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Resilient Industrial Systems
A Complex System Perspective to Support Business Decisions

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Gerben Bas

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PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
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door

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Keywords: adaptation, agent-based modelling, business decision assessment, complex adaptive systems, industrial systems, market dynamics, resilience, system perspective

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I think life on Earth must be about more than just solving problems... It's got to be something inspiring, even if it is vicarious.

—Elon Musk, *Making Humans a Multiplanetary Species*

Acknowledgements

This thesis marks the end of a four year period that I would like to summarise as 'fun with agent-based models'. Fun, because I think that an important aspect of life (which for four years was largely consumed by my research) is to enjoy oneself; and agent-based models, because the main reason to do this project was that it got to develop and experiment with agent-based models. Even though I did not intent to get a PhD at first, I enjoyed myself so much that I continued the fun for four years with the doctorate as a bonus. In those four years, I learned so much more than I could write down in this thesis (sorry to disappoint you, but this thesis is just a mere reflection of the actual insights I obtained). Most of all, I learned about myself. Not just that I can be an expert at some things, but also that I have my limitations and that it is okay to have those and acknowledge them.

Although I am the sole author of this thesis, I did not do (and could not have done) the work presented here all by myself. First and foremost, I would like to thank my promotors and supervisors for their guidance and support during my research. Paulien, Telli, and Igor, you gave me the freedom and confidence to direct the focus of my research and arrange the details of execution. In times of setbacks, you were available to discuss those and how to proceed, or just drink a cup of tea. And off course, your feedback on my research proposals, experimental designs, draft papers, presentations, and thesis has been invaluable. Thank you for your time, effort, and confidence.

As researchers, we are the product of our environment. I have been fortunate that this environment consisted of my colleagues at the E&I section. I will always remember the lunch discussions (which on Fridays tended to escalate), the chats at (i.e., the complaining about) the coffee machine, and the insights into different cultures and mindsets you provided. Especially, Joolie has been the best office-mate anyone could wish for: always ready to help and in for a bit of fun. Your strong opinion about many subjects often challenged me and forced me to keep overthinking my own research. You truly shaped my thinking.

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Last but not least, I want to thank my family. You accepted that I spent four years on my life on something that was nearly impossible to explain on birthday parties. I do not imagine that this thesis is going to clarify that completely, so let's agree that I did something with computers. Special thanks goes to Marleen. You had to deal with a boyfriend that worked in the weekends, could be mentally absent, and sometimes frustrated by the apparent lack of progress. Your presence at home helped me distract my thoughts away from my research. In that sense, you positively influenced my research to a greater extent than you are probably aware of. Thank you for your support.

Gerben Bas
Sliedrecht, June 2017

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Chapter 1

Introduction

1.1 Industrial systems

A network of autonomous entities The vast majority of goods and services we use in our modern day lives are not produced by ourselves. And even if we wanted to, it would be practically impossible to manufacture even one all by ourselves. With his toaster project, Thwaites (2012) illustrates the effort involved with the construction of a 'simple' device such as a toaster. Even though he spends nine months, over € 1,350 , and cheats by using some modern day tools, Thwaites does not succeed in constructing a toaster that is as good as one that can be bought for about € 10 to € 20 in basically any electronics store. Long before Thwaites's undertaking it had already been argued that even simpler objects, like a pencil, cannot be produced by a single person, but require the involvement and know-how of millions of people (Read, 1958).

Pencils, toaster, and much more complicated goods are brought into our lives through *industrial systems*: vast global networks of technical artefacts and social elements involved in the manufacturing of goods (Johanson and Mattsson, 1987). Even though industrial activities are not limited to manufacturing (United Nations Statistics Division, 2016), this thesis focuses on industrial systems that manufacture goods. So, the term industrial system is used in this thesis to indicate a manufacturing industrial system – i.e., an industrial system that manufactures goods.

The technical artefacts in an industrial system are those artefacts that are used to manufacture goods; for instance, conveyor belts, robots, reactors, or heat exchangers. Each artefact executes operations on the goods to change their properties. The artefacts are usually organised into plants that use one or more types of good (i.e., feedstock) and convert those – through the operations of its artefacts – to one or more other types of good (i.e., products). Through the flow of goods, the artefacts (within and between plants) are connected and form a network that manufactures a particular end-product.

The social elements of an industrial system are the organisations, laws, institutions, and people that arrange the manufacturing of goods. In today's world, most manufacturing activities are organised by manufacturing companies, which therefore play a major role in industrial systems. Companies invest in technical artefacts, operate those artefacts, negotiate with other companies on the purchase and sale of goods, and organise people to perform tasks. Consequently, the social elements in an industrial system are connected with each other through information flows, contractual arrangements, market interactions, and personal relationships. Moreover, by owning and operating technical artefacts, the social elements are also connected to the technical artefacts. This makes the industrial system a tightly interconnected network of both social and technical entities: a socio-technical system. (Bijker et al., 1987)

The manufacturing of goods in an industrial system is not controlled by a central or external agency that plans the operations of all entities in the system (Johanson and Mattsson, 1987). The opposite is true: each manufacturing company operates autonomously and pursues its own objectives, within its limited span of control and the context of its environment. The interactions among the companies align their self-interested behaviour, so that they collectively succeed in the complex task of manufacturing a good and supplying it in the right quantity, for the right price, to the right person. Hence the behaviour of an industrial system emerges from autonomous actions of manufacturing companies and the interactions among them. The mechanism that drives this emergence has been referred to as the market's invisible hand (Read, 1958; Smith, 1776).

An industrial system is not static, but changes over time. Regarding those changes, we can distinguish two different types. On the one hand, there is are the topological changes, which concern the changes to the system's structure – i.e., the addition or removal of entities or their connections. For instance, companies are founded, new facilities come online, and novel products and processes are introduced (e.g., the development of the chemical industry, recorded in Aftalion, 2005). All those changes are 'tested' by the market; if they work others copy them, and if they do not work they are discarded (Schumpeter, 1942). On the other hand, within the context of the structure, the properties of the system's entities and connections change. This is referred to as the operational changes and concern the changes such as a new inventory policy of a company, a changed production rate of a facility, or changing shipments of goods between facilities. Both types of changes are caused by actions of individual entities, which – through the relations of the entities – can influence the system as a whole.

