal quantitative model [22]. In the following chapters, we will go through this procedure focussing on an initial supply chain model. With the help of this model, further scenarios relating to disruptions and technology impacts will be modelled in the subsequent work packages of the project and validated and implemented as part of the process model.

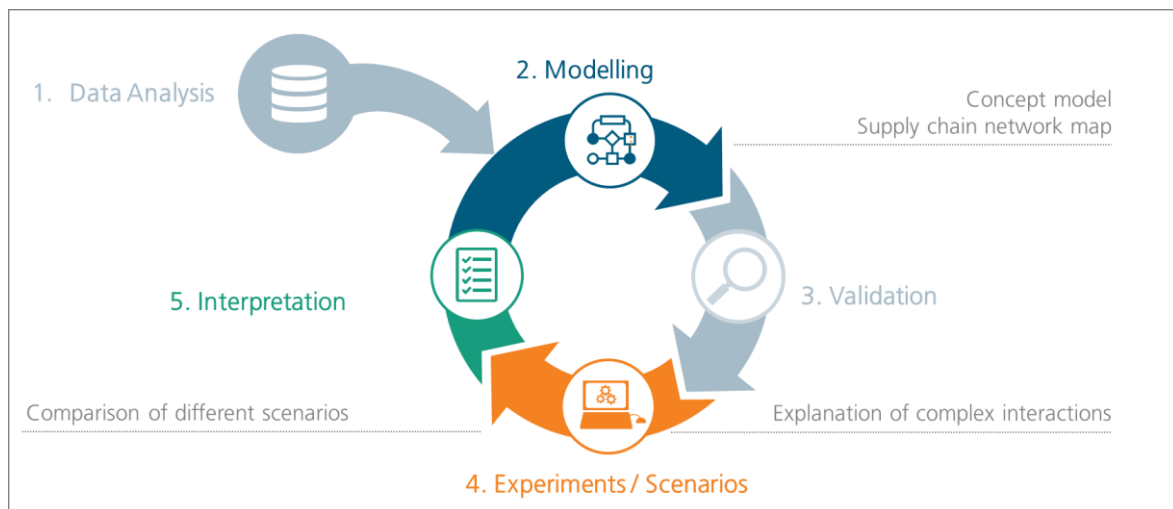


Figure 3-1: Application of the methodology for modelling supply chains [22]

To support the modelling in the second step, the supply chain mapping is first outlined in a conceptual model and then structured in increasingly detailed sub-models. Once the necessary information regarding the concept model has been collected, the model will be customized with detailed data to ensure it accurately reflects the specific case. This activity is run in T2.2 and the mapping of the supply chain of each ecosystem will be based on the design of the types of networks that accurately represent the ecosystem.

Within the scope of this deliverable, the respective steps of supply chain focussing, data collection and analysis, the derivation of a structural concept model that outlines the basic functionalities of the supply chain and the detailed design of the individual model components as part of the actual implementation are carried out for each ecosystem.

3.3 Agri-Food ecosystem

As described in D1.1, the agri-food ecosystem comprises all actors and activities in the food supply chain, including farmers, food producers, retailers as well as suppliers and other service providers in the food supply chain. In this ecosystem, a further subdivision is made into food, beverages and intermediate products. The first step is to identify a representative supply chain of the agri-food ecosystem that reflects both the strategic aspects described in D.1.1 and includes SMEs based in the EU.

Lamb production, the wine supply chain and crop cultivation are proposed as potential supply chains in the agri-food ecosystem. Based on the assessment by the ecosystem experts, as shown in Table 3-1, the wine supply chain is selected as the focus of the study. This supply chain stands out from the other supply chains, particularly in terms of its strategic relevance within the EU member states under consideration, such as Spain and Italy in terms of production volume.

Table 3-1: Agrifood – Supply chain selection

Supply Chains	Lamb	Wine	Horticulture
Value added / turnover	7	8	8
Strategic relevance	7	9,5	7
geographical significance	8	8,5	7
Representativeness	7	8,5	8
Share of SMEs	8	9,5	10
Availability of detailed SC information	6	9	8
Green & digital transition	7	9	7
Fit to the SC resilience fit model	6	9	8
Exposure to risks or disruptions	8	8	8
Weighted Score	7,11	8,75	7,9

3.3.1 Data collection

To obtain the information required for the design of the wine supply chain, a two-faceted approach is pursued. On the one hand, a structured search is carried out in scientific databases. At the same time, wine producers are interviewed using a structured data collection process and included in the development of the model. The aim of the literature research is to identify the relevant actors, processes and transports within a representative wine supply chain. Based on this, the actors involved are validated with the company partners and the processes are parameterized with additional data requirements at the detailed concept level such as process times, throughput times and capacities of the individual production, transport and storage nodes.

As a result, the wine supply chain is made up of four supply chain phases. These are Production (including harvest), filling, packaging and dispatch [23, 24]. Corresponding to the phases of the SC, the most important participants are to be identified: Raw Material

Suppliers, Grape Grower, Wine producer, Wine distributor, Packer/ Filling and Wholesaler [23, 25, 26]. The following materials, products and intermediates are identified as materials, products and intermediates to be analysed: Grapes, Barrels, Bottles, Cork, Yeast, Fertilizers, Pesticides, Packaging Materials, Labels, Sugar, Water (for irrigation), Agricultural Tools, Vineyard Equipment, Wine Stabilizers and Wine (Bottled, Packaged, Palletized) [25, 26]. Finally, a simulation method is selected, for which Table 2-5 is used as a basis for decision-making. The development of a specific model that can be adapted to different scenarios is made possible by DES implemented through OTD. The detailed description of the individual material flows represents an essential basis for model development.

3.3.2 Concept model development

As part of the system analysis, the interdependencies in the system are systematically processed based on the data collected. The result of the system analysis is the conceptual model of the supply chain. In this step, the scope and level of detail of the model is determined. For this purpose, the input and output variables are first defined for each node, i.e. process and participant. In this way, the edges of the network are clarified, and the structure is developed. The starting point for network modelling is a general four-phase model, consisting of: Production (including Harvesting), Filling, Packaging and Dispatch, as shown in Figure 3-2. Within these four phases, the individual process steps are now defined, and the associated input and output variables are determined.

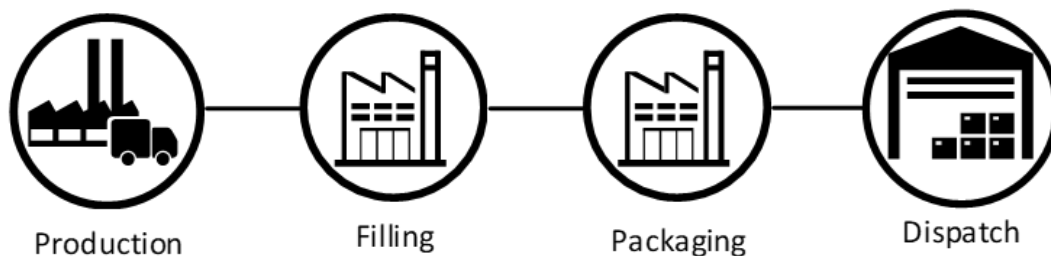


Figure 3-2: Wine supply chain – phases

The individual phases are broken down further in the next step. For this purpose, process steps are assigned to each phase. Winemaking is divided into four main process steps, which are shown in Figure 3-3. In the first step, the grapes are harvested. The next step is fermentation, in which yeast is introduced as the main ingredient in the process. The wine is filled into barrels and stored for maturation. In the final production step, the matured wine is filtered before the finished wine is bottled. In the next step, the wine is bottled. Bottles, corks and capsules are used for this. The bottles are then labelled. In the final step, the labelled wine bottles are taken for packaging. In the final step, the finished product is packaged and dispatched. With an overview of these necessary process steps, the process can now be formalized. Specific parameters are defined for the individual processes and transports.

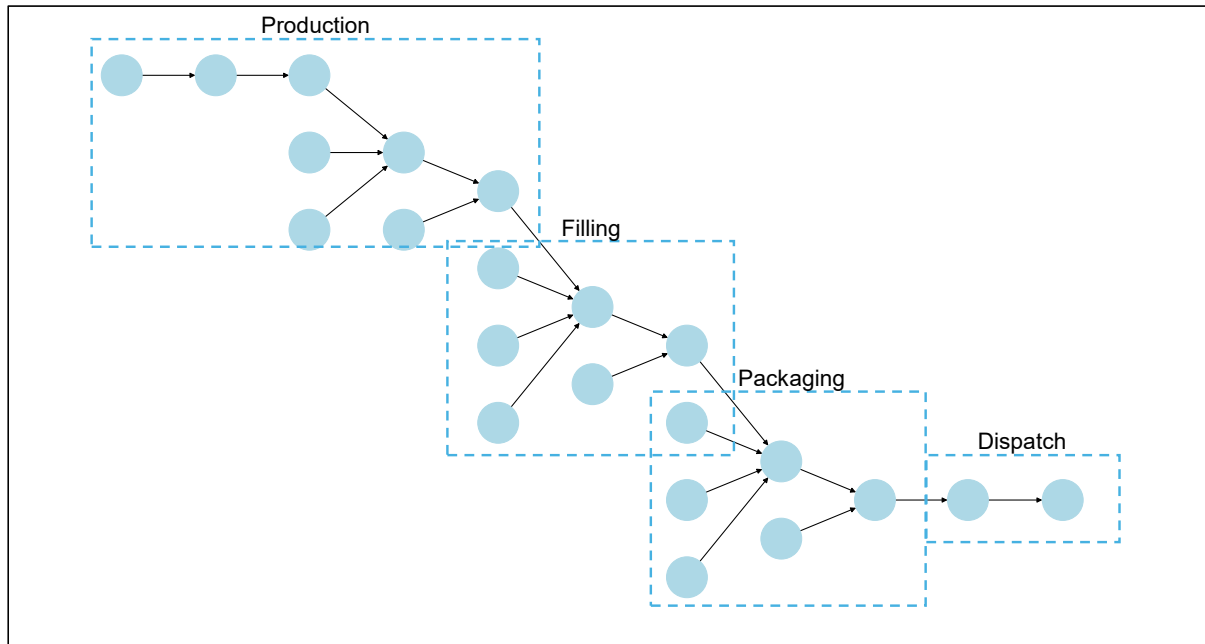


Figure 3-3: Wine supply chain – supply chain network map

The resulting supply chain network map is shown in Figure 3-3 and connects the different stages of the wine SC. As can be seen in Figure 3-3, it is a linear supply chain in which the individual components are integrated. To examine these in detail, individual supply chain maps are created for each phase of the wine supply chain. Table 5-2 lists the process steps with the associated parameters. With the help of the process steps (Table 5-2), the transportation and the suppliers (Table 5-1), the individual parts of the supply chain network can be designed. The figures (Figure 3-4, Figure 5-1, Figure 5-2 & Figure 5-3) show the supply chain sub-concepts of the individual phases. In combination with the parameters from the data collection (Table 5-1 & Table 5-2), this information forms the starting point for the formal model and implementation.

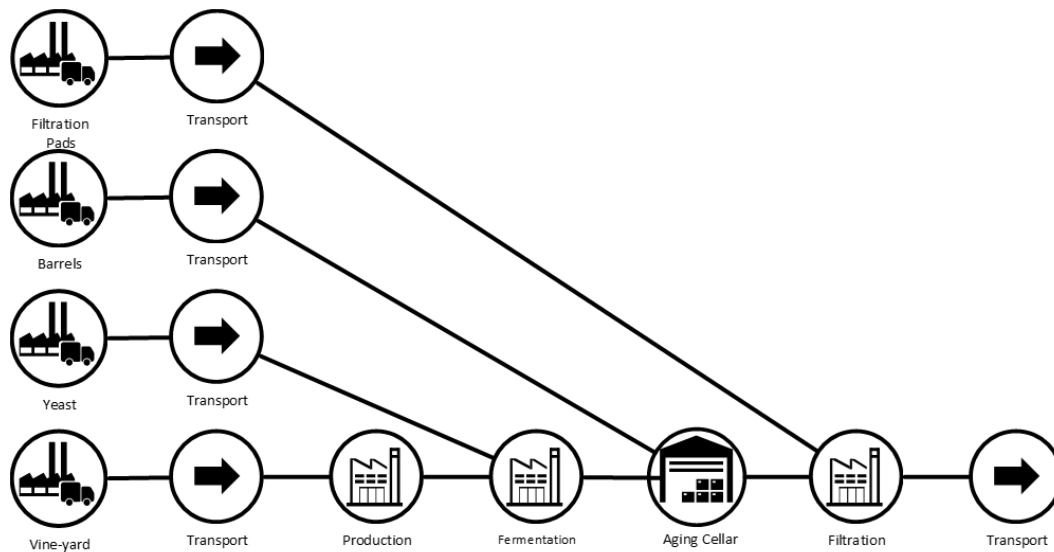


Figure 3-4: Wine supply chain – production phase

3.3.3 Implementation

Due to the detailed data available and the classic structure of the supply chain, it is suitable for quantification using discrete supply chain simulation. The supply chain is therefore mapped and analysed below with the help of the OTD tool. The specific modelling assumptions describe a pure red wine supply chain with strong regional roots in Spain. The detailed assumptions are a combination of expert estimates within a real frame of reference. The concrete details of this supply chain can be modified and further developed with little effort as part of the adaptation to other use cases.

In the next step, the partial supply chains described are transferred to the individual object types of one of the simulation models, as shown in section 2.3.2. The parameters are used to quantify the nodes and transports in detail. The configuration of the supply chain is gradually adapted during further specification. A batch production of initially 5000L is assumed in the implementation. This value is derived from the company survey and is used in the model as the smallest unit of measure for the batch processes. The loss incurred in the production process relates to the incoming 5000L, and the batches are reduced accordingly over the course of the process. As a boundary condition of the supply chain, it should be noted that the harvest of the raw material grapes takes place once a year. The grape harvest is dimensioned in such a way that the targeted production quantity can be achieved with the production waste. It is assumed that the company under consideration produces and sells 6 million bottles of wine per year. In this reference model (without disruptions), no under- or overproduction should be considered. The number of wine bottles to be produced is converted into production batches and thus represents the quantity of grapes harvested each year. Another special feature that needs to be shown is the ripening process. After fermentation of the grapes, the wine is filled into barrels in which it ages for 6 months. This ageing and storage process is represented in the supply chain implementation by a warehouse with a shipping lead time of 6 months. Figure 3-5 shows the geographical distribution of the supply chain network. It can be seen that this is a local

production with sourcing from the surrounding regions. The suppliers' choice of location is again based on the information provided by the company surveyed.

A constant demand pattern is assumed. This describes a situation in which the demand for a product remains constant over a certain period. This assumption is based on regular consumer behaviour, availability and price stability. For the simulation, daily demand is modelled, which corresponds to 6 million bottles of wine in 5000-liter batches over the course of a calendar year.

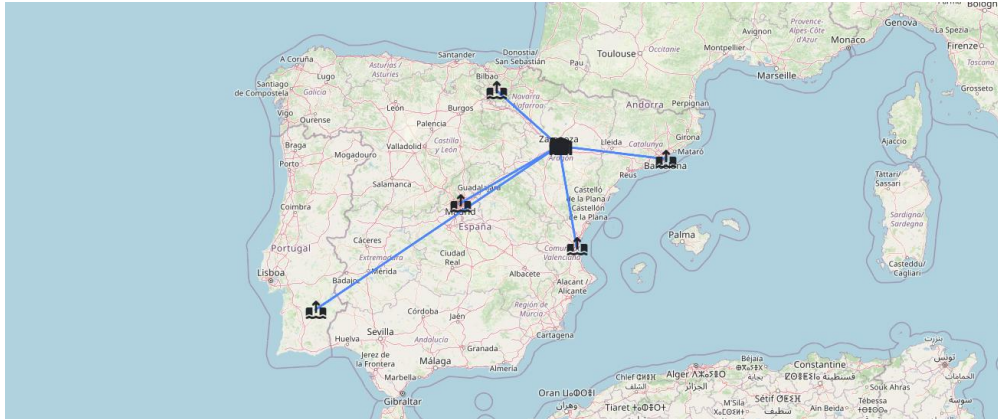


Figure 3-5: Wine supply chain – formal model

3.3.4 Results and Evaluation

As part of the analysis of the results, it must be determined whether the supply chain is behaving as expected. For this purpose, the change in inventories and output is examined over a period of three years.

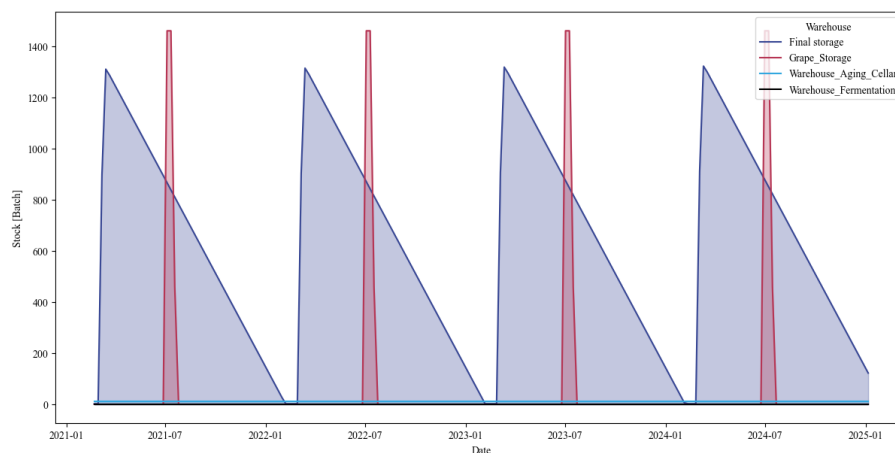


Figure 3-6: Wine supply chain – storage

To analyse the development of inventories in the wine supply chain shown here, the first step is to look at the various storage categories and their relationship to the harvest periods and the ripening process.

- Final Storage: The final storage stock levels indicate a slow continuous decline. This shows that the wine is transferred to final storage after maturation and filling, where it is kept ready for sale. The decline indicates a constant demand.
- Grape storage: Stocks in the grape storage cellar increase during harvest time, indicating that fresh grapes are collected there before going into processing. Stock levels follow a seasonal pattern. During the harvest periods (e.g. around August to October), stock levels rise sharply, indicating the arrival of fresh grapes.
- Warehouse Aging Cellar: These stocks show no significant changes as the stored wine is ordered directly from the final warehouse and is in a six-month aging process that represents maturation.
- Fermentation warehouse: Stocks in this warehouse usually increase during and after the harvest period as the grapes are processed and fermented. However, due to the downstream orders in the supply chain, the stocks in the warehouse are booked out directly.

Harvest periods: These periods are crucial for wine production as they represent the peak of grape deliveries. The increase in stock levels during this period reflects the number of grapes that need to be processed.

Ripening process: After the harvest, the grapes must be fermented and the wine ripened. This explains the increase in stocks in the fermentation and ageing warehouses. Maturation can take months to years. A maturation period of six months is used in the simulation. This is reflected in the time lag between harvesting and the increase in packaged wine in the final storage facility. The ripening period and the fermentation process time lie between the harvest and storage in the final warehouse.

3.4 Mobility ecosystem

As described in D1.1, the Mobility Ecosystem includes the automotive, rail transport, maritime transport sectors and the entire associated value chains. The following section describes the selection, design, and implementation of a reference supply chain from the Mobility Ecosystem. The procedure is based on the process model presented in chapters 3.1 and 3.2. The information used is made up of literature searches in scientific databases, research in the annual reports of listed companies, interviews with experts and reports from large consulting firms. Together, these sources of information provide a comprehensive picture of the supply chain under consideration.

3.4.1 Supply Chain Selection

The supply chain, which is representative of the mobility ecosystem, is selected according to the criteria described in the introduction. The selection includes the production of cars with combustion engines; electric vehicles; and bicycles. Based on the assessment of the ecosystem experts shown in Table 3-2, the two variants of the automotive value chain are selected as the object of investigation. In particular, the relevance of value creation in various EU member states, the strategic importance of the process of electrification of drive technologies for the green transition and the susceptibility to disruption due to complex, global and closely timed supplier relationships speak for the relevance of this SC study. Considering the SME focus within the project, the perspective of SMEs along the supply chain is focused on in the modelling, simulation and subsequent experiments. The structure of the supply chain is modelled in such a way that it is possible to switch between the two drive technologies for specific use cases. The development of the supply chains is described below using the process model presented in chapter two.

Table 3-2: Supply chain selection – mobility ecosystem

Supply Chains	Automotive (Combustion)	Automotive (EV)	Bicycles
Value added / turnover	9,5	8,5	5
Strategic relevance	8	9,5	4
geographical significance	8	6	6
Representativeness	9	7,5	5
Share of SMEs	8	6	8
Availability of detailed SC information	7	7	5
Green & digital transition	5	10	9
Fit to the SC resilience fit model	8	7	6
Exposure to risks or disruptions	9	9	6
Weighted Score	7,8	7,8	6,0

3.4.2 Data Collection

The first step of the modelling approach after narrowing down the scope is the collection and preparation of the necessary information and detailed data to describe and parameterize a representative automotive supply chain. Due to the complexity of the supply chain, a wide range of information sources are being consulted. These include expert interviews, annual business reports and publications that are identified through a literature search. In addition to publications from the literature research, annual reports and freely accessible company data from companies in real supply chains are also considered. A distinction is made between general information and EV-SC-specific information. Due to the complexity of the automotive value chain, the global structure is examined first, and then specific aspects of individual supply chain maps are addressed before a consistent detailed model is created. Through close feedback loops with technical experts, the theoretical data basis was checked for its practical suitability and representativeness and further developed as required. The values, correlations and quantifications assumed in the following chapters are based on the results of the initial literature analysis.

3.4.2.1 Concept model development

The analysed structure of the Automotive Supply Chain is presented in Figure 3-7. An automotive supply chain can be assigned to the group of producer-driven supply chains [27]. Producer-driven Supply Chains are characterized by high capital intensity and a structure controlled by central companies [28]. Another feature is the global distribution of the supply chain, in which a large number of countries are involved. The number of countries involved depends on the respective supply chain. For example, the automotive supply chain of a German car manufacturer sources its components from a large number of countries, while a Chinese manufacturer can source almost all of its components from its own country [29]. In the case of the automotive supply chain, this can be up to a thousand suppliers and sub-suppliers [29].

This becomes clear when looking at the concept maps for different partes of the overall supply chain. Another driver of complexity in the automotive supply chain is that the value-adding activities cover a broad spectrum [30–32]. In the automotive supply chain, the production steps are carried out from raw material extraction to the end product and include a large number of intermediate steps and components [31]. This fact becomes clear when looking at an automobile, which can consist of up to 10,000 individual parts [33]. The mapping of all components proves not to be expedient. For this reason, small parts are not included, as shown in Figure 3-7 .

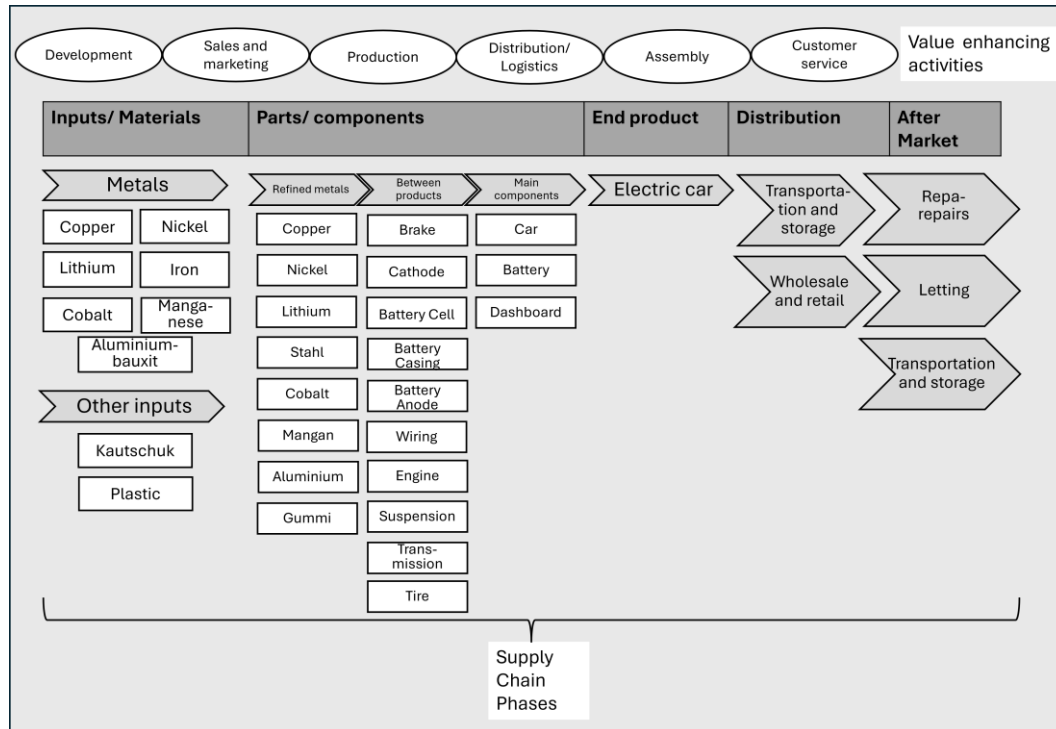


Figure 3-7: EV-supply chain –structure of the SC

In the next step, the level of detail is increased, and the supply chain map is created based on the structural overview. The supply chain network map structures the general structure into individual parts, which are explained in more detail below. Supply chain maps enable a more detailed analysis than supply chain network maps. Key elements of this method are the presentation of material flows between companies and the identification of other transportation and storage service providers involved in the supply chain. [34]

Figure 3-8 illustrates the supply chain of an electric vehicle produced in Europe, from the extraction of raw materials to the sales markets. The supply chain is divided into several stages. To create the supply chain map, the supply chain is segmented into several phases. The first level comprises the extraction of raw materials, followed by the refining of the ores.

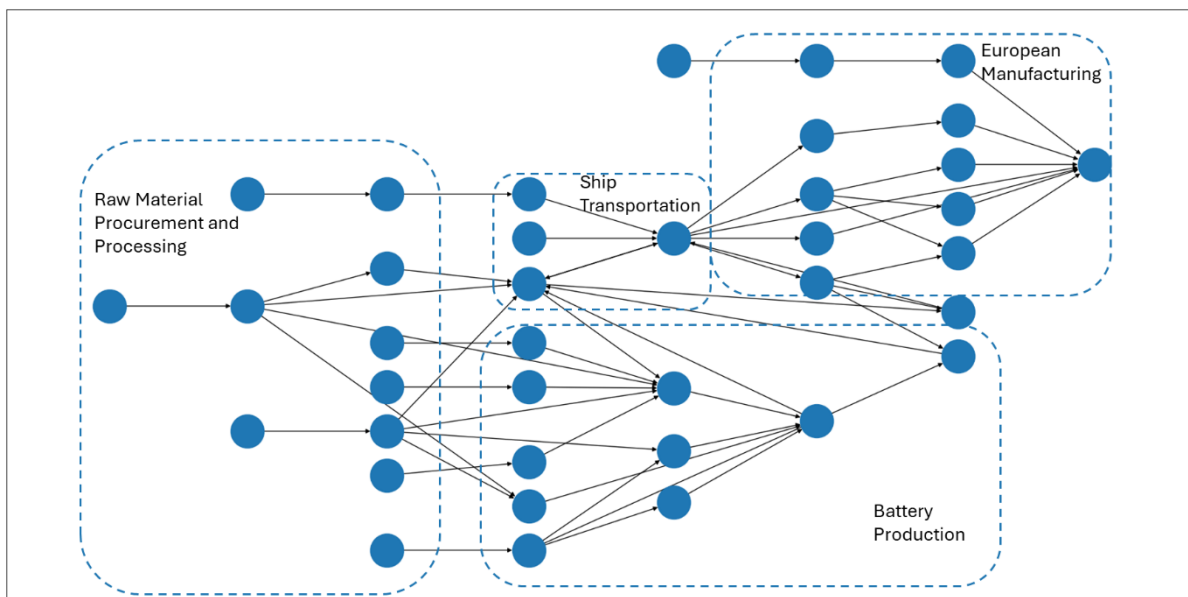


Figure 3-8: EV-supply chain – supply chain map

The individual detailed aspects of the supply chain map are described and visualised separately below due to the high complexity of the overall model. The sourced raw materials, the downstream supplier tiers, battery production, the transport network, final assembly and the downstream distribution network are analysed separately.

Raw Materials

The most important raw materials in the automotive supply chain in terms of quantity are iron and aluminium, as they account for most of the weight of the car. The analysis of the automotive supply chain reveals that rare metals such as lithium, cobalt and manganese are of significant relevance, as they are an integral part of the production of electronic components and batteries. [35, 36]

Aluminium oxide is mined in China, while further processing into aluminium takes place in India. The iron ore is also mined in China and smelted there to give it the form required for the subsequent steps (ingots, granules or blocks). The selection of raw materials shown is based on the percentage composition of an automobile. The most commonly used metal is iron with a mass percentage of 87%, followed by aluminium with 10.7% and copper with 1.7%. Table 3-3 provides an overview of the percentages of metals used in an automobile. The remaining metals, each of which accounts for less than one percent, are chromium and other precious metals. Plastics, rubber and leather are also required to produce a car. Rubber is an essential component of key car parts and is therefore included in the supply chain map. It is used in the production of tires, seals and the encapsulation of electronics. [37, 38]

Table 3-3: Automotive supply chain – raw material demands [38]

	Aluminium	Cobalt	Chrome	Copper	Iron	Lithium	Manganese	Nickel
Demand in t	12345	5	317	2049	116765	8	52	171
Percentages	9,4 %	0,01%	0,2%	1,6%	88,7%	0,01%	0,04%	0,13 %

Supplier tiers

During production, the raw materials are processed into components such as gearboxes, engines and suspensions (a complete list of parts can be found in Table 5-4 and Table 5-5). For the purposes of this study, small parts such as screws are not included in the supply chain map. The production sites and mines for raw material extraction are distributed globally. For the final links in the supply chain, it is assumed that the OEMs and the nearby first and second-tier suppliers are located in Germany, as in reality a large automotive industry is also located here. For example, tires and gearboxes are transported to Germany via long overseas transports and transhipped via the Port of Hamburg in the model. At the Port of Hamburg, the products are loaded onto trucks that continue to the next stage of the supply chain. A significant proportion of the parts required to produce an automobile are manufactured in Eastern Europe as part of nearshoring and transported directly from the plants to final assembly at the OEM. A special feature of the EV supply chain is the production of lithium-ion batteries, which takes place in a separate cluster. The production of these batteries is associated with certain difficulties. Another aspect that makes the supply of the necessary raw materials a challenge is the fact that a large proportion of the rare earth metals (also known as critical raw materials e.g. lithium or cobalt) required for production are mined in only a few countries. [38]

Battery

The battery production process chain is structured in the same way as the automotive production process chain. The raw materials are prepared in refineries and then processed into products. The components of a battery can be divided into four main products: Cathode, anode, casing and battery cell. [38-40]

Assembly and Shipment

The final assembly of the vehicle takes place at the production site, with the necessary materials being brought together at this location beforehand. The finished car is then transported to the distribution centre, from where it can finally be shipped to the target market. It should be noted that direct delivery to the seller from a plant only takes place in rare cases, namely in around 1% of cases. One possible intermediary between sellers and customers is a leasing company, which first leases the vehicles and then sells them. This approach is used in 10 % of cases. [35]

Supply Chain Network Analysis including transports

The supply chain map resulting from these detailed assumptions (this results in an illustration as in Figure 3-8, which would be extended by the labelling of the individual nodes) reflects a centralized archetype that is characterized by a small number of initial sources, a large number of production sites and a resulting endpoint structure. The latter in turn only pass on their products to a small number of other production facilities. A detailed analysis of the supply chain maps reveals that the material flows in the automotive supply chain are characterized by a high degree of complexity. It is also clear that transportation

and storage service providers play a significant role in the supply chain. Production spans several stages, from raw material extraction to final assembly, and is distributed globally. The production of lithium-ion batteries is associated with particular challenges, especially with regard to the procurement of rare earths. In contrast, the production of combustion engines is characterized by a wide range of individual components and a high level of vertical integration. [41]

The three model formats Global Value Chain Map, Supply Network Map and Supply Chain Map provide a comprehensive insight into the interrelationships and characteristics of the automotive supply chain (in this case initially presented to produce electric cars). The following explanations will deal with the specific characteristics of these forms of representation. They represent the starting point for the formalization of the model. The conceptual model is based on the supply chain map and integrates the research results of [33, 42, 43], who dealt with the automotive supply chain. The structure of the mapped supply chain was presented by [43], which depicts the phases of raw material procurement, transportation, production, distribution and customers. [33, 42–44]

In this simulation, the seven main components of an automobile were taken into account, as is the case in the simulation by [33]. The mechanics of supply consolidation were adopted from the work of [42] who describe how materials and products are transported in the automotive industry supply chain. The supply chain is modelled in four stages. First, raw materials are fed into the system from sources and then processed further. The upstream production steps for the manufacture of steel and aluminium are shown in Figure 3-9. It should be noted that the transportation routes between mining and processing can vary in length. In most cases, the relevant plants are in the immediate vicinity of the mining areas, but in some cases the raw materials have to be transported over long distances. Not all products are produced within Europe, as production has been relocated to other countries. Some products are shipped to Germany via a port. This study looks at two ports that ensure shipping traffic between Europe and Asia. These ports represent a critical component that will have a significant impact on subsequent processes in the event of disruptions or capacity bottlenecks. Figure 3-10 illustrates the networking of the ports with upstream and downstream nodes. [33, 42]

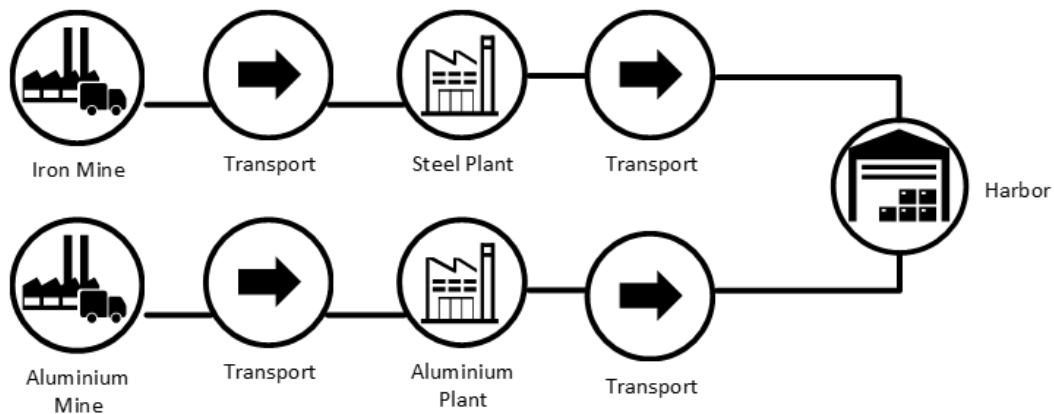


Figure 3-9: EV-supply chain – metal production

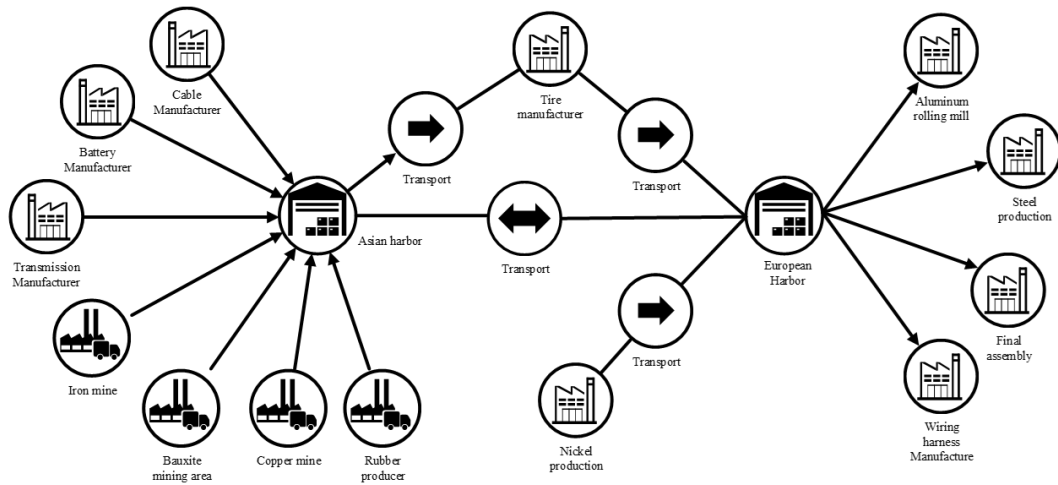


Figure 3-10: EV-Supply chain – main harbours in the transport network

General interaction between sources and SC knots

The sources are differentiated into pull and push sources. Raw materials and materials that are available on demand are referred to as pull sources. This implies that a node can place an order with a source and receive a delivery after a specified time. In contrast, rare earths are a limiting factor in the system. In contrast to metals such as steel and aluminium, which are available on the market in large quantities, supply bottlenecks are considered here. The corresponding source strategy is push-controlled. The production sites are designed in such a way that only one specific product is manufactured at each site. This means that steel, aluminium and copper are produced at different locations. This is followed by onward transportation to the production sites where the product is assembled from various metals or plastics. The production of the battery cathode, which consists of six components (lithium, cobalt, manganese, nickel, iron and aluminium), is shown in Figure 3-11.

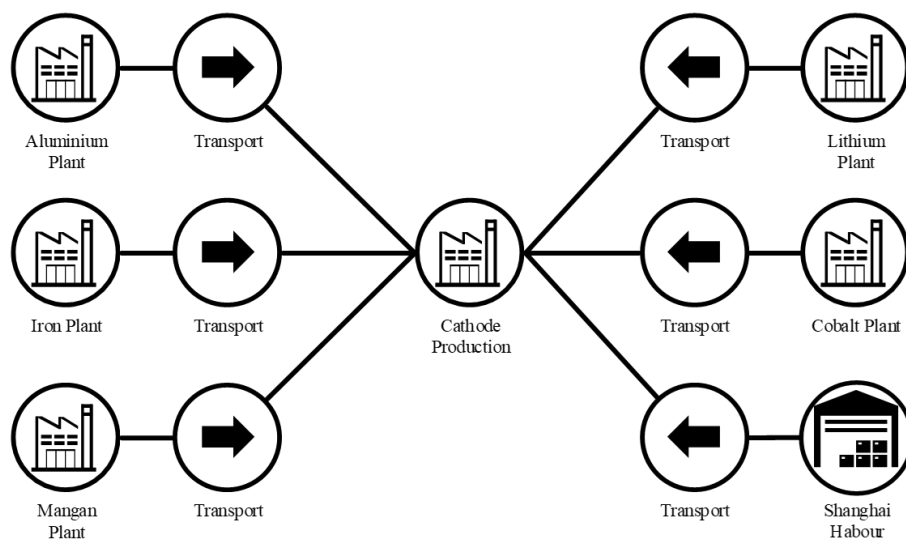


Figure 3-11: EV-Supply chain – production node e.g. Cathode

The vehicles are then transported to final assembly, where the body, suspension, brakes, transmission, wiring harness, tires, engine and battery components are assembled. In the final step, the vehicles are transported from final assembly to an interim storage facility and from there to the various sales markets. Figure 3-12 illustrates the process from the arrival of a raw material to the delivery of an automobile ready for shipment.