As a consequence of those properties, an industrial system is a highly complex system (Choi et al., 2001). It consists of many interacting and interconnected autonomous entities that are continuously adapting, while new entities are added and old entities are removed. As a result of this complexity, it is difficult – if not impossible – to predict the development of the industrial system. For manufacturing companies, this implies that they are operating in a highly complex environment that is very difficult to comprehend. As a company is influenced by developments in its environment, that company's inability to comprehend its environment may degrade its operations and performance (Fowler, 2003).

Efficiency and stability The manufacturing companies in industrial systems differ considerably, depending on the type of operations they perform. However, there are general patterns with regard to the manufacturing companies and how they arrange their operations that we see throughout the industrial systems.

- Due to the physical properties of their production process or to optimise their efficiency, many manufacturing companies operate large facilities. Those facilities require high capacity utilisation rates to operate, cannot be shut down easily, and operate efficiently under a limited range of circumstances (Seifert et al., 2012). However, once the circumstances fall outside that range, the efficiency of those facilities deteriorates quickly (Seifert et al., 2014).

- Many companies are locally optimising their own system, without accounting for their interconnectedness to the remainder of the industrial system (Shah, 2005). Only in recent years – due to the increased attention for supply chain management – companies have started to consider entities outside their direct span of control (Ibrahimov et al., 2009; Simchi-Levi et al., 2005). However, this is usually still limited to their existing supply chain and disregards large parts of the industrial system.

- The decisions of many industrial companies are executed through centralised top-down control (Martin, 2006; Mintzberg, 1993). The optimised operations leave little room for error and, therefore, companies try to reduce uncertainties. Consequently, there is little autonomy within the company and companies are hesitant to break down the walls around their business and cede some of the control to other companies, in the form of collaborations (Hughes, 2008).

- The relationships between companies are often specified in long-term contracts in order to promote stability in the industrial system (Zheng et al., 2007). Those long-term contracts provide companies with relative certainty about the supply of feedstock and the sale of product. This enables them to optimise their operations for a longer period of time, with the objective of meeting those contracts.

A consequence of this way of operating is that over time the industrial system has become highly efficient and optimised, but less resilient to shocks (Korhonen and Seager, 2008; Zhu and Ruth, 2013). As resilience is costly while business continues as usual (Sheffi and Rice Jr, 2005), resilient companies cannot compete with efficient companies as long as the industrial system operates as expected. Consequently, the industrial system is entrenched in the 'stability/efficiency' thinking, forcing all manufacturing to strive for efficiency and stability.

Developments in the industrial system In recent years, there have been some developments in and around industrial systems that may not go well with the highly efficient and optimised industrial systems. Whereas efficient systems thrive under stability and predictability, some recent developments point in the exact opposite direction: volatility and sudden developments. Examples of those developments are:

- *Volatile feedstock availability* The scarcity of natural resources and the transition from petroleum to bio-based raw materials makes the supply of feedstock more volatile and less predictable. Scarce resources can be part of geopolitical developments and their availability and price can change substantially due to developments external to the industrial system (Butts, 2014). Due to the use of bio-based materials rather than petroleum as a raw material, the availability of raw materials also becomes more dependent of the weather (Langeveld et al., 2012). Harvests can be destroyed in a single day due to extreme weather, thereby suddenly destroying a part of the raw materials supply. As climate change is anticipated to increase the frequency and severity of extreme weather events (IPCC, 2012), weather-induced supply chain disruptions are more likely to occur (Gledhill et al., 2013).

- *Increasing market volatility* The duration of contracts has slowly decreased (Franza, 2014). Under the influence of increased competition, relationships among companies have become less stable and companies thus need to participate in the market more often to buy and or sell goods. Consequently, their operations are influenced more and more often by market developments (e.g., changing prices).

- *Agile production concepts* Technological developments have led to the materialisation of new technologies that enable different ways of operating and may influence the industrial system considerably (Lier et al., 2013). New relatively small-scale production facilities (annual production capacity ranging between 1 and 2,000 metric tonne (mt) (Bieringer et al., 2013)) allow new companies to enter the industrial system more easily, which increases competition in the industrial system and thus poses a threat to the incumbent companies (Porter, 1979). Combined with their relative ease of relocation, the introduction of those new production facilities may cause the system's structure to change more often. The use of process intensification principles enables some of those new production facilities to produce intermittently (Bieringer et al., 2013), which may increase the volatility of the supplied volumes of goods.

- *Inventory reduction* Due to new supply chain management practices, such as just-in-time and lean manufacturing, the inventories are being reduced (Hofer et al., 2012). Inventories disconnect the operations of different companies and thus tend to stabilize the industrial system (Wisner et al., 2012). Reduction of those inventories thus may increase the industrial system's dynamics.

- *Shortened life cycles* Product life cycles are getting shorter (Lier et al., 2013). Whereas companies could produce a particular product over a long period, they nowadays need to change their operations or replace their technical artefacts more often in order to produce new products (Horn, 2012). As this replaces entities in the industrial system and changes connections between the entities, this can change the structure of the industrial system substantially.

The consequence of these developments is that industrial systems change more and more often – i.e., become more volatile (Christopher, 2000; Tukamuhabwa et al., 2015). Some of the developments increase the industrial systems' dynamics, by removing buffers between companies and increasing the influence of market developments on the companies' operations. Other developments lead to more changes to the industrial system's structure and thus accelerate the topological changes. The manufacturing companies thus operate in an environment that is highly complex, but that is also becoming increasingly volatile.