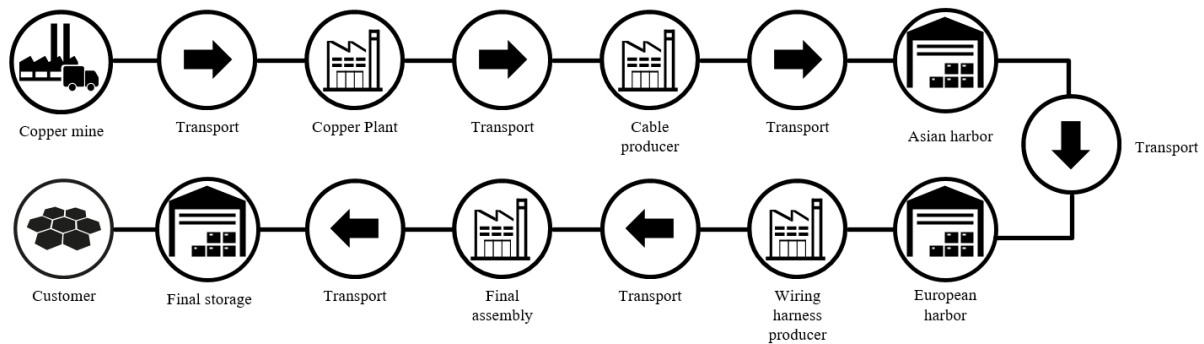


Figure 3-12: EV-Supply chain - supply chain map for cable harnesses

This description of the relevant sub-processes forms the basis for the subsequent parameterization of the 24 different production sites, the nine sources and all 32 intermediate and end products as well as the associated transport connections as part of the implementation. Consequently, this approach results in the design of the executable model of the EV supply chain.

3.4.3 Implementation

Due to the detailed data available and the complex structure of the supply chain, it is suitable for quantification using discrete supply chain simulation. The supply chain is therefore mapped and analysed below with the help of the OTD tool (Which is described in detail in chapter 2.4).

The bottleneck of rare earths is initially mapped via a source that follows a push logic and a warehouse that receives the materials. This is done because the production sites must pursue a sourcing strategy that can only work together from a source with demand-oriented control. However, this would no longer make it possible to simulate a bottleneck as the mine would release materials according to demand. The warehouse serves as an intermediate buffer and allows materials to be stored and released according to the needs of subsequent processes. Table 3-4 gives an overview of the used sources for the rare earths and a yearly production rate.

Table 3-4 Automotive supply chain – sourced materials

Material	Production Capacity	Location
Steel	300.000 tons/year	China

Material	Production Capacity	Location
Aluminium	7,1mil tons/year	China
Rubber	2,3mil tons/year	Germany
Copper	500.000 tons/year	Chile
Lithium	39.000 tons/Year	Democratic Republic of the Congo
Nickel	164.900 tons/year	Central-Sulawesi
Manganese	200.000 tons/year	Botswana, Namibia (Kalahari Basin)
Cobalt	30.000 tons/year	Australia

In the next step, the partial supply chains described are transferred to the individual object types of one of the simulation models, as shown in section 3.3.2. The parameters are used to quantify the nodes and transports in detail. The configuration of the supply chain is gradually adapted during further specification.

One of the longest transport route in the analysed automotive supply chain takes place between the Asian and European ports. For the simulation, 20 days were assumed for the transportation time. This corresponds to an average transportation time. In reality, however, considerable deviations from this time are to be expected as many factors have an influence on these long-distance transports. Table 5-3 contains all important information's for the other transports.

An example of the complexity of the supply chain that was implemented in the simulation is the preparation of the nickel and the subsequent further processing. One of the main producers of nickel, Vale S.A., operates one of the largest nickel mines in Canada with an annual production of 180,000 tons. However, this mine mainly extracts red nickel pyrite. However, this nickel can only be refined in its raw form using special processes. One of these companies has its production site in Germany and produces a significant proportion of the pCAM (precursor cathode active material) used worldwide, a preliminary product for the production of a cathode for electric batteries. The production of the batteries requires continuous and efficient transportation between European and Asian ports. This underlines the importance of smooth processes at these key ports. A standstill at these points would have a significant impact on the entire supply chain

A constant demand pattern is assumed. This describes a situation in which the demand for a product remains constant over a certain period. This assumption is based on regular consumer behaviour, availability and price stability. For the simulation, daily demand is modelled, which corresponds to 11.000 cars over the course of a calendar year.

Table 5-4 and Table 5-5 contain a complete overview of the model parameters used. The simulation results are presented below. The resulting supply chain network is shown in Figure 3-13.



Figure 3-13: Automotive supply chain – formal model

3.4.4 Results and Evaluation

The analysis begins with the customer and the demand triggered by him. A total demand for the type of car produced of eleven thousand units per year is assumed. The demand is distributed over the year to a daily demand of 30 electric cars. This demand is fulfilled at the final warehouse. Figure 3-14 shows the corresponding stock flow in the final storage facility. It can be seen here that the stock is kept constant between 200 and 380 through a continuous reordering process. There are hardly any irregularities in the periodic fluctuations, which suggests that the supply chain is a continuous process.

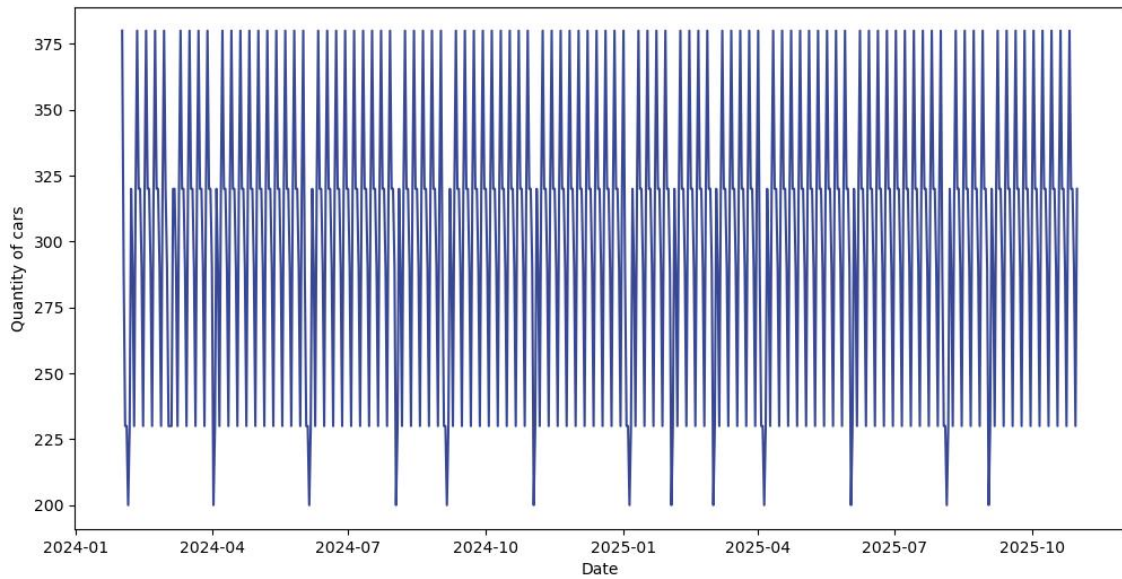


Figure 3-14: EV Supply chain – final warehouse

As shown in the supply chain map, various components are delivered via overseas transportation routes. The port of Hamburg is considered here, where various intermediate products are handled. The port acts as an interim storage facility in the simulation. As can be seen, the individual intermediate products each have their own individual stock levels over time Figure 3-15.

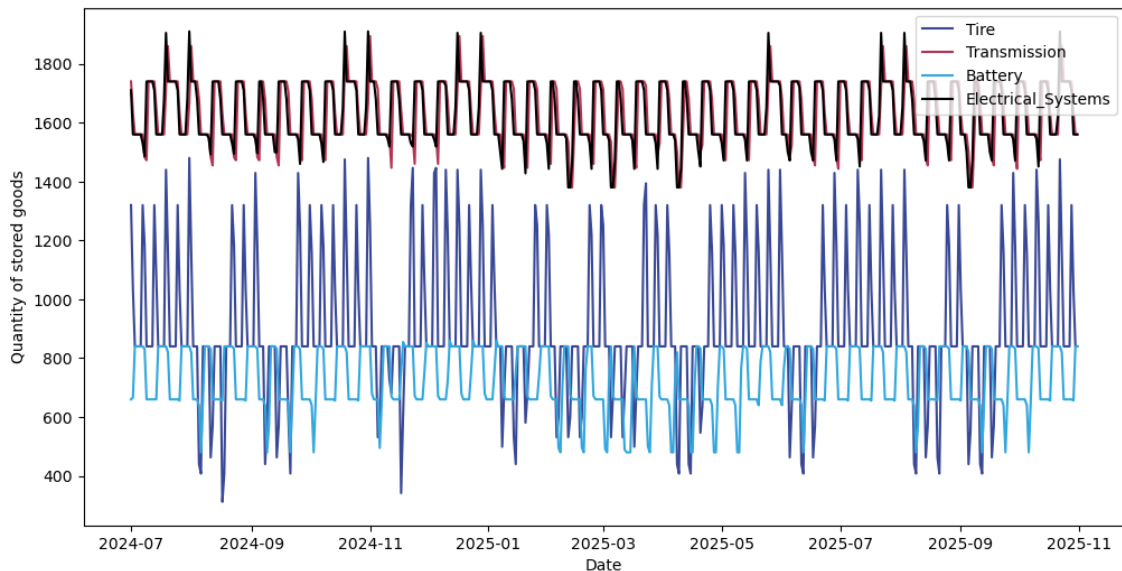


Figure 3-15: EV Supply Chain – Hamburg Harbour

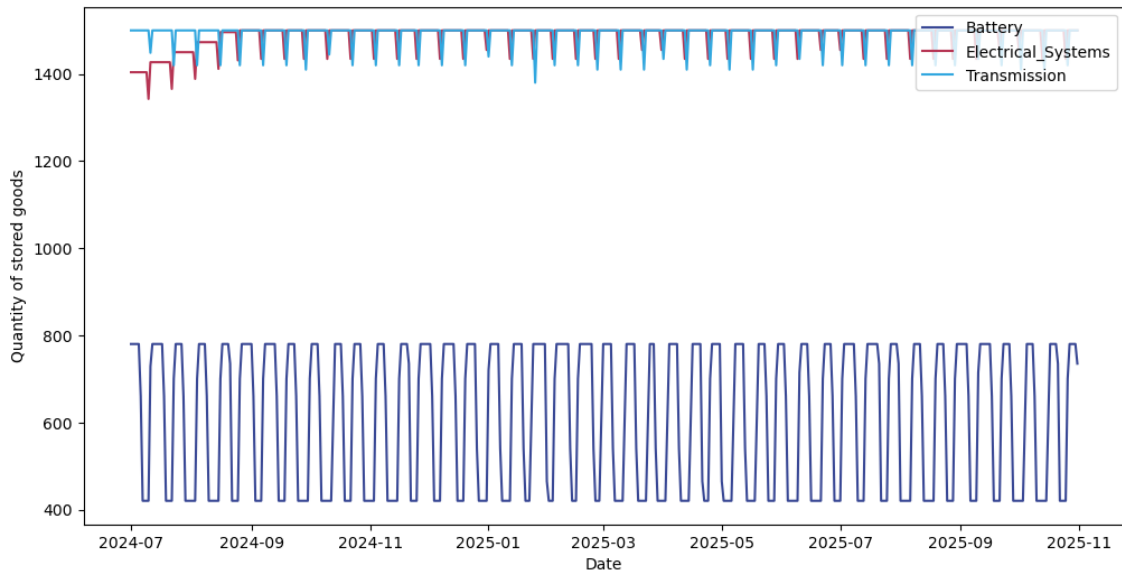


Figure 3-16 EV Supply Chain – Shanghai harbour

An interesting observation can be made in Figure 3-17 by comparing the anode warehouse and the battery warehouse. It can be observed that after the disruption in battery production, a drop in stock can be recorded in the anode warehouse. This is because after the disruption is over, the backlogs have to be made up and larger quantities of components are required. This increased demand leads to the anode warehouse subsequently being brought into negative territory. This dynamic is the beginning of the “bullwhip effect”¹, which runs through the entire supply chain and would continue to increase without sufficient production capacity. The effect shown is manifested in the figure in the correlation between the drop in brake stocks and the final product. Due to the temporal proximity between the production of the brakes and the final assembly, the time span between the interruption of the brake stocks and the final stock levels is shorter.

¹ The bullwhip effect in supply chains describes the phenomenon where small fluctuations in customer demand lead to disproportionate changes in order quantities and inventory levels along the supply chain. This often occurs due to delays in information transfer, inaccurate demand forecasting and excessive safety stock, leading to inefficiencies and higher costs for manufacturers and suppliers. [45–47]

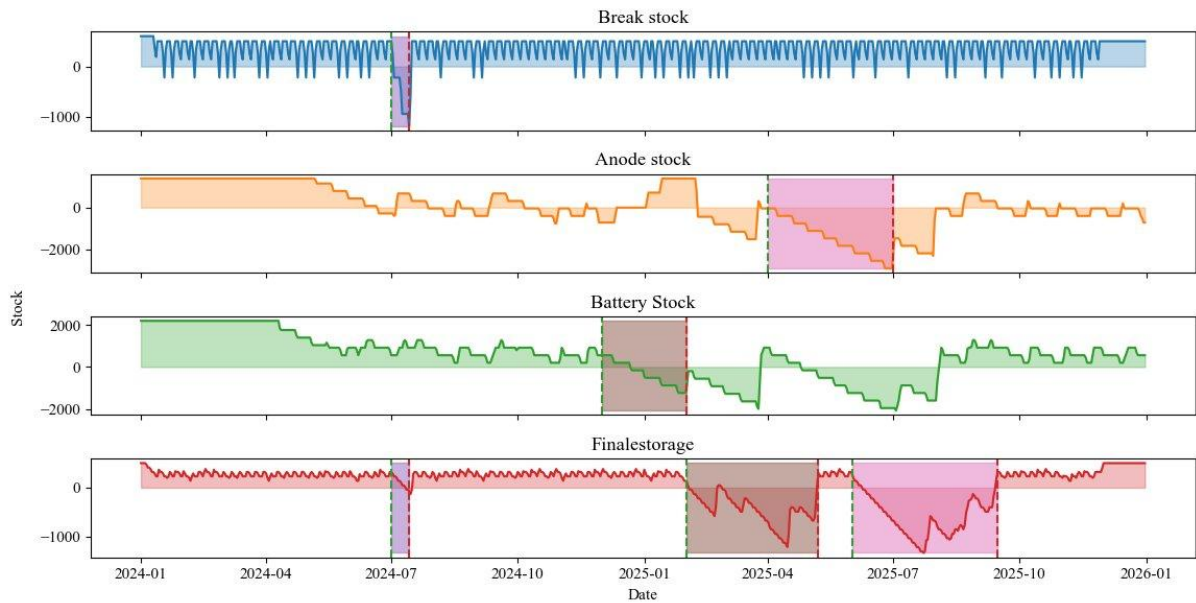


Figure 3-17 Analysis of disruption patterns in the EV supply chain

The disruption duration also provides a deeper insight into the simulation, as it can be observed that if a disruption affects production for its actual duration of one or two months. For example, it can be observed that the disturbance duration in the final storage facility is one to two weeks longer than initially estimated. This is because the bottle neck does not have sufficient capacity to immediately compensate for the resulting residues.

3.5 Textile ecosystem

As described in D1.1, the textile ecosystem is very complex due to the large number of SMEs and global competition. It has a strong link between major brands and suppliers. Looking at the sectors and subsectors defined in the NACE classification, the textile ecosystem includes the processing of natural (e.g. cotton, flax, wool), man-made and synthetic (synthetic polyester and viscose fibres) fibres into yarns and fabrics, the production of yarns, home textiles, industrial filters, technical textiles, carpets and apparel. The ecosystem also includes the production of shoes and leather, the manufacture of intermediate products and fashion items and the distribution of these products. The fashion industry is the most important market for textile products.

3.5.1 Supply chain Selection

To select a suitable supply chain in the Textile ecosystem together with the participating research parties, criteria were extracted from D1.1 that can be used to evaluate possible supply chains. The criteria are described in the introduction to Chapter 4, and the evaluation by the experts is shown in the table below. Within the potentially considered product classes, the ecosystem experts selected the footwear supply chain. In particular, the relevance of the corresponding industries in the EU member states under consideration, such as Italy, and the high number of SMEs affected played an important role in the decision. As the weighted values are so close to each other, the strategic decisions and the fundamentally comparable characteristics of the various product supply chains have been weighted more heavily here. In the further course of the project, however, the Clothing Supply Chains will also potentially be focused more strongly.

Table 3-5: Textile Supply Chain – Supply Chain Selection

Supply Chains	Sportswear	Clothing	Footwear
Value added / turnover	9	8	7,5
Strategic relevance	8	8,5	8,5
geographical significance	9	9,5	8
Representativeness	9	9	7,5
Share of SMEs	8	8	10
Availability of detailed SC information	8	8,5	9
Green & digital transition	9	8,5	8,5
Fit to the SC resilience fit model	8	8,5	8
Exposure to risks or disruptions	9	9	8,5
Weighted Score	8,6	8,6	8,7

3.5.2 Data collection

The information required for the design of the shoe supply chain is obtained through structured research in scientific databases. Furthermore, publicly available data, business reports and expert opinion are used to obtain a comprehensive and coherent picture of the supply chain network. The aim of the research is to identify the relevant actors, processes and transportation. Based on this, the actors involved are validated with the company partners and the processes are parameterized with additional data, including process times, throughput times and capacities. The following tables summarize the materials, suppliers, processes (i.e. production locations), transports and distribution locations to be modelled. The shoe supply chain is made up of four phases in the value creation process. These are: Raw material procurement, production, quality control and distribution. Corresponding to the phases of the supply chain, the most important players must be named:

- Raw Material Suppliers,
- Logistics service provider,
- Shoe producer,
- Quality controller and
- Shoe distributors.

The materials, intermediate products and products to be examined are:

- Leather,
- Fabric,
- Toe
- Counter,
- Upper,
- Lining,
- Outsole,
- Midsole,
- Insole,
- String,
- Mould,
- Lacing,
- Laces,
- Lace tag and
- Boxes.

Based on the publicly available information, the scientific studies and the additional information from the company surveyed, the necessary details can be added. Table 5-6, Table 5-7 & Table 5-8 provide an overview of the data used. Based on this information, a conceptual model of the supply chain is designed in the next step.