1.2 Challenges for manufacturing companies

Limited resilience of manufacturing companies The increased volatility of the industrial system challenges the 'efficiency/stability' paradigm of the manufacturing companies (Lee, 2004). Therefore, manufacturing companies may benefit from changing their paradigm to one that is more resilience oriented (Hamel and Valikangas, 2003). Resilient companies have the capacity to continuously anticipate and adjust to changes in their environment without compromising their performance (Hamel and Valikangas, 2003). In this thesis, we distinguish between agility and adaptability (Lee, 2004). Agility is the ability to quickly respond to changes in demand or supply – i.e., the operational changes in the industrial system. Those operational changes are changes in the industrial system that are directly related to the operations of the manufacturing companies, such as changing material flows and prices of exchanged goods. Adaptability, on the other hand, is the ability to adapt over time to structural shifts in markets – i.e., the topological changes in an industrial system. Those topological changes are changes in the industrial system that involve changes in the structure of industrial system: the (properties of the) manufacturing companies and their interconnections. The current paradigm of most manufacturing companies limits their resilience: the large facilities often have limited tolerance to make adjustments, nor are they quickly replaced; the centralised decision-making tends to be relatively slow; and the long-term relationships between companies often require extensive negotiations to be changed. On multiple occasions, the limited resilience of companies has gotten them into trouble and even caused them to end their business (e.g., Birkinshaw, 2013; Johnson, 2011).

To develop the resilience needed to thrive in a volatile industrial system, manufacturing companies need to alter their business by making the right business decisions. We define a *business decision* as the selection of an action that affects the company's primary activities: inbound logistics, operations, outbound logistics, marketing and sales, and service (Cyert et al., 1956; Porter, 1985). To select the most attractive action, companies need to assess the consequences of the potential actions. The value of enhanced resilience (caused by an action) depends to a large extent on the developments in the company's environment. In a stable environment, resilience has no added value, while it can be very valuable in a volatile environment. Therefore, the assessment of actions that can enhance the company's resilience needs to account for the influence of the environment on the action's consequences (Fowler, 2003). In this thesis, we refer to this influence as the indirect effects of the action. We call them indirect effects, because – in contrast to the often studied direct effects (e.g., costs reduction) – they affect the company's performance via the environment.

To evaluate the indirect effects of an action, its assessment (i.e., the process of determining the effects of a future action) needs to capture the adaptation of the company's environment to the assessed action. This requires that the assessment includes the behaviour and interactions of the entities in the company's environment, so that those entities can adapt to assessed action and thereby influence the company's financial performance. Throughout this thesis we use the term *system perspective* to indicate that an assessment includes the behaviour of the system as a whole and the relationships between the different parts of the system (Bar-Yam, 2011). This internalises the complexity of the company's environment in the assess-

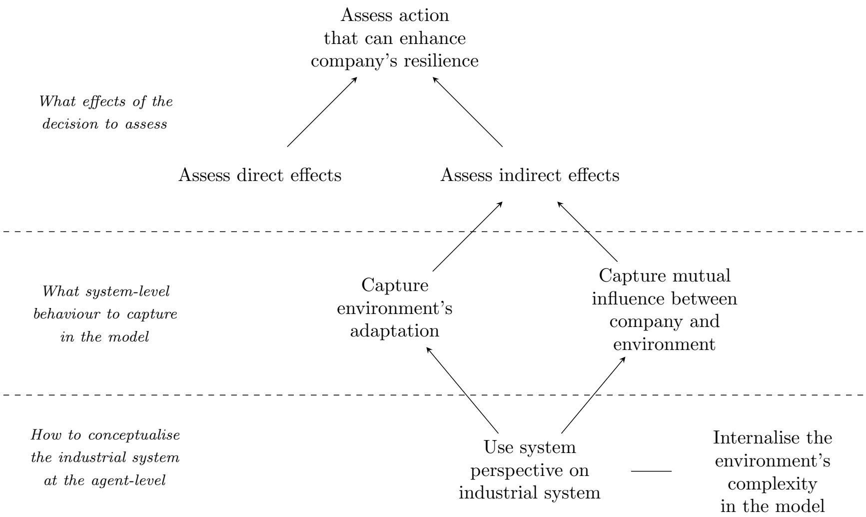

Figure 1.1: Concepts associated with the assessment of a resilience-improving decision

ment, in order to enrich the evaluation of the company's action.

Figure 1.1 presents an overview of those concepts, which are central to this thesis. The top layer of concepts concerns the type of effects that an assessment needs to be able to assess, in order to assess an action that can enhance the company's resilience. The concepts in the middle layer concern what system-level behaviour[1] needs to be captured in the assessment, in order to be able to assess the effects of the top layer. At the lowest layer, the concepts concern what elements and (inter)actions of the represented industrial system need to be included in the assessment.

Inability of current assessment tools to assess the indirect effects of an action Over the years, a wide variety of methods to assess actions have been developed (Hillier and Lieberman, 2012). Many of those methods aim to find the optimal solution to a problem, such as the optimal production planning (Pochet and Wolsey, 2006). However, for that purpose, strict assumptions are made to describe the system, which make it more difficult to realistically represent complex systems (Campuzano and Bru, 2011). Therefore, those methods are not suited to capture the environment's complexity that is needed to assess the indirect effects of an action.

Computer simulations, on the other hand, can more realistically represent complex system, as they explore how the system may develop in the future and do not aim to find an optimal development (North and Macal, 2007). In recent decades, computer simulations have increasingly been used to assess the effects of an action on a company's performance (Jahangirian et al., 2010). The majority of computer simulations that support business decisions focus on the focal company' internal complexity and pay little attention to the complexity in its environment (Ehlen et al., 2014). Those simulations are particularly suited to assess actions that mainly affect the company's internal operations and typically only assess the action's direct

[1]The system-level (and other levels of a complex adaptive system) is discussed in detail in section 3.

effects. To assess the indirect effects of actions that can enhance the company's resilience, the simulation model needs to internalise the environment's complexity into the model, which many of the existing computer simulations are not capable of. There thus is a need for a new conceptualisation of industrial systems that internalises the environment's complexity into the simulation model and thereby in the assessment of actions that can enhance the company's resilience.

1.3 Research objective and questions

In this research, we develop a conceptualisation of an industrial system that can be used to simulate both the direct and indirect effects of an action on the focal company's performance. With this conceptualisation, we aim to enable a more comprehensive assessment of (the direct and indirect effects of) actions that can enhance a manufacturing company's resilience. This requires that – next to developing the conceptualisation – we demonstrate that an assessment that internalises the environment's complexity can assess both the direct and indirect effects of the assessed action and that assessing the indirect effects enables a more comprehensive assessment.

The main research question (RQ) that we set out to address in this research is the following:

RQ How can we conduct a more comprehensive assessment of a company's actions that can enhance its resilience?

This main research question can be divided into multiple sub-questions (SQ). Each of the sub-questions is addressed in one chapter of this thesis.

SQ1 What are the requirements to a simulation model to enable the assessment of an action's indirect effects?

SQ2 To what extent can current computer simulation models be used to assess an action's indirect effects?

SQ3 What theories are needed to internalise the environment's complexity into a simulation model?

SQ4 How is the mutual influence between a focal company and its environment driving the indirect effects of a resilience-enhancing action?

SQ5 How and to what extent do a resilience-enhancing action's indirect effects materialise in the developed simulation models?

SQ6 How and to what extent do the indirect effects of an action influence the assessment outcomes?

SQ7 How can our system perspective be used to assess future actions that may enhance a company's resilience?

1.4 Research methods

The methods used to perform this research can be divided into three groups: *1*) study of the existing literature to create a theoretical foundation for the new conceptualisation; *2*) case studies in which we implement the new conceptualisation in simulation models to assess a number of actions that can enhance a company's resilience; and *3*) a synthesis of the case studies to get insights into the use of our conceptualisation.

Literature studies Before any simulation models with a system perspective are developed, we study two bodies of existing literature. First of all, literature that describes the existing computer simulations that are used to support business decisions. This gives us insights into their capability to assess the indirect effects of an assessed action, in what ways the environment's complexity has already been internalised, and what further steps are needed. The second body of literature is studied to formalise the relevant aspects of industrial systems. We use a number of theories to analyse an industrial system from a variety of perspectives. Each perspective highlights different aspects of the system: the focal company, its environment, the drivers of complexity in the system, the mutual influence between the focal company and its environment, and the environment's adaptation. Together, those insights describe how an action directly and indirectly affects the focal company's performance, how this is influenced by the industrial system, and what elements and mechanisms need to be included in a model to asses an action's indirect effects.

Case studies through simulation models The new conceptualisation is developed through five case studies. In each case study, we use a computer simulation to support a particular business decision that can enhance a company's resilience. Each case study starts with a literature review to obtain insights into the elements and behaviour specific to business decision that is central to the case. Those insights are used – together with the description of the industrial system – to develop a model that can be used to simulate the industrial system and assess the focal company's performance.

The models developed in the case studies are agent-based models. An agent-based model represents a system as a set of heterogeneous agents that decide autonomously and interact with each other and their environment (Shalizi, 2006). This type of models is particularly suited to represent systems with complex macro-behaviour that emerges from relatively simple micro-behaviour (Bonabeau, 2002). Using this type of models, we thus can internalise the complexity of the company's environment by specifying the 'simple' behaviour and interactions of the companies in the industrial system. The adaptation and complex macro-behaviour subsequently emerge from those interactions. So, even when it is difficult to understand and predict those emergent phenomena, this type of model enables us to study them.

Each model is developed using the model development process of Nikolic et al. (2013) that consists of 10 steps: *1*) problem formulation and actor identification, *2*) system identification and decomposition, *3*) concept formalisation, *4*) model formalisation, *5*) software implementation, *6*) model verification, *7*) experimentation, *8*) data analysis, *9*) model validation, and *10*) model use. As complex system cannot be designed from scratch (Gall, 2002), we use a co-evolutionary method to develop increasingly complex models (Nikolic, 2009). This implies that the model used in the first case study is relatively simple, but the complexity of the models increases with each succeeding case study. This complexity evolves along two lines: the scope of the model, and the behavioural richness of the agents.

The scope of the model specifies what elements, behaviour, and interactions of the industrial system are included in the model. A larger scope of the model increases the heterogeneity and interconnectedness of the model, causing the complexity of the model to increase. The scope of a model is specified by six dimensions:

1. *Diameter of the industrial system*: specifies the maximum number of tiers connecting the system's most upstream company to the most downstream company. When the model only represents a focal company, the diameter of the system is one; however, the diameter increases to three companies when also the suppliers and customers of the focal company are considered. This can be further extended by considering the suppliers' suppliers, the customers' customers, and so on.
2. *Possible market interactions*: specifies with what groups of companies the focal company can interact and thereby which companies in the system are connected to each other. The lowest level of possible interactions is when the focal company only interacts with its current suppliers and customers. One level higher, the focal company can interact with all potential suppliers and customers that participate in the markets in which it buys its feedstock and sells its goods. The level of possible market interactions is the highest when the focal company can interact with the potential suppliers and customers in all markets in which it potentially can participate.
3. *Types of changes caused by the focal company*: specifies the type(s) of changes that the focal company can cause in the industrial system through its behaviour. We distinguish two types of changes: operational and topological changes. The operational changes concern non-structural changes to the system, such as changed prices of goods or different production rates, and are (as their name suggests) often caused by operational decisions. The topological changes, on the other hand, concerns changes to the structure of the industrial system, such as relocated plants, and are often caused by decisions with a longer time horizon.
4. *Types of changes caused by the environment*: specifies the type(s) of changes that the companies in the environment can cause to the industrial system through their behaviour. As for the focal company, we distinguish two types of changes caused by the environment: operational and topological.
5. *Types of changes caused by market interactions*: specifies the type(s) of changes to the system are caused by market interactions. Whereas the previous two dimensions concerned the changes caused by the decisions of individual companies, this dimension explicitly focuses on the type of changes that is caused by (inter)actions of multiple companies. Again, we distinguish between operational and topological changes.
6. *Detail of the environment's representation*: specifies how detailed the entities in the focal company's environment are represented in the model. The entities in the environment can be aggregated, which reduces the heterogeneity and

interactions in the model and thus also decreases its complexity. The level of detail is measured by the percentage of entities in the environment that do not represent aggregated entities. At the lowest level of detail, the environment is aggregated in a single entity and 0 % of the environment is represented in full detail. The highest level of detail entails that all entities in the environment are represented as individual entities and 100 % of the environment is not aggregated. Between those two extremes there is a wide variety of options, with different levels of detail.