3.5.3 Concept model development

As part of the system analysis, the interdependencies in the system are systematically processed using the collected data. The result of the system analysis is then the concept

model. In this step, the scope and level of detail of the model is determined. For this purpose, the input and output variables are first defined for each node, i.e. process and actor. In this way, the edges of the network become clear, and the structure is developed. The starting point for network modelling is the three-phase model consisting of: Raw Material Procurement, Production (including: Quality Control, Boxing) and Distribution, as shown in Figure 3-18. Within these three phases, the individual process steps are now defined, and the associated input and output variables are determined.

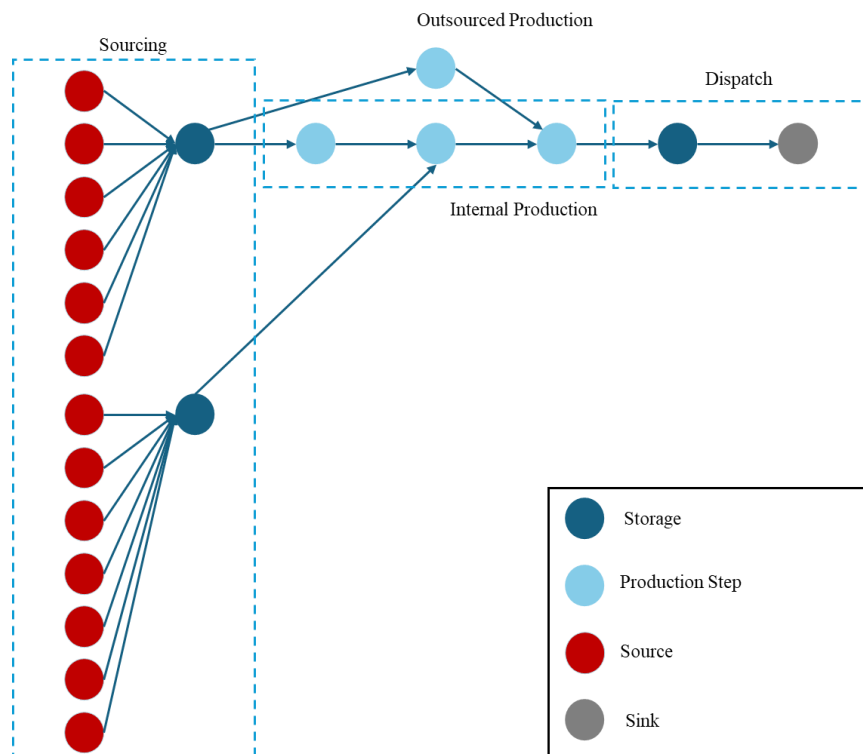


Figure 3-18: Shoe Supply Chain - Supply Chain Network Map

The individual phases are broken down further in the next step. For this purpose, process steps are assigned to each phase. In the first phase, raw material procurement, the raw materials are procured and stored in a temporary warehouse and checked for quality before use. This is illustrated by the example of raw material procurement in Figure 3-19.

The second phase is the shoe production. This is divided into four main process steps, which are shown Figure 5-4 in the appendix. In the first process step, materials such as fabric and leather are cut, their surface and edges are treated (skiving). The following phase begins with stitching the upper to form the structure, followed by adding decorative elements and accessories to enhance the design. The lining is added for comfort, and reinforcements are included to improve the shoe's durability (stitching).

In the second process step, the toe and heel areas of the upper are reinforced through assembling of the counters (counter wrapping).

The third step kit assembly refers to the process in which all the necessary components and parts of a shoe (e.g. upper, sole, lining, laces, etc.) are put together to form a “kit” or set for further processing. The kit assembly is an important step in ensuring a smooth production process and increasing efficiency in sports shoe manufacturing. All phases are visualized in the supply chain network map in Figure 3-18.

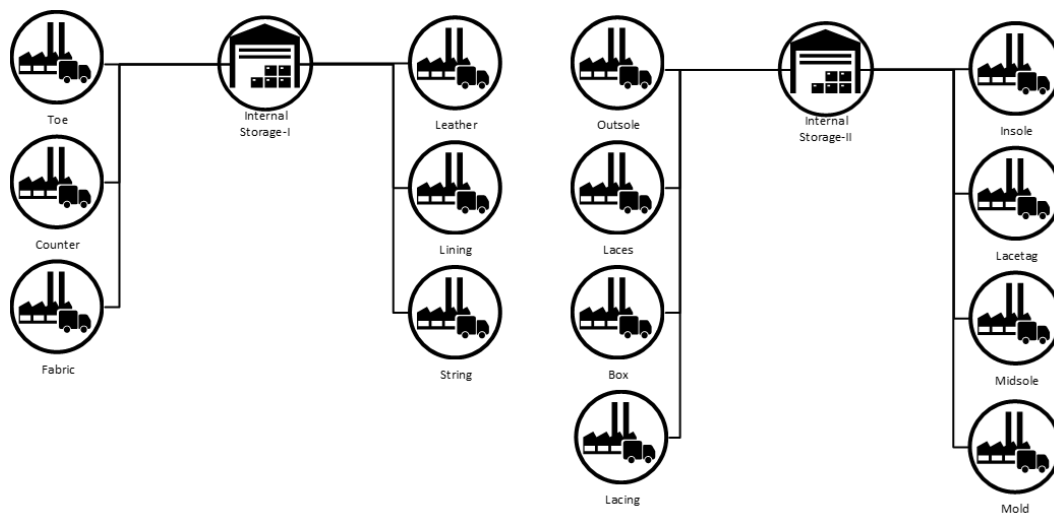


Figure 3-19: Shoe Supply Chain – Sourcing phase

In the fourth and final production step, the components of the assembly kit are put together and the sports shoe is finalized. In the third phase, the finished sports shoe is checked for quality, whereby an inflow of further sports shoes from outsourced production is possible.

The fourth and final phase involves packaging the finished product in boxes and shipping it to wholesalers globally. With the overview of these required process steps, the process can now be formalized. Specific parameters for the individual processes and transports are defined for this purpose. Table 5-6 shows the process steps with the input and output variables. This results in the structure of the SC network shown in Figure 5-5.

3.5.4 Formal Model and Implementation

The shoe production supply chain is complex and strategically structured to ensure quality, efficiency and cost-effectiveness. The process begins with the procurement of raw materials, whereby the required materials are procured, stored and checked for quality before use. The materials for the upper, toe and fabric are sourced from China. China is not only known for its low-cost production capabilities but also has a well-developed infrastructure and extensive production capacity that enables large quantities of materials to be supplied quickly. These factors are crucial to meet the demands of mass production in the sports footwear industry [48].

The leather is sourced from Italy, a country known for its high standards of workmanship and tradition in leather processing. Italian manufacturers offer not only high-quality leather,

but also innovative designs and craftsmanship, which is important for the brand integrity and image of sports footwear. The combination of traditional craftsmanship and modern design in Italy is a key factor in the quality of the end products. The soles, lace tag and counters come from Thailand, which has established itself as an important production location for shoe components. Thailand offers access to a variety of high-quality materials and has built a reputation for low-cost manufacturing. Manufacturing in Thailand makes it possible to further optimize production costs while ensuring the quality of the components. The materials are then procured from a company based in Italy.

The majority of shoe production also takes place in Italy, which ensures that the high-quality requirements are met. Italian manufacturing enables precise workmanship and close control over the production process, which helps to minimize errors and ensure product consistency. Part of the shoe production is outsourced to Romania. Romania offers cost-effective production facilities and a strategic location close to the European market. This not only reduces transportation costs but also enables a faster response to market demands and greater flexibility in production. The combination of the Romanian production facilities with quality control in Italy ensures that the shoes produced meet the high standards of the Italian brand.

The boxes for packaging the shoes are sourced from Spain through an Italian trading company. Spain offers logistical advantages, including a well-developed infrastructure for transportation and distribution. In addition, manufacturers in Spain can use sustainable packaging materials that meet the growing demand for environmentally friendly products. These items coming from all over the world are purchased from Italian dealers which act as intermediaries between companies in Thailand, Spain etc and the footwear producers.

Overall, the structure and allocation of this supply chain ensures realistic modelling. The choice of locations considers both cost efficiency and quality, which is crucial for competitiveness in the footwear industry. The combination of local production in Italy and the use of global suppliers makes it possible to create a balance between quality and costs. These strategies reflect current trends in global supply chain management in the textile industry, where companies are optimizing their production and supply processes to meet market demands.

Implementation

The supply chain is simulated in OTD with a simulation timeframe of one year. The parameterization was carried out in 4 steps, with the supplier values being set at the beginning. The lead time of the suppliers was set to 1.5 days instead of the usual 5 days. This corresponds to the specifications for the transport duration in Table 5-7. The parameterization of this table is described in more detail below. As suppliers 9 and 11 are modelled without transports, their lead times are not taken into account. The bills of materials are implemented as shown in the table. Regarding the countries of origin, one country is initially used for each source, although this is not a restriction as long as the lead time is modelled sensibly. Demand-based logic is used as the sourcing strategy for all suppliers. Figure 3-20 shows the global transport routes between suppliers and production that characterize the supply chain.

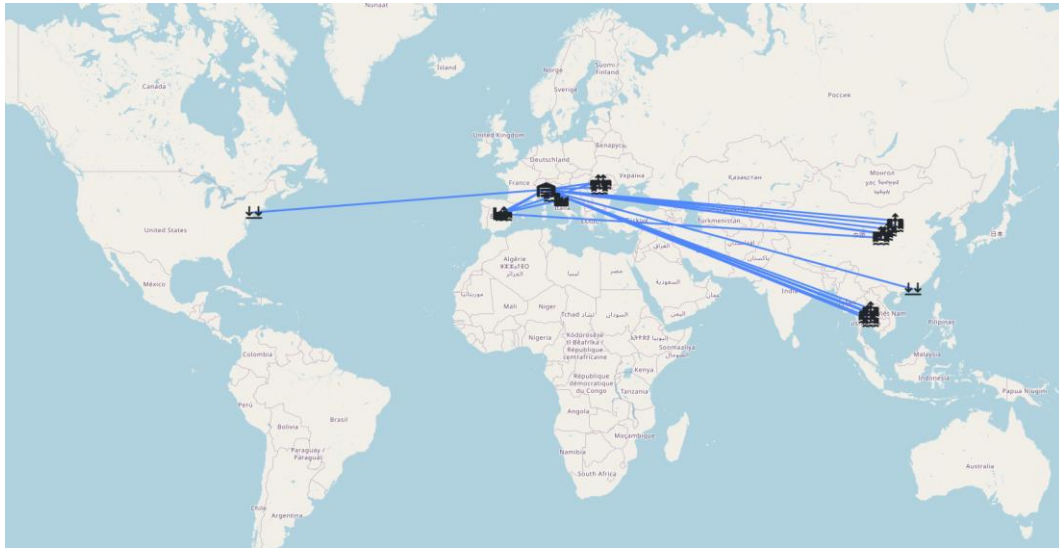


Figure 3-20: Textile supply chain – geographical representation

As part of the parameterization of the production facilities, the information in Table 5-6 on the inputs and outputs of each location is implemented. The production capacity corresponds to the specifications, regarding the working time of 8 per day. The production capacity was scaled accordingly so that the daily capacity remained unchanged. The lead time to deliver one pair of shoes was implemented according to the specification, the lead time is scaled to match the working shifts. With a daily production capacity of 640 (units/day), this results in a lead time of $(1440 \text{ min}) / (640 \text{ units}) = 2.25 \text{ min/unit}$ in addition, the lead time considers the fact that several workers carry out the respective production step without this having to be explicitly modelled.

The preliminary lead time, which results from the sum of the lead time and the transportation time routes of the upstream production sites, is also implemented for the operability of the model, although it is not explicitly required by the specifications. The preliminary lead time was set to zero minutes if the production sites source their intermediate products from the warehouse, as the warehouses and production sites are located in the same place. It should be noted that no connections between input materials and output materials are described in Table 5-6. This means that a maximum of one of the various input materials must be used in the respective production facility to produce an output.

In the next step, the transports are modelled. The length of the transports is derived from the transport times of the suppliers as described in the table. By including the lead times both the transportation times and the handling times at the supplier side are considered. The length of the transportation route is implicitly included in the transportation time.

The integration of the warehouses is based on the definition of the materials to be stored and the selection of the associated sources. This is implemented in accordance with the supply chain concept model. A maximum capacity is not considered for the warehouses.

The s, Q policy² is used as the inventory policy. The initial stock level of the warehouses, except for the final warehouse, is set to 6000 units. The reorder point is set at Y units. When this point is reached, the warehouses each reorder 100 units of the respective material. The quantities are selected in such a way that the model triggers an order directly at the start of the simulation period in accordance with this parameterization.

Three demand markets were considered – Europe, Asia and America – to expand the supply chain network to include further overseas transportation and interactions between different markets. These assumptions are initially to be understood as a current snapshot of a demand situation and are individually customized in the subsequent scenarios. The focus is initially on the American market. Due to the capacity restriction in the production of 137 units per day, a demand of 1300 shoes every 10 days (i.e. the equivalent of 130 shoes per day) is set for the American market. An additional demand of 10 shoes every 10 days is set for the Asian market. Due to the bottleneck in production, the described changes in demand are made, as unfulfilled demand in OTD does not trigger an order in the supply chain.

Table 3–6 Textile Supply Chain – Supplier

Supplier ID	Material	Lead Times (Days)	Location	Batch Sizes	Minimum Order quantity	Country of origin (raw materials)	Replenishment strategy
1	Upper	5	Italy	20	100	China, Italy (High Quality)	MTO
10	Upper	10	East Europe	20	100	East-Europe	MTO
2	Toe	5	Italy	20	100	China, East-Europe, Italy (High Quality)	MTS
3	Lining	5	Italy	30 m ²	100	East-Europe, Romania	MTO
3	Lacing	5	Italy	20	100	China, East-Europe, Italy (High Quality)	MTS
3	Laces	5	Italy	40	100	China, East-Europe, Italy (High Quality)	MTS
3	Lace tag	5	Italy	20	100	China, East-Europe, Italy (High Quality)	MTS
2	Counter	5	Italy	20	100	Thailand, Vietnam, China	MTS
4	Outsole	5	Italy	20	100	Thailand, Vietnam, China	MTS
4	Midsole	5	Italy	20	100	Thailand, Vietnam, China	MTS
4	Insole	5	Italy	20	100	Romania, Thailand	MTS
5	Leather	5	Italy	30 m ²	100	Italy, China	MTO
6	Fabric	5	Italy	30 m ²	100	Italy, China	MTO
7	Box	5	Italy	20	100	Spain, Germany	MTS
6	String	5	Italy	100 m ²	100	China, India, Italy	MTS
8	Mold	5	Italy	20	100	Romain, Italy	MTS

² An (s, q) ordering policy is a method of stock management in which a specific order quantity (q) is initiated as soon as the stock level has reached a certain order point (s).

Supplier ID	Material	Lead Times (Days)	Location	Batch Sizes	Minimum Order quantity	Country of origin (raw materials)	Replenishment strategy
9	Outsourced shoes assembly	10	Italy	100	50	Europe	MTO
11	Outsourced shoes assembly	14	East Europe	100	50	East-Europe	MTO

This model is based on previous works made by the project team with footwear companies and related local associations in combination with scientific research studies [49].

3.5.5 Results and Evaluation

The results of the simulation are analysed below. The focus here lies on evaluating the interaction between the individual phases of the supply chain. To achieve such an assessment, the temporal stock flows in the warehouses and the production outflows are considered.

The simulation illustrates the importance of available capacities. The two internal material warehouses have high stock levels compared to the daily demand of 131 units. The minimum total stock level, i.e. the sum of the stocks of all stored materials, of the first internal warehouse is 35,300 units. In contrast, the minimum stock level of the second internal warehouse is 44,400 units. On average, the total stock of the end product, i.e., the total stock in the final warehouse, is 1,300 units. The stock decreases with the continuous inflow of orders. The development of stock levels is shown in Figure 3-21. Between the customer orders, products continuously flow into the final warehouse. Both effects result in the trend shown. Production and demand are aligned, as there are no shortages or excess stock.

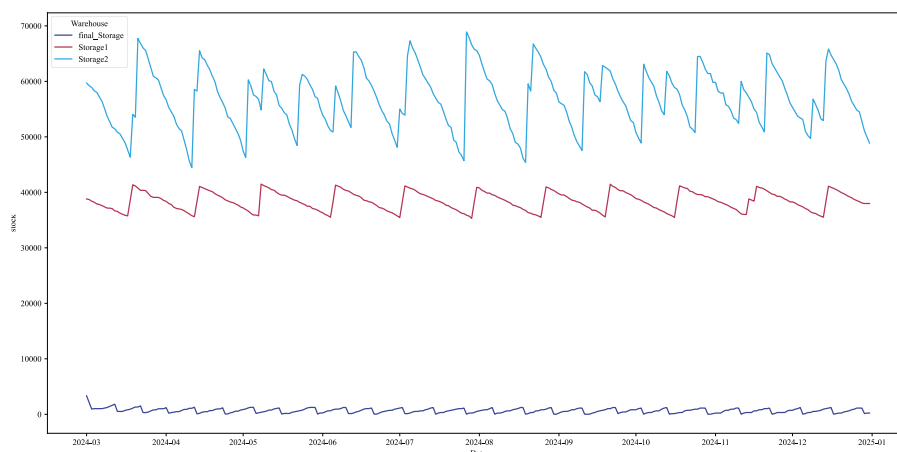


Figure 3-21: Textile Supply Chain – Combined Stock per Warehouse

Figure 3-22 illustrates several other features of the supply chain. Firstly, the bottleneck in the production chain is shown here in the kit assembly step, whose maximum production

quantity is 120 units per day. Secondly, the high production volume of the stitching production step shows that there are no capacity restrictions due to the warehouses. Furthermore, the fluctuations in the Finishing production step between 100 and 200 units with occasional drops in production to below 100 units are consistent with the fact that the requested demand is 131 shoes.

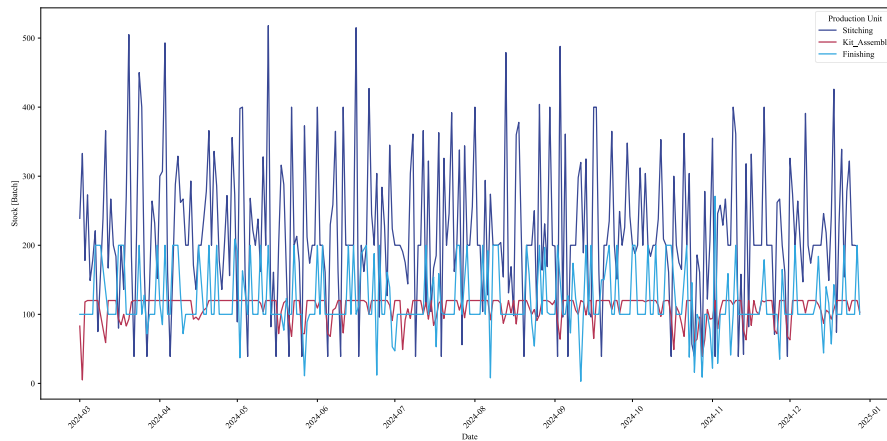


Figure 3-22: Textile Supply Chain – Production Units per Day

The figures show the pattern of the s, Q stock policy. The stock level decreases continuously as the materials are called off for production. When the reorder arrives, the stock level rises sharply. This results in the classic sawtooth curve. The continuous supply of the production facilities is ensured in the simulation scenario, as there are no shortages during the simulation period. In the current design of the supply chain, the bottleneck is therefore in the manufacturing sequence. It should be noted that due to the large number of input materials stored in the warehouses, only a partial quantity was visualized to maintain visual clarity.