The behavioural richness concerns how the behaviour – and thus not what behaviour – is represented in the model and what features are considered in those decisions. The behavioural richness thus consists of two dimensions:

1. *Decision rules*: specifies what kind of decision rules are used to implement the agents' (inter)actions in the model. The type of decision rules influence the complexity of the behaviour and interactions of the agents. The least complex decision rules used in the case studies concerns a double-sided auction through which the market interactions are bundled in a centralised marketplace (Parsons et al., 2006). The most complex used decision rules concern a Q-learning algorithm through which the companies learn how to make decisions in the market (Tesauro and Kephart, 2002).
2. *Considered features*: specifies what features (of other companies) a company consider when making its decisions. In the context of the market interactions, those features can be the supply, demand, location, and market power of the other companies. As more of those features are considered, the companies become more interconnected, which increases the model's complexity.

Reflection Given the different focus of each case study, each simulation model conceptualises the industrial system differently and thus also internalises the complexity differently. In this third phase of the research, we reflect on the models that were developed for the case studies. The first part of this phase analyses how the eight dimensions of complexity were used in each of the models. So, what level of complexity (as indicated by the eight dimensions) was internalised into the model in order to assess a particular action? Through this analysis, we obtain insights into how the conceptualisation should be applied to assess a specific action. Those insights consist of recommendations for the development of future models on what factors should be considered to select the internalised complexity through each of the dimensions.

The second part of the reflection considers all previous research to give and overview of the new conceptualisation. It shows *1*) how different theories are combined to form the foundation of the conceptualisation, *2*) how this conceptualisation is applied in the case studies, *3*) how the conceptualisation influences the assessment's accuracy, and *4*) how the conceptualisation should be employed to support future business decisions. Combined with a discussion of the strengths and limitations of the developed conceptualisation, this addresses the main research question on how we can assess actions that can enhance a company's resilience more comprehensively.

1.5 Structure of the thesis

This thesis consists of nine chapters that are grouped into three parts. Figure 1.2 presents an overview of those chapters, indicating their content and their relation to each other. Chapters 2 and 3 together form the first part of this thesis that presents the theoretical foundations for the system perspective that can be used in the assessment of a company's actions. Chapter 2 reviews the existing computer simulations that are used to support business decisions. Chapter 3 analyses industrial systems from a variety of perspectives to get an understanding of those systems and the mutual influence between it and a focal company.

The second part of the thesis concerns the case studies in which we develop simulation models to support a company's business decision. The developed models build upon the theoretical foundations of the first parts, which is supplemented with theoretical insights that are specific to the assessed business decision. Next to that, each model builds upon the models that are developed in previous case studies, so that their complexity increases iteratively. Figure 1.2 shows for each model how it scores on the dimensions of complexity. The dimensions for which a model's complexity changes – in comparison to the previous models – are emphasised. Chapter 4 studies the effect of decentralised operations on the company's operating margin. In chapter 5, we develop a model to assess the value of a transportable plant. Building upon this, chapter 6 evaluates the investment in a plant with a flexible production process that allows it to switch between markets. Chapter 7 assesses the possibilities of a company to collaborate extensively with other companies. And finally, in chapter 8, we evaluate a company's strategic investment decision in a world that is changing due to new regulations.

In the third part, the insights of the previous parts are synthesised into an overview of the new conceptualisation and how it can be used to support business decisions. Chapter 9 reflects on the complexity that was internalised in the case studies, in order to establish recommendations on how to apply the developed conceptualisation for the assessment of a specific action. In chapter 10, we reflect on the developed conceptualisation by explicitly answering the sub-questions on basis of the previous chapters. This overview of the developed conceptualisation addresses the main research question and provides leads for the future use of the conceptualisation.

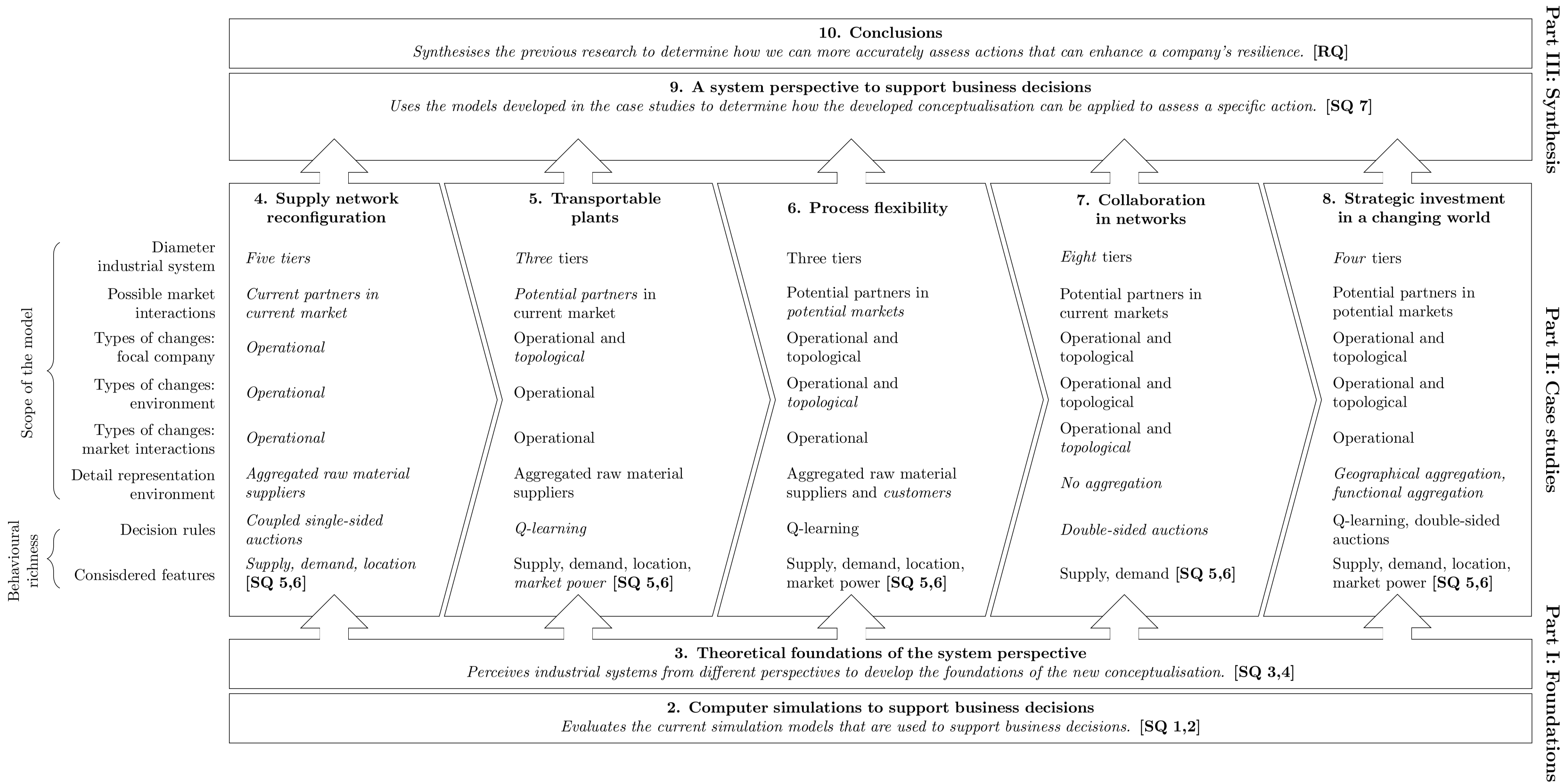

Figure 1.2: Structure of the thesis (italics indicate evolved aspects of the models)

Part I

Foundations

Chapter 2

Computer simulations to support business decisions

2.1 Introduction

In the previous chapter, we introduced the need for manufacturing companies to assess the indirect effects of their actions. We argued that this requires that they extend their assessments to capture the mutual influence between the focal company and its environment, and the adaptation of the environment. As a way to capture the mutual influence and the adaptation, the assessment needs to internalise the complexity of the company's environment and thereby capture the entire (relevant) industrial system. Furthermore, we introduced computer simulations as a method that can represent the system's complexity and assess the effects of a potential action. To date, a large number of computer simulations have been developed to support business decisions (by assessing potential actions), which used different conceptualisations of the focal company and its environment. However, it is not clear to what extent those conceptualisations can assess the indirect effects of an action.

In this chapter, we review the existing simulation studies that are used to support business decisions. We aim to identify the different types of conceptualisations used in those studies, and their ability to assess the indirect effects. Section 2.2 starts by introducing computer simulations – and the other related concepts – in general and their use to support business decisions. Before we review the existing computer simulation studies, we determine, in section 2.3, the requirements for a conceptualisation to account for the indirect effects. The existing simulation studies are reviewed in section 2.4, in which we identify the different approaches (i.e., types of conceptualisations) and discuss to what extent they can assess an action's indirect effects.

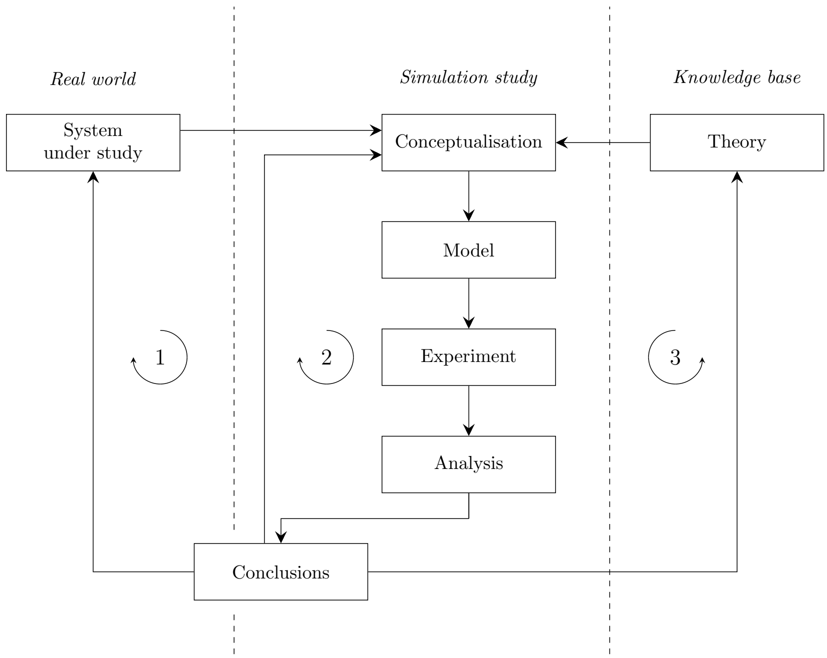

Figure 2.1: Simulation study schematic (based on Maria (1997) and Hevner (2007))

2.2 Business applications of computer simulations

2.2.1 Computer simulations in general

A computer simulation is the 'imitation of the operation of a real-world process or system over time' (Banks, 2011, p. 3). Computer simulations have been used to support a variety of decisions, such as the reengineering of business processes or the design of transportation systems (Law and Kelton, 2000). Many decisions have become so complex that humans no longer can comprehend the consequences of their choices. In a simulation study it is possible to evaluate a potential action, by representing the system under study in a computer and observe the system's performance indicators when the action is applied to the system (Carson II, 2004). For example, when assessing different inventory management policies, the flows of goods through the supply chain are simulated and the focal company's inventory holdings costs are recorded (e.g., Cachon and Fisher, 2000). Throughout this thesis, the changes of the (simulated) system's performance indicators due to a particular action are referred to as the effects of that action.