3.6 Digital ecosystem

Small and Medium-sized Enterprises (SMEs) form the backbone of Europe's economy, representing a substantial proportion of businesses across various sectors. In 2022, the EU had 32.3 million enterprises, employing 160 million persons. Of that total, 99% were micro and small enterprises employing up to 49 persons. Micro and small enterprises employed 77.5 million persons, i.e. almost half (48%) of the total number of all persons employed in enterprises. They generated €11.9 trillion in turnover, representing 31% of the total (€38.3 trillion). [50]

Despite their economic significance, the digitalization of SMEs remains a pressing challenge. Recent data from Euronews indicate that only 58% of EU SMEs have achieved at least a basic level of digital intensity, as measured by the Digital Intensity Index (DII). This index assesses the adoption of key digital technologies such as Artificial Intelligence (AI), social media, cloud computing, and Customer Relationship Management (CRM) systems. In stark contrast, 91% of large enterprises have reached this baseline level of digitalization. Such a digital gap poses significant barriers for SMEs, especially within sectors experiencing rapid technological evolution, like transport and mobility. [51]

The transport and mobility sectors are undergoing profound transformation through automation and digital integration, and SMEs play a crucial role in driving innovation and offering specialized services within this ecosystem. However, their limited digital adoption hinders their ability to adapt to technological advancements and respond to market fluctuations. Therefore, focusing on the supply chain of Mobility as a Service (MaaS) presents a strategic opportunity to bolster SME resilience amid ongoing changes and instabilities. For all of this, MaaS can be a catalyst for SME sustainability and resilience.

According to the MaaS Alliance [52], Mobility as a Service seamlessly integrates different transport options—public transport, ridesharing, cycling, taxis, car rentals, and more—into a single, on-demand service. Through one app and one payment channel, users can plan, book, and pay for their journeys without juggling multiple tickets or platforms.

Beyond convenience, MaaS reshapes mobility by offering sustainable alternatives to private car use, helping reduce congestion and improve transport efficiency. It also opens new business models for transport operators by providing better insights into user demand and uncovering untapped service opportunities. Ultimately, MaaS aims to deliver smarter, more flexible, and eco-friendly mobility solutions for individuals and communities alike.

MaaS offers a solution by providing users with multimodal transportation options, which in turn reduces the number of private vehicles on the road and alleviates traffic congestion. In most cases, these services are flexible and highly customized per independent user. Faster internet connectivity, falling vehicle ownership, and the need to reduce traffic congestion and vehicular emissions will fuel the demand for seamless MaaS applications for end-to-end multimodal transport solutions.

MaaS is rapidly emerging as a transformative model in Europe's transportation landscape, integrating various mobility services into cohesive, user-centric digital platforms. This approach revolutionizes how individuals navigate urban environments while aligning with broader societal and environmental objectives.

The global mobility as a service market size was valued at USD 5.7 billion in 2023 and is expected to reach USD 40.1 billion by 2030, at a CAGR of 32.2% over the forecast period. With rapid urbanization, congestion and traffic-related challenges are increasing. [53]

According to the European Shared Mobility Annual Review 2023 by Fluctuo, Europe had 930,000 shared vehicles in operation in 2023. These vehicles facilitated 600 million trips and generated €2.3 billion in revenue from end users. [54]

Key points to choose MaaS in the digital ecosystem:

1. **Rapid Emergence and Growth in Europe** MaaS is experiencing swift growth across Europe, driven by the demand for seamless, efficient, and flexible transportation solutions. By integrating public transit, ride-sharing, cycling, and car rentals into unified platforms, MaaS offers tailored mobility options that enhance convenience and accessibility for users. This growth is bolstered by initiatives such as the MaaS Alliance, which fosters collaboration among stakeholders to create an open MaaS ecosystem [52].
2. **Alignment with Decarbonization and Sustainability Goals** MaaS directly contributes to the European Green Deal's objective of decarbonizing the transport sector. It promotes the use of shared and public transportation, reducing reliance on private vehicles and subsequently lowering carbon emissions. This shift not only supports environmental sustainability but also alleviates urban congestion, fostering more sustainable and liveable cities [55].
3. **Predominance of SMEs in the Ecosystem** Europe's mobility ecosystem encompasses over 1.8 million firms, the majority of which are SMEs. These businesses are pivotal in driving innovation, delivering specialized services, and responding swiftly to evolving market demands. Their active participation in the MaaS supply chain ensures a dynamic and competitive market, enabling continuous adaptation and improvement [55].
4. **Digital Dependency and Technological Integration** MaaS platforms are inherently digital, relying on advanced technologies for real-time data processing, user interface design, and secure payment systems. The smooth operation of MaaS hinges on effective data sharing and interoperability among diverse transport services, highlighting the critical need for digital proficiency among participating SMEs.
5. **Complex and Interconnected Value Chains** the MaaS ecosystem involves multiple actors, including transport operators, technology providers, regulatory bodies, and end-users. This interconnectedness requires meticulous synchronization and collaboration to ensure seamless service delivery. Such complexity goes beyond traditional value chains, demanding robust coordination and integration efforts.
6. **Integration with the Automotive Ecosystem** The effective deployment of MaaS relies on collaboration with Europe's established automotive sector. Partnerships with vehicle manufacturers, infrastructure developers, and technology firms support innovations such as electric and autonomous vehicles. This integration leverages existing automotive expertise to enhance MaaS offerings and create a seamless mobility experience.

7. Expertise of ZLC and IML in Transport and Mobility Institutions such as the Zaragoza Logistics Center (ZLC) and the Fraunhofer Institute for Material Flow and Logistics (IML) bring extensive experience in transport and mobility. Their involvement in both private and public MaaS projects has provided them with deep insights into the challenges and opportunities within the MaaS supply chain.

The integrated MaaS supply chain offers a strategic pathway to strengthen SME sustainability and resilience. By embracing digital technologies, fostering collaboration, and aligning with Europe's environmental goals, SMEs can better navigate the complexities of the modern mobility landscape. This approach not only bolsters their competitiveness but also contributes to a more sustainable and adaptable digital mobility ecosystem in Europe.

3.6.1 Concept model development

As the focused area of the MaaS system is less of a classic material supply chain, the modelling of a quantitative model for this value chain will differ from the other ecosystems. However, this approach is also suitable for the entire ecosystem beyond the scope selected here, as the digital ecosystem as presented in D1.1 primarily summarizes software development activities, consulting and publications. The hardware aspects are deliberately kept small in the definition (such as PCs, semiconductors or other electrical devices).

However, the model development also follows the basic principles of conceptual modelling, which is then further detailed and specified. The tool for modelling is selected as part of the development process with a view to the depth of information, the structural basis of the value chain and the quantification objectives.

The model proceeds from the assumption that the interdependencies of a MaaS system will be examined within the geographical, political and KPI-related boundaries of a European city to find a suitable system boundary for the modelling. While the modelling of the basic model, as in the other supply chain models, is carried out independently of a specific reference, all model parameters are set up in such a way that the model can be easily transferred to a real environment. Quantitative interconnections, basic parameters and type characteristics are initially defined based on justified assumptions in order to be able to develop a generally valid model.

As an overview of various existing quantitative models for MaaS systems with different objectives shows, the interactions of the model can be modelled most realistically by separating the demand and supply sides [56]. Following this approach, on the highest level of the value chain model, demand and supply are the main two elements in the model.

As summarised by [56] different influencing factors exist on both market sides leading to an increased or decreased demand or supply [56]. While the demand side is realized by the (potential) users, the supply side of MaaS offerings is embodied by the mobility service providers and the infrastructure providers behind them. As the research shows, there are influencing factors here that affect both the potential users of the service in a population of residents and the supply side. Another important actor in the value chain impacting the basic foundation and functioning of the system are authorities influencing the market and

the underlying rules itself. As shown in the concept model in Figure 3-23, factors influencing the demand are weather conditions, environmental awareness, the income of potential users, the average travel time of trips, the trust in technology. Other important aspects playing an important role on MaaS-demand are the age and gender distributions, the app performance and the physical service coverage. [56].

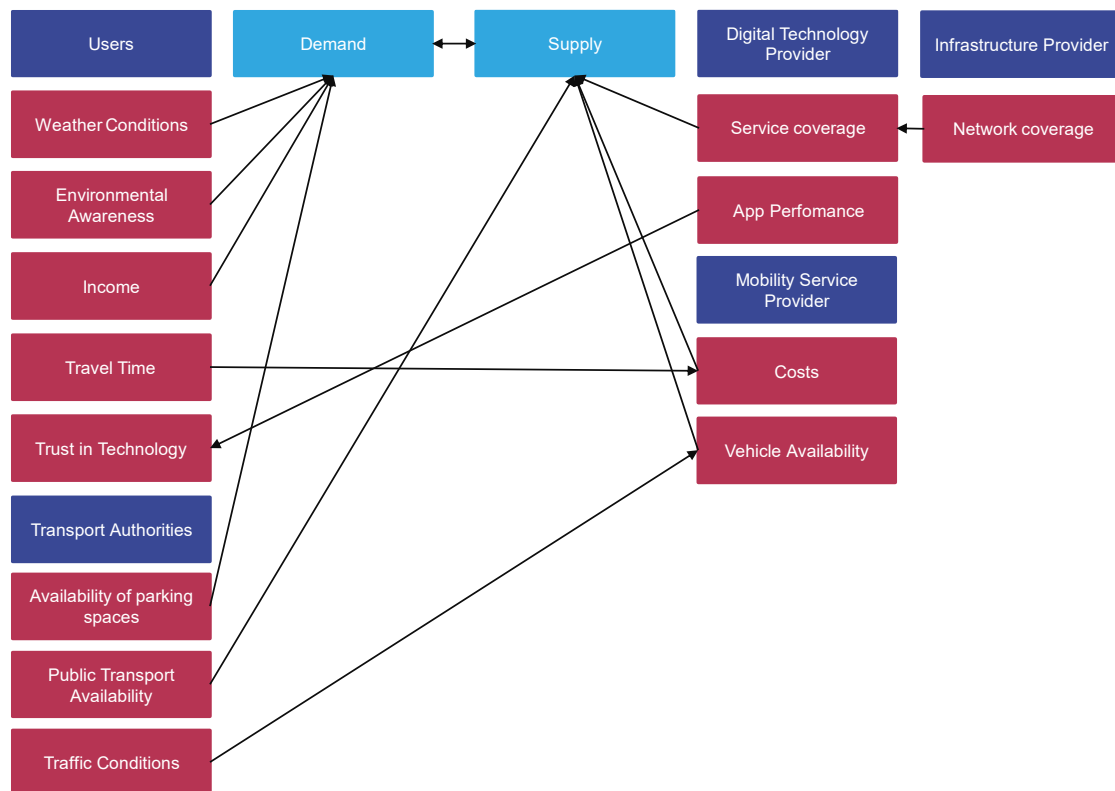


Figure 3-23: MaaS – Concept model

Mobility service providers are defined as digital services combining different MaaS services into one seamless travel and usage experience as described in [57]. The focus of the basic value chain model is the use of transport services with a shared car or an alternative means of transport, such as bicycles or e-scooters.

There is potential for technological advancements and the use of modern technologies within this supply chain, particularly on the supply side, as this is where infrastructures need to be provided, services improved and disruptions intercepted [58].

In order to optimally utilise the potential and strengthen the technological basis, the concept model presented here will be converted into a quantitative model in the following chapter, broken down according to the supply and demand side described above and according to aspects of digital technology.

3.6.2 Implementation

As described in Chapter 2, various tools and methods are suitable for generating quantitative models. Due to the less physical characteristics of the MaaS value chain, which are based more on indirect influencing factors, impact relationships, and market mechanisms, modelling is carried out using the System Dynamics method. A System Dynamics model is developed step-by-step using the VenSim software to quantitatively specify the actors, influencing factors, and relationships and integrate them into a joint model.

In system dynamics models, the system is modelled using stocks, variables, and flows. These different elements describe the states in a system, the influences, and temporal developments.

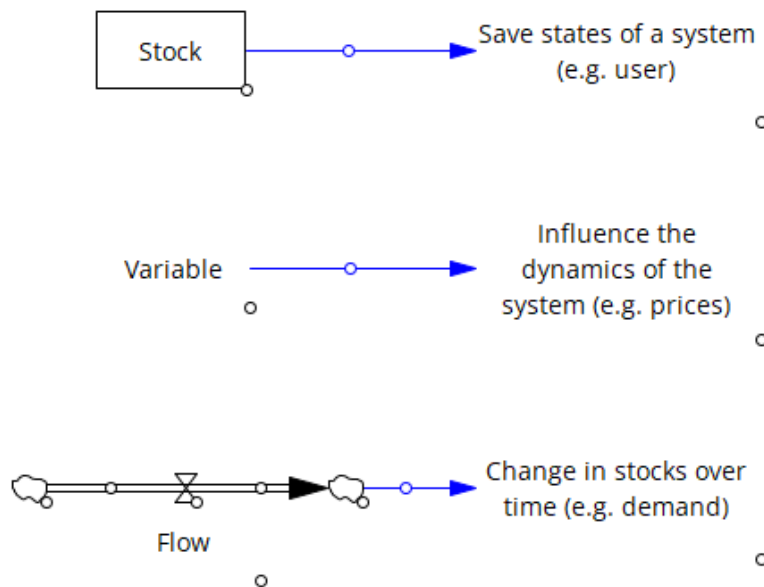


Figure 3-24: System Dynamics modelling – Elements in the model

The complete model is shown in Figure 3-25. Here, the users, the physical fleets, the infrastructure providers (payments and technology) and the other influencing factors are mapped in the model, which can be divided into a supply side and a demand side.

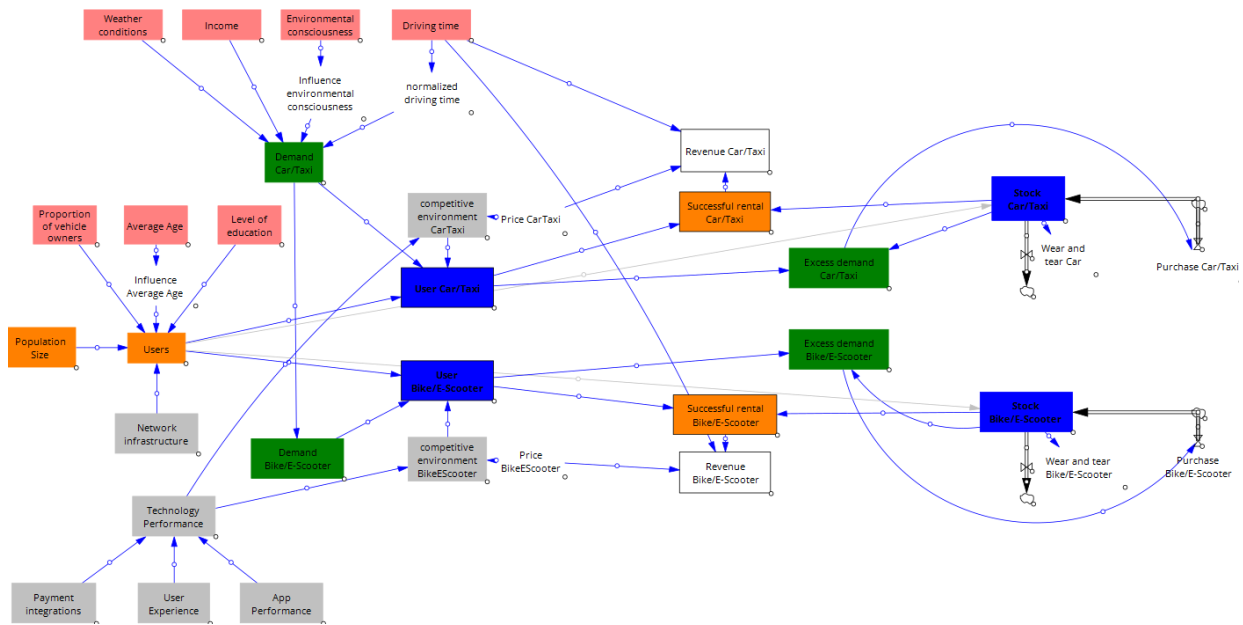


Figure 3-25: Mobility as a service – Model

Demand Side

The demand side of the Mobility as a Service (MaaS) model is shaped by several key factors that influence users' transportation choices. These include environmental consciousness, weather conditions, travel duration, and user income. Together, these variables determine whether individuals opt for cars, taxis or bicycles, e-scooters.

The total number of users in a given area directly impacts the distribution of users among different transportation modes. It is estimated that the number of available vehicles correlates with the total user population, with approximately 100 bicycles or e-scooters per 10,000 inhabitants and 10 vehicles allocated for cars and taxis [59]. This estimation considers factors such as vehicle wear and tear and the potential for new acquisitions when demand exceeds supply.

Successful rentals depend on both the number of users and the availability of transportation options. Revenue generated is influenced by travel duration and pricing. Additionally, demographic and socioeconomic elements, including average age, education level, and the proportion of vehicle owners, affect the overall user population [56].

Demand is approximated through input variables like population size and vehicle ownership rates. The demand for cars and taxis is affected by environmental awareness and economic conditions, while preferences can shift between modes such as bicycles and

e-scooters based on user needs. Following simulations, analysing user distribution across transportation modes provides valuable insights into urban mobility patterns.

The implementation of these logics in the System Dynamics model is presented in Figure 3-26.

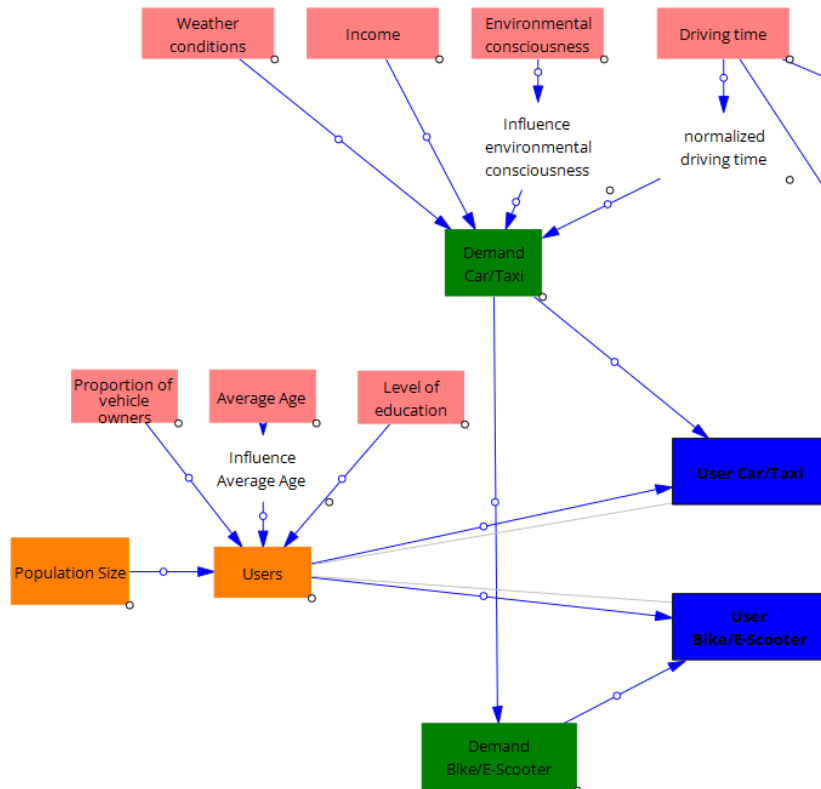


Figure 3-26: Mobility as a service – Demand Side

Supply Side

The supply side of the MaaS model is primarily influenced by the number of vehicles available, which is determined according to the population size. This foundational aspect allows for a systematic calculation of excess demand, identifying the difference between the demand for transportation and the available supply of vehicles.

Dynamic adjustments of vehicle fleets are essential to meet changing demands. When there is excess demand, new vehicles are procured to expand the fleet and ensure adequate service provision. Conversely, as vehicles experience wear and tear, they may leave the fleet, necessitating a careful balance between acquisition and retirement of vehicles to maintain optimal service levels.

The interaction between supply and demand creates various effects, such as bottlenecks when demand outstrips supply and overcapacities when supply exceeds demand. Analysing these dynamics over time helps to understand how supply and demand can balance each other out, leading to more effective fleet management and resource

allocation. The implementation of these logics in the System Dynamics model is presented in Figure 3-27.

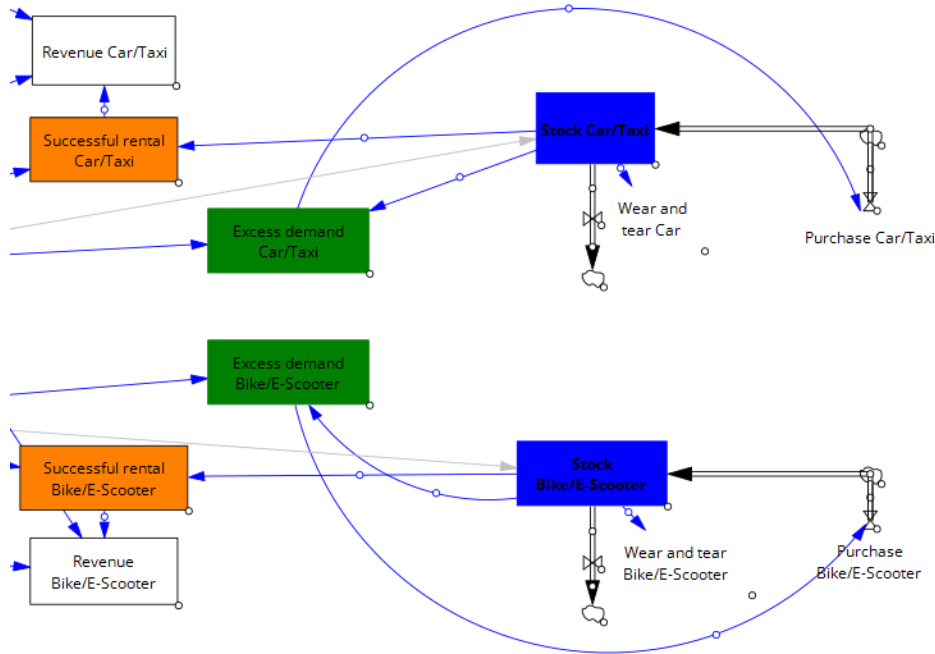


Figure 3-27: Mobility as a service – Supply Side

The combination of demand and supply side results in the final model, as visualised in Figure 3-28.

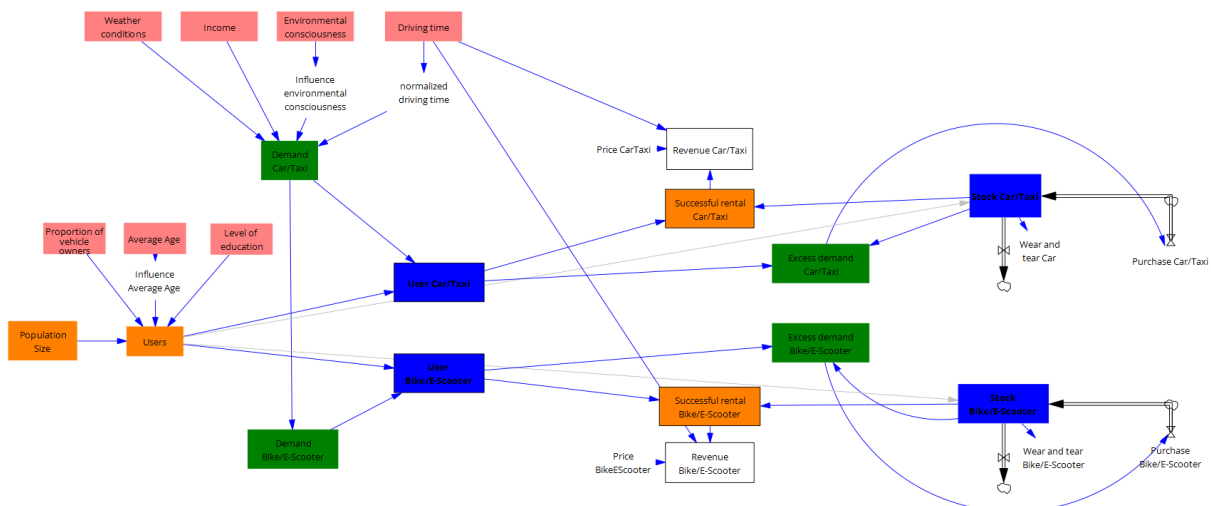


Figure 3-28: Supply- and Demand Side

Impact of digital technologies

The technological performance of the MaaS application (Mobility as a Service) is a decisive factor for success in the competitive environment and has a significant influence that must be considered in the model. Technology performance is determined by three key influencing factors: the integration of payment methods, the user experience and app performance. A failure in one of these areas, for example in payment processing, can lead to a complete collapse in technology performance and thus to a critical bottleneck. As the digital payment system is the only viable option, this leads to a single point of failure, emphasising the need for a robust infrastructure. Reduced technology performance has a direct negative impact on the competitive environment and market presence, as high technology performance creates essential conditions for positive market positioning.

Another aspect of the technological side that influences the number of users is the available network infrastructure. Insufficient network coverage leads to a decline in user numbers, as the app cannot be used without a network. With optimal network coverage, the number of users remains stable and unrestricted.

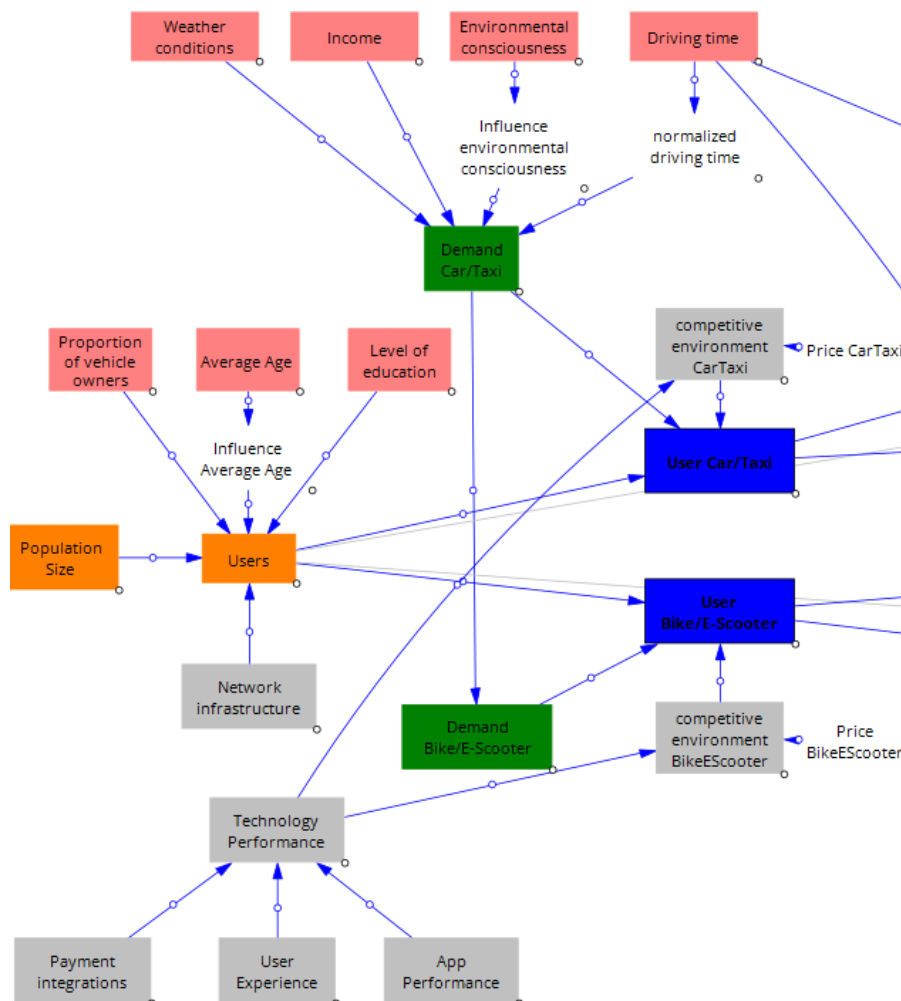


Figure 3-29: Digital Technologies

The infrastructure of both the payment methods and the MaaS app itself therefore plays a key role. The technological foundations and a smoothly functioning payment infrastructure

represent the core aspect of this value chain within the digital ecosystem. Taking potential bottlenecks into account and minimising single points of failure are crucial to ensure the stability and efficiency of the entire system and to strengthen the interdependencies between supply and demand within the MaaS ecosystem.

3.6.3 Results and Evaluation

The aim of the modelling is to simulate and analyse the potential effects of disruptions in the area of Mobility as a Service (MaaS). The investigation of the interactions between different influencing factors and system components contributes to a deeper understanding of the dynamics of the model. The results of the modelling form the basis for the identification of critical influencing factors and derive future strategies for technology-based improvement of the resilience of the value chain in the MaaS system.

A key influencing factor is the integration of payment methods. According to the results of a simulation in which payment integration fails (Payment Integration = 0), technology performance is reduced to a minimum (Technology Performance = 0). It is possible to observe these results in using Technology Performance's causes strip (Figure 3-30). This illustrates the significant role of the payment infrastructure within a MaaS system and the associated risks of a single point of failure. The identification of the causal structures of this relationship is made possible by a root cause analysis.

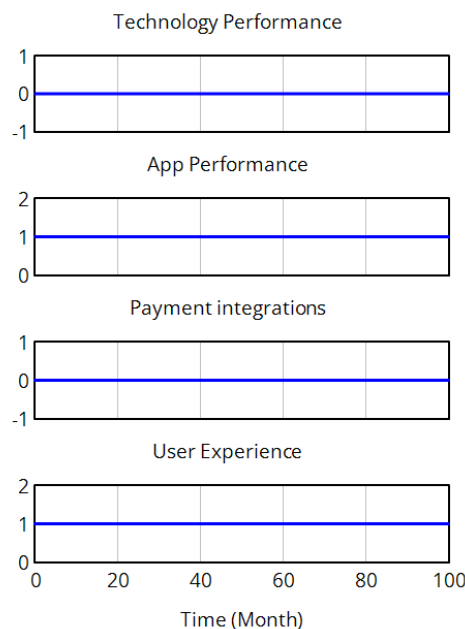


Figure 3-30: Technology Performance

Another influencing factor of significant relevance is network coverage. Insufficient network coverage results in a significant user deficit, which in turn has a negative impact on the demand for transportation services. The simulation of different network conditions

illustrates how user numbers can be influenced by network quality but are also dependent on other factors.

These findings are crucial for the planning of infrastructure measures to support the MaaS system and highlight the need to increase the resilience of the value chain in the MaaS model. These findings form a sound basis for the next step, namely the implementation of disruptions and their effects on the influencing factors and thus on the entire system. Through targeted disruptions, such as sudden changes in demand, technical failures or external economic influences, the system's reactions to changes can be better understood. The identification of critical influencing factors and their interactions enables the development of strategies to minimize the effects of disruptions. Future technological developments should therefore aim to increase the reliability of the payment infrastructure and improve network coverage to ensure a stable user base. The detailed analysis of the influencing factors and causal structures in the Vensim model not only sheds light on the current challenges in the MaaS system but also serves as a basis for strategic decisions to improve system resilience. The visualization of these dynamics enables effective communication of the results and supports the development of robust solutions for future challenges in the digital ecosystem.

4 Conclusion

Based on the methodological findings and developments from Task 2.1, this deliverable summarised the various developed quantitative supply chain models from Work Package 2. For each ecosystem, this deliverable presents the individual development steps as well as the supply chain models that are detailed down to the last node and interact with each other. In addition, the methodology that bundles the entire work package 2, this and the 2 subsequent deliverables, is presented and derived. By comparing the described methodology with the scientific literature, this approach was selected as robust and suitable for the task. The suggested framework includes a step-by-step process for defining the supply chain's scope, choosing relevant factors, collecting necessary data, running simulations, and analysing the results.

The specifically developed SC models can be assessed as representative and complete through validation with expert assessments and quantitative analysis of the functional capability. As part of the modelling in the various ecosystems, a wide variety of diverse types of prototypical reference supply chains were modelled and converted into quantitative SC models. This collection of reference systems provides a basis for the subsequent tasks of the project. The following Chapter 4.1 summarizes and evaluates the results of the first two tasks of WP2. The future interactions with disruptions and technology effects introduced into the basic supply chains are then considered.

4.1 Results and validation of the developed models

The selection of the various supply chains described and modelled within the ecosystems is based on a multi-criteria weighting of several factors. In this deliverable, and as part of the actions outlined in Task 2.2, only one supply chain per ecosystem was developed in detail. Given the high representativeness of the modelled supply chain relationships and the inherent logics of the ecosystems, it is possible to transfer insights to other use cases within the same ecosystem.

The detailed assumptions underpinning the models are derived partly from expert estimates and partly from workshop outcomes. Consequently, all aspects of the modelling—including capacities, throughput times at individual nodes, ordering policies, and geographical locations of suppliers—were established based on these assumptions. This approach is essential for transparently presenting the selected assumptions, as the specifics of the modelled supply chain are crucial for subsequent analyses at this level.

By categorizing and mapping different types of disruptions and their impacts, this research illustrates the dynamic nature of supply chains and highlights the importance of employing robust modelling techniques. The findings indicate that utilizing diverse data types and models is critical for accurately predicting and managing the effects of disruptions. This analysis will also inform the next steps, providing valuable support and guidance for future efforts aimed at enhancing supply chain resilience.

Validation of the supply chain relationships—unaffected by disruptions in the baseline model—was achieved through consultation with technical experts, ensuring a representative depiction of real interdependencies within the model, as far as the chosen

level of abstraction allows. The behaviour of individual nodes in the supply chain in response to specific assumptions can be hypothesized and subsequently evaluated. In future scenario studies, disrupted supply chains and more resilient versions of the supply chain, in conjunction with disruptions, can be compared using relevant key performance indicators (KPIs).

In contrast to the system description and modelling tool support utilized, the MaaS value chain model should be viewed differently from traditional supply chain models. The analysis of system dynamics can also be applied here to investigate system interrelationships within this digital environment and assess potential future disruption influences and technological opportunities. While the granular detail of individual value chain actors is not as critical in this context, accurately quantifying interdependencies will be advantageous when mapping real use cases in future work packages.

4.2 Future integration of disruptions and technology impacts

As described in Deliverable D1.2 [2], specific critical factors act in the various ecosystems, which can materialise in specific disruptions. By further specifying these disruptions from the ecosystem-wide critical factors to supply chain-specific disruptions, these disruptions can be precisely integrated into the SC models and analysed for their full impact. Due to the interdependencies within the supply chains, an integrated view within the models is now essential.

The effects of individual disruptions can – depending on their impact – be integrated into SC nodes or edges of the network at different times. This allows capacities to be reduced, output quantities to be changed or transport times to be varied. Localised disruptions only affect individual parts of the SC, while global disruptions have correspondingly larger effects. Disruptions can also be integrated into the models on both the supply and demand side.

The disruptions per ecosystem identified in Task T2.1, including their direct impact on certain areas of the SC, are analysed in the subsequent impact studies in Task 2.4 and will be described in the upcoming Deliverable D2.3. By describing the probability and general impact of the identified main critical factors, a general risk level can be selected as a rough expected value as a basis for further prioritisation. The corresponding risk matrices are described as the basis for these further considerations in Deliverable D1.2 [2].

Specific disruptions can then be identified for the most significant factors by describing and specifying them in more detail for the individual supply chain. By describing the network nodes affected by such a disruption and the exact effects, the disruptions can be reprioritised to consider the most important disruptions first in the context of the impact analyses, as described methodologically in Chapter 2.3. The impacted KPIs, which are recorded in the supply chain, allow the influences to be quantitatively assessed here. It is precisely the interaction of causal relationships within the SC that makes it crucial to

analyse the specific effects of a disruption in a fully quantitative model and the appropriate KPI measurement [60].

4.3 Outlook and Next steps

The results presented in this deliverable D2.1 describe the procedures and results from tasks T2.1 and T2.2 of the Rise-SME project. These tasks are integrated both into the overall project and into the subsequent tasks of Work Package 2. Together with the technologies researched and described in parallel in Task 2.3 for the technological optimisation of the resilience capabilities of SMEs in Europe, the SC models presented in this report form the basis for further investigations – as those to be conducted in Task 3.2.

As described in the supply chain resilience fit model (see Deliverable D1.1 [1] and Figure 4-1), the project analyses the influences of critical factors in the form of disruptions on supply chain performance and the moderating influences of digital technologies on these impacts. The quantitative supply chain models presented here, the specified disruptions and the technologies described in detail in T2.3, together with their effects and influences, allow various scenarios to be constructed and analysed using the SC resilience fit model.

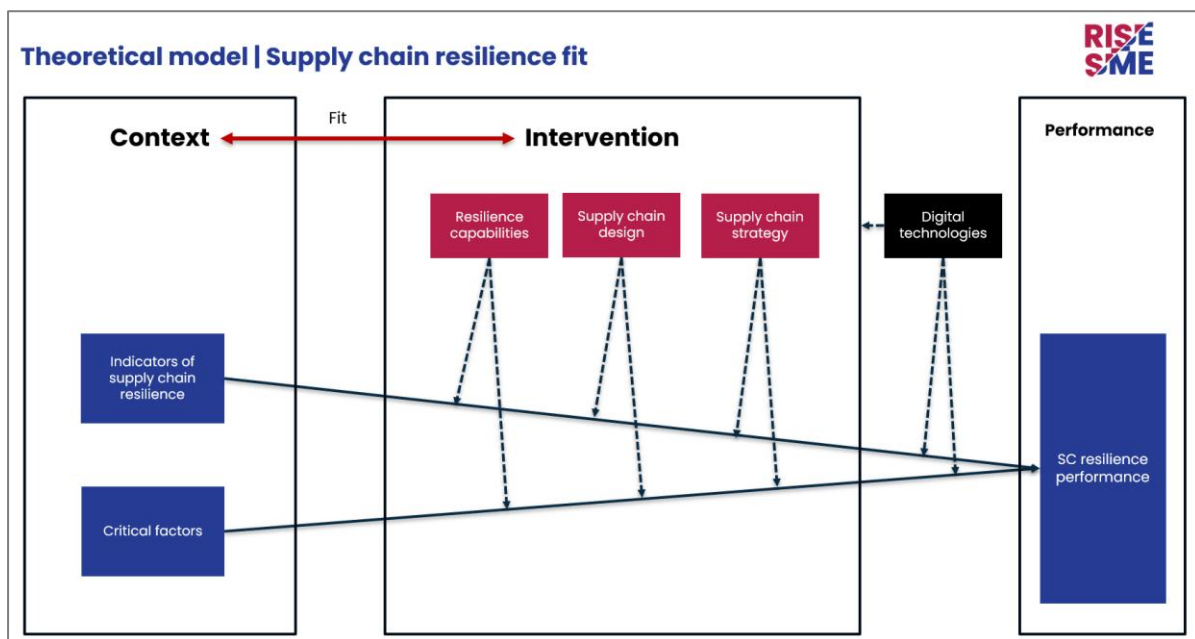


Figure 4-1: Supply chain resilience fit Model (see Deliverable D1.1 for further details [1])

After developing KPI systems in Task T2.4 for measuring supply chain performance in undisrupted supply chains, disrupted supply chains and supply chains that are more resilient with the help of technologies, it is precisely these scenarios that can be modelled and analysed with the adaptable models. These investigations, which are still general and representative here, can then be concretised in concrete industry pilots with real systems as part of Work Package 3 and the knowledge from the investigations can be transferred.