The development and use of a simulation study is carried out according to a simulation study schematic, which is presented in Figure 2.1. This schematic combines the schemes of Maria (1997) and Hevner (2007) and specifies the different aspects of the simulation process and how they build upon each other. In line with Hevner (2007), the schematic consists of three cycles: *1*) the system-simulation cycle ('relevance cycle' in Hevner (2007)); *2*) the model improvement cycle (the 'design cycle'); and *3*) the theory-simulation cycle (the 'rigor cycle').

A simulation study is generally executed to obtain insights into a certain problem in the *system under study*, which thus needs to be represented in a computer. A system is ‘a collection of entities (e.g., people or machines) that act and interact together toward the accomplishment of some logical end’ (Schmidt and Taylor, 1970, quoted in Law and Kelton (2000)). This does not necessarily have to be a clearly delineated object, but can be a set of geographically dispersed entities, such as a supply chain.

To represent the system in a computer, first, a detailed overview is needed of the structure and behaviour of the system (Randers, 1980). This overview is referred to as a *conceptualisation* (or conceptual model) of the system and systematically describes what elements of the system are studied and how the modeller thinks the system works. The conceptualisation is not only based on observations of the system, but also on *theories* that describe a thinking of how (parts of) the system functions. For instance, principles of inventory management that describe how companies make decisions about their inventories (Silver et al., 1998).

On the basis of this conceptualisation, a mathematical representation of the system is implemented in the computer. This *mathematical model* is ‘a representation of the construction and working of some system of interest’ (Maria, 1997) and describes the system in terms of variables and equations. The development of a mathematical model is (either implicitly or explicitly) done with a certain modelling paradigm in mind. A modelling paradigm specifies some fundamental assumptions and underlying concepts regarding how a system should be represented in a model (Lorenz and Jost, 2006). Even though a variety of modelling paradigms exist (Landriscina, 2013), three paradigms have frequently been discussed to model industrial systems for simulation studies: agent-based modelling, discrete-event simulation, and system dynamics (Behdani, 2012).

As the time progresses in a simulation, the variables of the mathematical model are updated according to the model’s equations. A simulation thus is a process during which the behaviour of a system is imitated, while a mathematical model is an object that represents a system in the computer. The values of the model’s variables can be recorded, thereby forming an artificial history of the modelled system that can be used to assess the behaviour of the system. In an *experiment*, the simulation is run under certain circumstances (e.g., different actions) and the performance indicators (i.e., relevant variables of the model) are recorded, indicating the behaviour of the modelled system and the effects of the actions.

By *analysing* the outcomes of different experiments, it is possible to observe the effects of the changed circumstances on the behaviour of the modelled system. The insights that this provides can be used to draw *conclusions* with regard to the system performance, the identification of problem areas in the system, and an improved understanding of system behaviour (Carson II, 2004). Those conclusions can be used by decision makers to support decisions that concern the system under study. The conclusions of the simulation study thus influence the system under study, which closes the system-simulation cycle.

Next to insights into the problem of the system under study, the conclusions also provide insights into the functioning of the model and the chosen conceptualisation. As the development of simulation models is an iterative process (Nikolic et al., 2013), those insights can be used to develop the conceptualisation of the following iteration, thereby closing the model improvement cycle. Moreover, the conclusions can also provide insights into the theories that were underlying the conceptualisation. The outcomes of the simulation study may support or contradict existing theories, or can give rise to new theories. This is referred to as 'the third way of doing science' (Axelrod, 1997) or 'generative science' (Epstein, 2006) (in contrast to inductive and deductive science), and closes the loop of the theory-simulation cycle.

2.2.2 Use of simulations for business decisions

Commercial use Over the years, the systems, processes, organisation, and structure of companies have become increasingly complex (Buytendijk et al., 2010). As companies are growing ever bigger (Flowers, 2015), it becomes increasingly difficult to keep oversight of what happens within the company. This is further exacerbated by the interconnection of elements within the company, which causes developments in one part of the company to propagate through the organisation and cause unexpected developments in other parts of the company (Birkinshaw and Heywood, 2010; Sargut and McGrath, 2011). Next to that, companies are confronted with more complicated and (sometimes) contradicting requirements, such as having to be both adaptive and reliable, or sell high-quality products at low prices (Trapp, 2014).

This rise in complexity makes it increasingly difficult for decision-makers to comprehend what effect their decision is going to have on the company's performance (Harrison et al., 2007). A certain decision may have side effects that adversely affect the intended consequences of the decision, or may have a different effect altogether. Consequently, decision makers need to be supported by tools that enable them to obtain insights into the full effects of certain action on the company's performance. Using those insights, the decision maker can make an informed decision that influences the company's performance as anticipated on beforehand.

Companies have increasingly been using computer simulations to get a better understanding of the effects of certain actions and support their business decisions (Harrison et al., 2007; Melão and Pidd, 2003; Montazer et al., 2003). Those simulations have been used to support a variety of business decisions on many different levels of the organisation (Tako and Robinson, 2012). Those decisions range from operational decisions, such as inventory management problems (Guerrin, 2004) or production planning and scheduling (Venkateswaran and Son, 2005), to strategic decisions, such as the design of a company's supply network (Wikner et al., 1991).

The mathematical models used in computer simulations that support a business decision contain those elements of the company that are thought to be relevant to the decision, specifying the state of those aspects and the rules governing their change. For instance, in a simulation that is used to assess the benefits of using lean manufacturing principles in a plant (Abdulmalek and Rajgopal, 2007), the model represents a plant as a set of different production stations. In the model, the production stations have different characteristics (e.g., capacity, setup time, maintenance time) and are connected to each other to allow goods to be processed at succeeding stations. The rules of this model specify how the goods move through the production stations as they processed from feedstock to product. Using the simulation, it is possible to compare the performance of the plant (in terms of lead times, inventory, and production rate) using different ways of operating. This comparison then provides the decision makers insights into how the new way of operating could improve the plant's performance (Wenzler and Chartier, 1999).