5 Appendix

5.1 Agrifood

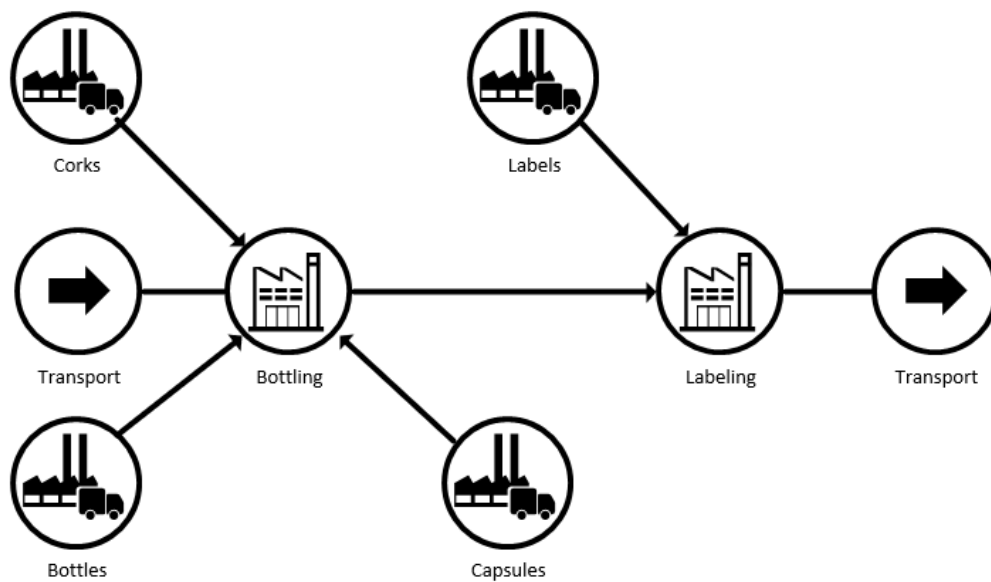


Figure 5-1: Wine Supply Chain – Filling phase

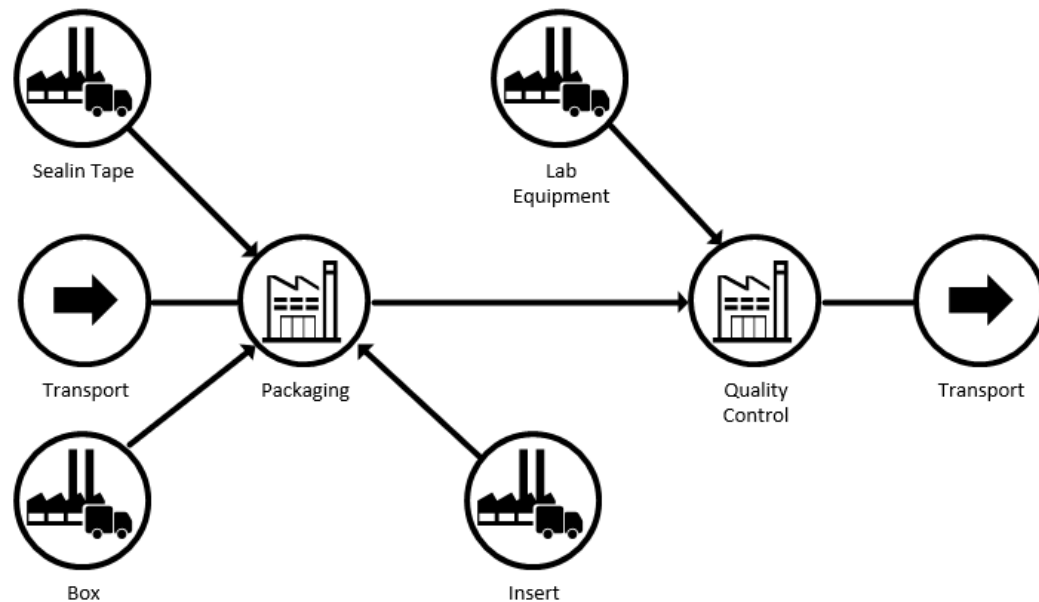


Figure 5-2: Wine Supply Chain – Packaging Phase

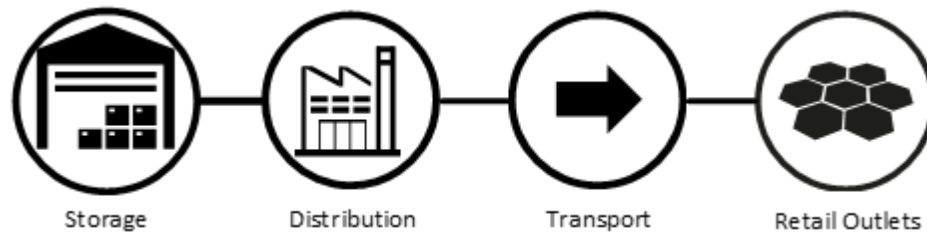


Figure 5-3: Wine Supply Chain – Dispatch Phase

Table 5-1: Wine Supply Chain – Suppliers

Suppliers	Annual Consumption	Delivery Time	Max. Delivery Time	Transport bundling	Location	Batch sizes
Bottles	6.102.536	2 days	2 days	Palletized	Spain	42.224
Boxes	1.092.809	15 days	20 days	Palletized	Spain	2.000
Capsules	5.358.267	30 days	40 days	Palletized	Spain	24.000
Corks	6.775.422	15 days	30 days	Palletized	Spain	24.000
Labels	6.841.028	20 days	30 days	Palletized	Spain	5.000

Table 5-2: Wine Supply Chain – Production Units

Product	Material	Storage Capacity	Production Capacity	Lead Time	Average Production Time	Batch Size	Loss
Grape Harvest	Grapes	25,000 tons	200 tons/day	2 days	1 month	5 tons	5%
Fermentation	Fermentation	40 million L	10,000 L/day	2 weeks	2 weeks	5,000 L	10%
Aging in Oak Barrels	Barrels	20,000 barrels	200 barrels/day	6 months	6 months	10 barrels	2%
Filtration	Filtering	600.000 L	18.000 L/day	1 day	1 day	5.000 L	1%
Filling	Bottle	50.000 bottles	36.000 bottles/day	2 days	1 day	6.500 bottles	0%
Distribution	Warehouse	2.000.000 bottles	25.000 bottles/day	2 weeks	18 days	2.000 bottles	0%

5.2 Mobility

Table 5-3: EV Supply Chain – Transports

From	To	Duration	Means of transport	Capacity	Schedule/ Trigger
Steel factory	Engine factory		Truck	40 tons	On Demand
Steel factory	Transmission Factory		Truck	40 tons	On Demand
Steel factory	Brake Factory		Truck	40 tons	On Demand
Steel factory	Suspension Factory		Truck	40 tons	On Demand
Aluminium Factory	Body Factory		Truck	40 tons	On Demand
Aluminium Factory	Tire Manufacturer		Truck	40 tons	On Demand
Rubber Factory	Electrical Systems Manufacturer	696 h	Schiff	200.000 tons	On Demand
Rubber Factory	Suspension Manufacturer		Truck	40 tons	On Demand
Rubber Factory	Tire Manufacturer	696 h	Ship	200.000 tons	On Demand
Cooper Factory	Electrical Systems Manufacturer		Ship	200.000 tons	On Demand
Engine factory	Assembly	8:30h	Truck	40 tons	On Demand
Transmission Factory	Hamburg Harbor	480h	Ship	200.000 tons	On Demand
Hamburg Harbor	Assembly	5:33h	Truck	40 tons	On Demand
Brake Factory	Assembly	7:17h	Truck	40 tons	On Demand
Suspension Factory	Assembly	4:45h	Truck	40 tons	On Demand
Body Factory	Assembly	0,5h	In house	40 tons	On Demand
Tire Factory	Hamburg Harbor (Tire)	200h	Ship	200.000 tons	On Demand
Electrical Systems Manufacturer	Hamburg Harbor (Electrical)	480h	Ship	200.000 tons	On Demand
Steel Mine	Steel Factory	480h	Ship	200.000 tons	On Demand
Aluminium mine	Aluminium Factory	480h	Ship	200.000 tons	On Demand
Aluminium mine	Refined Aluminium Factory	480h	Ship	200.000 tons	On Demand
Rubber Farm	Rubber Factory	480h	Ship	200.000 tons	On Demand
Copper Mine	Cooper Factory	480h	Ship	200.000 tons	On Demand
Copper Mine	Refined Cooper Factory	480h	Ship	200.000 tons	On Demand
Rare earths Mines	Storage	8h	Truck	40 tons	On Demand
Battery Anode Factory	Battery Factory	50h	Ship	200.000 tons	On Demand
Cathode Factory	Battery Factory	100h	Ship	200.000 tons	On Demand
Cell Casing Factory	Battery Factory	100h	Transport by ship or air	200.000 tons	On Demand
Cell Factory	Battery Factory	50h	Ship	200.000 tons	On Demand

From	To	Duration	Means of transport	Capacity	Schedule/ Trigger
Battery Factory	Assembly	480h	Ship	200.000 tons	On Demand
Refined Lithium Factory	<i>Cathode Factory</i>	480h	Ship	200.000 tons	On Demand
Refined Aluminium Factory	<i>Cathode Factory</i>	80h	Truck	40 tons	On Demand
Refined Nickel Factory	<i>Cathode Factory</i>	120h	Ship	200.000 tons	On Demand
Refined Iron Factory	<i>Cathode Factory</i>	200h	Ship	200.000 tons	On Demand
Refined Manganese Factory	<i>Cathode Factory</i>	50h	Truck	40 tons	On Demand
Refined Cobalt Factory	<i>Cathode Factory</i>	20h	Truck	40 tons	On Demand
Refined Copper Factory	<i>Cell Casing Factory</i>	500h	Ship	200.000 tons	On Demand
Refined Copper Factory	<i>Battery Anode Factory</i>	500h	Ship	200.000 tons	On Demand
Refined Aluminium Factory	<i>Cell Casing Factory</i>	50h	Truck	40 tons	On Demand
Refined Iron Factory	<i>Cell Factory</i>	50h	Ship	200.000 tons	On Demand
Refined Aluminium Factory	<i>Cell Factory</i>	100h	Truck	40 tons	On Demand
Storage	<i>Refined Lithium Factory</i>	600h	Ship	200.000 tons	On Demand
Storage	<i>Refined Nickel Factory</i>	600h	Ship	200.000 tons	On Demand
Storage	<i>Refined Manganese Factory</i>	600h	Ship	200.000 tons	On Demand
Storage	<i>Refined Cobalt Factory</i>	600h	Ship	200.000 tons	On Demand

Table 5-4: EV Supply Chain – Production Units

Product	Production Capacity	Bill of Materials	Schedule/ Trigger	Location
Engine	32 units/day	Steel	On Demand	Győr, Hungary / Shenyang China ZF
Body	32 units/day	Aluminium	On Demand	Neckarsulm
Transmission	32 units/day	Steel	On Demand	Shenyang China ZF
Brake	32 units/day	Steel	On Demand	Viale Europa, 2, 24040 Stezzano BG, Italy
Electric System	32 units/day	Copper, Rubber	On Demand	Tokyo, Japan
Suspension	32 units/day	Steel, Rubber	On Demand	Dielingen (ZF)
Tire	32 units/day	Aluminium, Rubber	On Demand	Ohio
Assembly	32 units/day	Engine, Body, Transmission, Brake, Electrical System, Suspension, Tire, Battery	On Demand	Neckarsulm
Battery Anode	32 units/day	Kupfer	On Demand	China, Wuhan
Cathode	32 units/day	Lithium 3,2%, Nickel 15,7%, Magnesium 5,4%, Cobalt 4,3%, Eisen 2,7%, Aluminium 18,9%	On Demand	Thailand, Bangkok

Cell Casing	32 units/day	Aluminium, Kupfer	On Demand	Cambodia, Phnom Penh
Cell	32 units/day	Aluminium, Steel	On Demand	China, Korea, Japan
Battery	32 units/day	Anode, Cathode, casing, Cell	On Demand	China, Samsung; Panasonic; BYD; LG Energy; Amperex China
Refined Lithium	39.000 tons/Year	Lithium	On Demand	Australia, Perth
Refined Aluminium	7,1mil Tons/year	Aluminium	On Demand	China
Refined Nickel	164.900 tons/year	Nickel	On Demand	Germany: Ettingen
Refined Steel	300.000 tons/year	Iron ore	On Demand	South Korea; Busan
Refined Manganese	200.000 tons/year	Magnesium	On Demand	Afrika
Refined Cobalt	30.000 tons/year	Cobalt	On Demand	China;
Refined Copper	500.000 tons/year	Kupfer	On Demand	Chile

Table 5-5 EV Supply Chain – Sources

Material	kg/unit	Production Capacity	Transport bundling	Schedule/ Trigger	Location	Geo. Koordinaten
Steel	200	300.000 tons/year	Bulk	On Demand	Zhanjiang, Guangdong (Baogang Zhanjiang Iron and Steel Co.)	Long: -43.4174862 Lat: -20.3781468
Aluminium	900	7,1mil Tons/year	Bulk	On Demand	China	Long: 107.49902640625 Lat: 38.61851859679918
Rubber	20	2,3mil Tons/year	Bulk	On Demand	Waldkraiburg	Long: 12.4021839 Lat: 48.2061851
Copper	60	500.000 tons/year	Bulk	On Demand	Santiago Torres, Puchuncaví	Long: -71.4150065 Lat: -32.7259856
Lithium	9,6	39.000 tons/Year	Bulk	Push	Wodgina	Long: 118.6710804 Lat: -21.1912175
Nickel	47,1	164.900 tons/year	Bulk	Push	Central-Sulawes	Long: 120.8088555 Lat: -1.6937786
Manganese	16,2	200.000 tons/year	Bulk	Push	Kalahari Basin	Long: 22 Lat: -23
Cobalt	12,9	30.000 tons/year	Bulk	Push	Kolwezi	Long: 25.4669918 Lat: -10.7169952

5.3 Textile

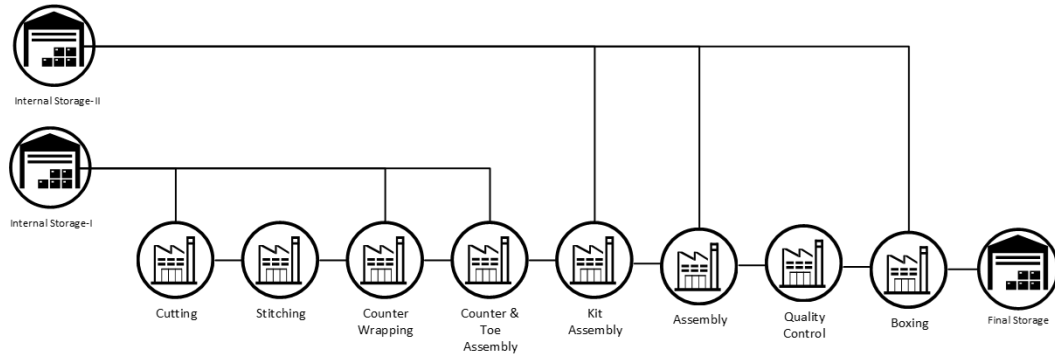


Figure 5-4: Shoe Supply Chain – Production Phase

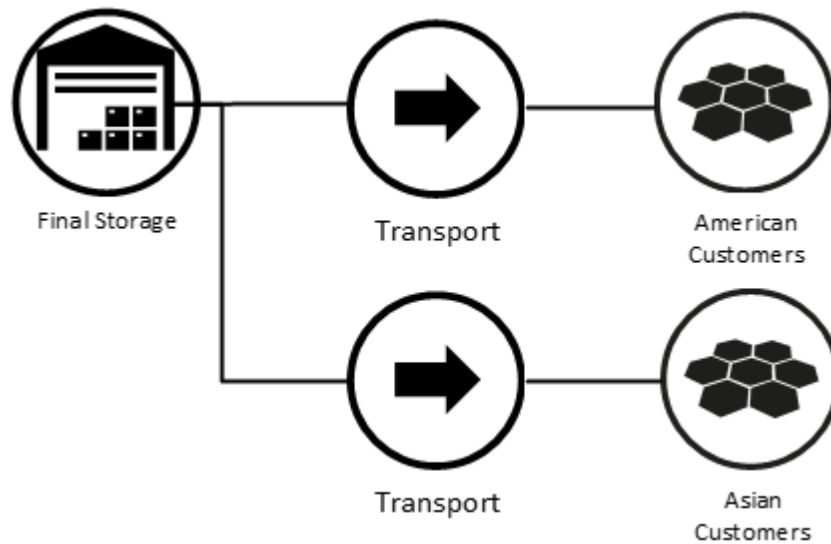


Figure 5-5: Shoe Supply Chain – Dispatch

Table 5-6: Textile Supply Chain – Production Units

Production-Unit-Id	Product	Input Material	Output Material	Stock	Storage Capacity (Days)	Production Capacity	Lead Time to delivery	Average Production Time	Batch Size	Bill of Materials	Number of workers
1	Control Quality	Fabric/leather/ Outsourced materials	Fabric/leather/ Outsourced materials		7	640	3	2	30	Fabric, leather	4
2	Cutting and Skiving	Fabric/leather	Cut fabric/leather	10500	7	384	5	3	30	Cut fabric, leather	4
3	Stitching	Cut fabric, leather, String Lining	Upper	3060	3	960	10	8	20	Upper	20
4	Counter wrapping	Leather, Fabric, Counter	Wrapped Counter	3060	3	274,285714	7	5	20	Wrapped Counter	4
5	Counter and Toe Assembly	Wrapped Counter, Toe, Upper	Assembled Upper	3060	3	288	5	3	20	Assembled Upper	3
6	Assembly Kit preparation	Assembled Upper, Mould, Outsole, Midsole	Assembly Kit	3000	3	137,142857	7	5	20	Assembly Kit	2
7	Shoes Assembly	Assembly Kit	Shoes	3000	3	1371,42857	7	5	20	Shoes	20
8	Finishing	Shoes, Lacing, Insole	Finish Shoes	3000	3	800	12	10	20	Shoes + Lacing	20
9	Quality Control	Finish Shoes	Controlled Finish Shoes	3000	3	288	5	3	20	controlled Finish Shoes	3
10	Boxing	Controlled Finish Shoes, Box	Finish Product	3000	3	800	3	1	20	Finish Product	5

Table 5-7: Textile Supply Chain – Transports

Transport-ID	From	To	Duration	Length	Capacity
1	Supplier 1	Company	1-2 days	10-20km	50-100 tons
2	Supplier 2	Company	1-2 days	10-20km	50-100 tons
3	Supplier 3	Company	1-2 days	10-20km	50-100 tons
4	Supplier 8	Company	1-2 days	10-20km	50-100 tons
5	Supplier 5	Company	1-2 days	10-20km	50-100 tons
6	Supplier 6	Company	1-2 days	10-20km	50-100 tons
7	Supplier 4	Company	1-2 days	10-20km	50-100 tons
8	Supplier 7	Company	1-2 days	10-20km	50-100 tons
9	Supplier 9	Company	1-2 days	10-20km	50-100 tons
10	Company	Customer	1-2 days	10-20km	50-100 tons
11	Storage ID 1	Company	1-2 days	10-20km	50-100 tons
12	Company	Storage ID 1	1-2 days	10-20km	50-100 tons
13	Company	Storage ID 2	1-2 days	10-20km	50-100 tons

14	Storage ID 2	Customer	1-2 days	10-20km	50-100 tons
15	Supplier 10	Company	3-4 days	600-1200 km	50-100 tons
16	Supplier 11	Company	3-4 days	600-1200 km	50-100 tons

Table 5-8: Textile Supply Chain – Demands

Sales Market	Markets (Macro & Countries/ Regions)	Demand specifics (Description)	Demand (pieces a year)	Pieces per order	Frequency of orders (order per week)
1	EU (East, North, South, West)	0,12	25080	525	4
2	Asia (Central, East, South, West)	0,301	62909	2625	2
3	American (NA, Middle, South)	0,5	104500	20200	4
4	mid-east countries	0,079	16511	690	2

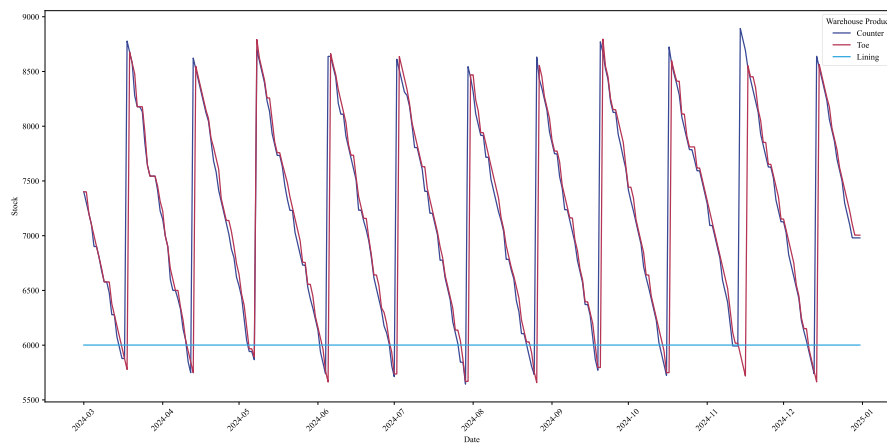


Figure 5-6 Inventory development of selected materials off the first warehouse

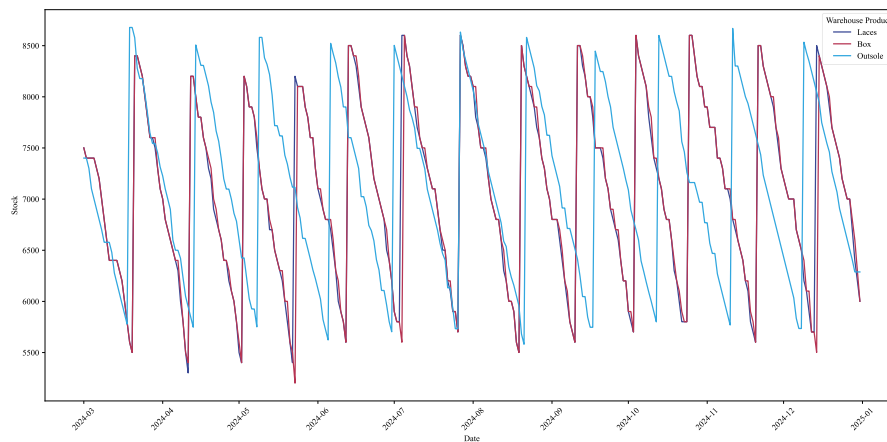


Figure 5-7 Inventory development of selected materials off the second warehouse

6 References

- [1] RISE-SME (2024). *D1.1 Industrial ecosystems and existing risk-driven supply chain models: Report*.
- [2] RISE-SME (2024). *D1.2 Mapping of supply chain models to the industrial ecosystems with readiness and responsiveness measurement analysis: Report*.
- [3] Dmitry Ivanov and Alexandre Dolgui (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control* 32, 9, 775–788. DOI: <https://doi.org/10.1080/09537287.2020.1768450>.
- [4] Armin Jabbarzadeh, Behnam Fahimnia, and Fatemeh Sabouhi (2018). Resilient and sustainable supply chain design: sustainability analysis under disruption risks. *International Journal of Production Research* 56, 17, 5945–5968. DOI: <https://doi.org/10.1080/00207543.2018.1461950>.
- [5] Ramji Nagariya, Subhodeep Mukherjee, Manish M. Baral, and Venkataiah Chittipaka (2024). Analyzing blockchain-based supply chain resilience strategies: resource-based perspective. *IJPPM* 73, 4, 1088–1116. DOI: <https://doi.org/10.1108/IJPPM-07-2022-0330>.
- [6] Rohit K. Singh, Sachin Modgil, and Adam Shore (2024). Building artificial intelligence enabled resilient supply chain: a multi-method approach. *JEIM* 37, 2, 414–436. DOI: <https://doi.org/10.1108/JEIM-09-2022-0326>.
- [7] Balan Sundarakani, Vijay Pereira, and Alessio Ishizaka (2021). Robust facility location decisions for resilient sustainable supply chain performance in the face of disruptions. *IJLM* 32, 2, 357–385. DOI: <https://doi.org/10.1108/IJLM-12-2019-0333>.
- [8] Zahid Hussain (2019). Implementing Monte Carlo simulation model for revenue forecasting under the impact of risk and uncertainty. *Management and Production Engineering Review*. DOI: <https://doi.org/10.24425/mper.2019.131448>.
- [9] Nguyen Tram and Bich Thi (2022). Simulation modeling – An effective method in doing business and management research. *HCMCOUJS – ECONOMICS AND BUSINESS ADMINISTRATION* 12, 1, 108–124. DOI: <https://doi.org/10.46223/HCMCOUJS.econ.en.12.1.1916.2022>.
- [10] Ruiying Li, Qiang Dong, Chong Jin, and Rui Kang (2017). A New Resilience Measure for Supply Chain Networks. *Sustainability* 9, 1, 144. DOI: <https://doi.org/10.3390/su9010144>.
- [11] Kai Gutenschwager, Markus Rabe, Sven Spieckermann, and Sigrid Wenzel (2017). *Simulation in Produktion und Logistik*. Springer Berlin Heidelberg, Berlin, Heidelberg.
- [12] Sigrid Wenzel (2018). Simulation logistischer Systeme. In *Modellierung logistischer Systeme*, Horst Tempelmeier, Ed. Fachwissen Logistik. Springer Vieweg, Berlin, Heidelberg, 1–34. DOI: https://doi.org/10.1007/978-3-662-57771-4_1.
- [13] Stewart Robinson (2004). *Simulation: The practice of model development and use*. Wiley, Chichester.

- [14] VDI . *Simulation of systems in materials handling, logistics and production – Fundamentals*, VDI 3633 Blatt 1, 2014. Retrieved from.
- [15] Yingfang Li, Xingxing He, Luis Martínez, Jiafeng Zhang, Danchen Wang, and Xueqin A. Liu (2024). Comparative analysis of three categories of multi-criteria decision-making methods. *Expert Systems with Applications* 238. DOI: <https://doi.org/10.1016/j.eswa.2023.121824>.
- [16] Amr Arisha and Waleed Abo-Hamad (2010). Simulation Optimisation Methods in Supply Chain Applications: a Review.
- [17] Lukas Schoenenberger, Alexander Schmid, Radu Tanase, Mathias Beck, and Markus Schwaninger (2021). Structural Analysis of System Dynamics Models. *Simulation Modelling Practice and Theory* 110. DOI: <https://doi.org/10.1016/j.simpat.2021.102333>.
- [18] George P. Richardson (2011). Reflections on the foundations of system dynamics. *System Dynamics Review* 27, 3, 219–243. DOI: <https://doi.org/10.1002/sdr.462>.
- [19] Evripidis P. Kechagias, Dimitrios M. Miloulis, Georgios Chatzistelios, Sotiris P. Gayialis, and Georgios A. Papadopoulos (2021). Applying a System Dynamics Approach for the Pharmaceutical Industry: Simulation and Optimization of the Quality Control Process. *WSEAS TRANSACTIONS ON ENVIRONMENT AND DEVELOPMENT* 17, 983–996. DOI: <https://doi.org/10.37394/232015.2021.17.91>.
- [20] Antuela A. Tako and Stewart Robinson (2012). The application of discrete event simulation and system dynamics in the logistics and supply chain context. *Decision Support Systems* 52, 4, 802–815. DOI: <https://doi.org/10.1016/j.dss.2011.11.015>.
- [21] OECD (2021). *Strengthening Economic Resilience Following the COVID-19 Crisis*. OECD Publishing.
- [22] Markus Rabe, Sven Spieckermann, and Sigrid Wenzel (2008). *Verifikation und Validierung für die Simulation in Produktion und Logistik: Vorgehensmodelle und Techniken*. . Springer, Berlin, Heidelberg.
- [23] José Díaz-Reza, Jorge García-Alcaraz, Valeria Martínez-Loya, Liliana Avelar-Sosa, Emilio Jiménez-Macías, and Julio Blanco-Fernández (2018). Impact of Infrastructure and Production Processes on Rioja Wine Supply Chain Performance. *Sustainability* 10, 1, 103. DOI: <https://doi.org/10.3390/su10010103>.
- [24] Franco Basso, Juan P. Contreras, Raúl Pezoa, Alejandro Troncozo, and Mauricio Varas (2023). Optimizing the wine transportation process from bottling plants to ports. *Oper Res Int J* 23, 2. DOI: <https://doi.org/10.1007/s12351-023-00778-6>.
- [25] Fernanda A. Garcia, Martin G. Marchetta, Mauricio Camargo, Laure Morel, and Raymundo Q. Forradellas (2012). A framework for measuring logistics performance in the wine industry. *International Journal of Production Economics* 135, 1, 284–298. DOI: <https://doi.org/10.1016/j.ijpe.2011.08.003>.
- [26] R. Šperková and H. Hejmalová (2011). Suppliers in the Wine Sector. *Acta univ. agric. et silvic. Mendel. Brun.* LIX, 7, 439–446.

- [27] S. Dubey, Rajeev Singh, Swatendra P. Singh, Mishra, Abhishek, and Nikhil V. Singh (2020). A brief study of value chain and supply chain. *Agriculture Development and Economic Transformation in Global Scenario*, 177–183.
- [28] Céline Abecassis-Moedas (2006). Integrating design and retail in the clothing value chain. *IJOPM* 26, 4, 412–428. DOI: <https://doi.org/10.1108/01443570610650567>.
- [29] Gary Gereffi (1994). The organization of buyer-driven global commodity chains: How US retailers shape overseas production networks.
- [30] Seyda Serdarasan (2013). A review of supply chain complexity drivers. *Computers & Industrial Engineering* 66, 3, 1–8. DOI: <https://doi.org/10.1016/j.cie.2012.12.008>.
- [31] Kevin Turner and Geoff Williams (2005). Modelling complexity in the automotive industry supply chain. *Journal of Manufacturing Technology Management* 16, 4, 447–458. DOI: <https://doi.org/10.1108/17410380510594525>.
- [32] Gerrit Remane, Björn Hildebrandt, Andre Hanelt, and Lutz M. Kolbe (2016). Discovering new digital business model types—a study of technology startups from the mobility sector.
- [33] Wen Wang, Weiping Fu, Hanlin Zhang, and Yufei Wang (2013). Hybrid modeling and simulation of automotive supply chain network. *Research Journal of Applied Sciences, Engineering and Technology* 6, 9, 1598–1605.
- [34] Bart L. MacCarthy, Wafaa A. Ahmed, and Guven Demirel (2022). Mapping the supply chain: Why, what and how? *International Journal of Production Economics* 250, 108688. DOI: <https://doi.org/10.1016/j.ijpe.2022.108688>.
- [35] N. Suthikarnnarunai (2008). Automotive supply chain and logistics management. *Proceedings of the International MultiConference of Engineers and Computer Scientists 2008 Vol II* 2.
- [36] Huanyu Ren, Dong Mu, Chao Wang, Xiongping Yue, Zhenglong Li, Jianbang Du, Longfeng Zhao, and Ming K. Lim (2024). Vulnerability to geopolitical disruptions of the global electric vehicle lithium-ion battery supply chain network. *Computers & Industrial Engineering* 188, 109919. DOI: <https://doi.org/10.1016/j.cie.2024.109919>.
- [37] E. Söderbaum (2008). Requirements for automotive textiles – a carproducer’s view. In *Textile Advances in the Automotive Industry*, Roshan Shishoo, Ed. Woodhead publishing in textiles, 79. Elsevier; CRC Press; Woodhead, Boca Raton, Fla., Cambridge, 3–16. DOI: <https://doi.org/10.1533/9781845695040.1.3>.
- [38] Ben Jones, Robert J. R. Elliott, and Viet Nguyen-Tien (2020). The EV revolution: The road ahead for critical raw materials demand. *Applied energy* 280, 115072. DOI: <https://doi.org/10.1016/j.apenergy.2020.115072>.
- [39] Harsha Walvekar, Hector Beltran, Shashank Sripad, and Michael Pecht (2022). Implications of the Electric Vehicle Manufacturers’ Decision to Mass Adopt Lithium-Iron Phosphate Batteries. *IEEE Access* 10, 63834–63843. DOI: <https://doi.org/10.1109/ACCESS.2022.3182726>.

- [40] Anahita Jannesar Niri, Gregory A. Poelzer, Steven E. Zhang, Jan Rosenkranz, Maria Pettersson, and Yousef Ghorbani (2024). Sustainability challenges throughout the electric vehicle battery value chain. *Renewable and Sustainable Energy Reviews* 191, 114176. DOI: <https://doi.org/10.1016/j.rser.2023.114176>.
- [41] Yusoon Kim, Yi-Su Chen, and Kevin Linderman (2015). Supply network disruption and resilience: A network structural perspective. *J of Ops Management* 33–34, 1, 43–59. DOI: <https://doi.org/10.1016/j.jom.2014.10.006>.
- [42] Saskia Sardesai and Katja Klingebiel (2023). Maintaining viability by rapid supply chain adaptation using a process capability index. *Omega* 115, 102778. DOI: <https://doi.org/10.1016/j.omega.2022.102778>.
- [43] C. M. Harland (1996). Supply Chain Management: Relationships, Chains and Networks. *British J of Management* 7, sl. DOI: <https://doi.org/10.1111/j.1467-8551.1996.tb00148.x>.
- [44] Helena Carvalho, Ana P. Barroso, Virgínia H. Machado, Susana Azevedo, and V. Cruz-Machado (2012). Supply chain redesign for resilience using simulation. *Computers & Industrial Engineering* 62, 1, 329–341. DOI: <https://doi.org/10.1016/j.cie.2011.10.003>.
- [45] Robert L. Bray and Haim Mendelson (2015). Production Smoothing and the Bullwhip Effect. *M&SOM* 17, 2, 208–220. DOI: <https://doi.org/10.1287/msom.2014.0513>.
- [46] Rachel Croson and Karen Donohue (2006). Behavioral Causes of the Bullwhip Effect and the Observed Value of Inventory Information. *Management Science* 52, 3, 323–336. DOI: <https://doi.org/10.1287/mnsc.1050.0436>.
- [47] Hau L. Lee, V. Padmanabhan, and Seungjin Whang (2004). Information Distortion in a Supply Chain: The Bullwhip Effect. *Management Science* 50, 12_supplement, 1875–1886. DOI: <https://doi.org/10.1287/mnsc.1040.0266>.
- [48] Hans-Christian Pfohl and Xin Shen (2008). Apparel supply chain between Europe and China. *A Guide to Apparel Sourcing and Distribution in China*. Darmstadt.
- [49] Laura Macchion, Rosanna Fornasiero, and Andrea Vinelli (2017). Supply chain configurations: a model to evaluate performance in customised productions. *International Journal of Production Research* 55, 5, 1386–1399. DOI: <https://doi.org/10.1080/00207543.2016.1221161>.
- [50] Eurostat (2024). *Eurostat: Micro & small businesses make up 99% of enterprises in the EU* (2024). Retrieved from <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20241025-1>.
- [51] Euronews (2024). *Euronews: EU SMEs well behind on digitalisation, Eurostat report finds* (2024). Retrieved from <https://www.euronews.com/my-europe/2024/11/14/eu-smes-well-behind-on-digitalisation-eurostat-report-finds>.
- [52] Maas-alliance . *Maas-alliance*. Retrieved from <https://maas-alliance.eu/>.
- [53] MarketsAndMakers (2022). *Mobility as a Service Market Size, Share, Analysis, Report, 2030: Mobility as a Service Market by Service (Ride-Hailing, Car Sharing, micro-*

- mobility, Bus, Train), Solution, Transportation, Vehicle, OS, Business Model, Payment (Subscription, PAYG), Commute (Daily, Last Mile, Occasional) Region - Global Forecast to 2030 (2022)*. Retrieved from https://www.marketsandmarkets.com/Market-Reports/mobility-as-a-service-market-78519888.html?utm_source=chatgpt.com.
- [54] FLUCTUO (2024). *European Shared Mobility: Annual Review 2024 (2024)*. Retrieved from <https://european-index.fluctuo.com/>.
- [55] RISE-SME . *RISE-SME*. Retrieved from <https://rise-sme.eu/>.
- [56] Sylvain Daou and Fabien Leurent (2024). Modelling mobility as a service: A literature review. *Economics of Transportation* 39, 100368. DOI: <https://doi.org/10.1016/j.ecotra.2024.100368>.
- [57] Vincent A. van den Berg, Henk Meurs, and Erik T. Verhoef (2022). Business models for Mobility as an Service (MaaS). *Transportation Research Part B: Methodological* 157, 203–229. DOI: <https://doi.org/10.1016/j.trb.2022.02.004>.
- [58] Sara Paiva, Mohd A. Ahad, Gautami Tripathi, Noushaba Feroz, and Gabriella Casalino (2021). Enabling Technologies for Urban Smart Mobility: Recent Trends, Opportunities and Challenges. *Sensors (Basel, Switzerland)* 21, 6. DOI: <https://doi.org/10.3390/s21062143>.
- [59] Statista (2023). *Anzahl Der Fahrzeuge Verschiedener Shared-mobility-angebote In Ausgewählten Städten In Deutschland Im Jahr 2022 (Pro 10.000 Einwohner) (2023)*. Retrieved April 25, 2025 from <https://de.statista.com/statistik/daten/studie/1537381/umfrage/shared-mobility-angebote-in-staedten-deutschland/>.
- [60] Lukas Fleisch and Oliver von Dzengelevski (2024). Supply chain resilience and international manufacturing strategy: a case study from the semiconductor industry. *Journal of Manufacturing Technology Management*.