Scientific interest Besides companies, in recent years, the scientific community has also been increasingly engaged in the development of computer simulations that can support business decisions. In the Scopus database (i.e., the largest database of peer-reviewed literature), the query `KEY((simulat* OR "system dynamics") AND (manufacturing OR business OR management))`[1] returns almost 80,000 document results, of which around 80 % has been published in the last 10 years. A variety of literature reviews have been performed to obtain an overview of the computer simulations that can support business decisions (e.g., Jahangirian et al., 2010; Negahban and Smith, 2014; Shafer and Smunt, 2004; Tako and Robinson, 2012; Terzi and Cavalieri, 2004). For a more detailed discussion of this type of simulations, readers are referred to those reviews.

Those simulations have been performed in a variety of fields of study, such as operations management (Shafer and Smunt, 2004), supply chain management (Sachan and Datta, 2005), operational research (Tako, 2008), and decision support (Power and Sharda, 2007). However, those fields overlap considerably, which makes it difficult to attribute a particular simulation to one of the fields of study. The business decisions most commonly supported by computer simulations in the literature concern scheduling, process management, supply chain management, strategy, transportation management, and project management (Jahangirian et al., 2010). However, other business decisions (e.g., maintenance management, organisational design, or quality management) are also supported regularly by computer simulations. Regarding the used modelling paradigms, discrete-event simulation is used in 40 % of the papers reviewed by Jahangirian et al. (2010), 15 % of the papers used system dynamics models, and 5 % used agent-based models. The other modelling paradigms, such as traffic simulation, simulation gaming, and petri-nets, were used more sparsely.

2.3 Requirements to assess indirect effects

Before we review the existing computer simulations, we determine the requirements for a conceptualisation that would enable the assessment of an action's indirect effects. As we introduced earlier, the objective of a simulation is to assess how a certain action influences the financial performance of the simulated focal company. This implies that the conceptualisation needs to be able to measure the total *financial performance*; not only the effect of the decision on the operational expenses, but also the profitability or any other financial metrics (e.g., Fridson and Alvarez, 2011).

The financial performance of the focal company materialises from the costs of procuring feedstock, the costs to convert the feedstock into product, and the revenues of selling the product. Both the costs of procuring feedstock and the revenues of selling the product are a direct consequence of the volumes and prices that are agreed upon in the supply contracts between the focal company and its suppliers and

[1] This is the same query as used by Jahangirian et al. (2010) in their literature review of simulation in manufacturing and business.

customers. Hence, to assess the indirect effects of an action, the conceptualisation needs to enable both the *volumes and prices to emerge endogenously.*

What volumes and prices are specified in the supply contracts is the result of the market interactions in the industrial system. In that regard, not only the focal company's interactions with its existing suppliers and customers are relevant, but also those with potential suppliers or customers, or even interactions that do not directly involve the focal company. Those other market interactions act as a reference for the interactions between the focal company and its suppliers and customers. For instance, if another potential supplier is willing to sell the feedstock at a lower price than the current supplier, the focal company is unlikely to pay the higher price. This forces the current supplier to lower its price, or the focal company will order its feedstock from the other potential supplier. Likewise, the (potential) suppliers and customers do not interact exclusively with the focal company, but also with its competitors. This causes the focal company to adjust its behaviour to the interactions between the suppliers/customers and its competitors, even though it is not directly involved in those interactions. Consequently, the system perspective requires that a simulation model includes – next to the focal company – all relevant *potential suppliers*, *competitors*, and *potential customers.*

However, merely including all those actors in the simulation does not suffice in itself. The behaviour of the actors needs to be modelled in such a way that *all included actors can adapt their behaviour* to a change in their environment, which subsequently can influence the market interactions among them. For instance, if we assess the effects of investment into a technology that lowers a company's operational expenses, the environment can only adapt if the surrounding actors can alter their behaviour and market interactions in response to the lower expenses. Those market interactions can only fully reflect the adaptation of the actors' behaviour if both interacting parties can influence them. If one of the parties is forced to accept any proposal made by the other party, the adaptation of the former's behaviour can never be reflected in the market interactions – and thereby not in the emerging volumes and prices. Thus, to assess the indirect effects, the conceptualisation needs to enable *both interacting parties to influence the relations that are formed* between them.

These requirements effectively imply that the system boundaries of the conceptualisation need to extend beyond the boundaries of the focal company. However, as this internalises the environment's complexity into the model, representing this system into a simulation model has severe consequences for the used conceptualisation.

2.4 Literature review of the existing simulations

To get insight into the ability of the existing simulations to assess an action's indirect effects, we need an overview of what conceptualisations have been used in those simulations. We review the conceptualisations – and not the models – to obtain insight into what elements of the industrial system are considered, without being distracted by how they are implemented. To date, there is no clear insight in the conceptualisations used, even though there have been many different literature reviews. Those reviews typically focused on the application of the simulations, the used modelling paradigm, and some aspects of model's scope, but did not review the structure and behaviour of the industrial system. In this section, we perform a literature review of simulation studies that aim to support business decisions, with a focus on the conceptualisation used in those studies.

2.4.1 Methodology

Selection criteria The literature review is performed on simulation studies that are selected from the Scopus scientific database, using the following query:

```
KEY(((simulat* OR "system dynamics") AND (manufacturing OR business OR management)))
AND NOT (train*) AND NOT ("monte carlo") AND (LIMIT-TO(SUBJAREA,"BUSI")).
```

As of May 2016, this returns 3,737 document results. We review the 10 % newest and 10 % most cited studies in further detail, to capture both the most common practices and the latest developments. The selected 748 studies are further filtered on whether they actually include a simulation that supports a business decision. This excludes papers that present the outcomes of games (e.g., Peón et al., 2014), surveys (e.g., Ikome et al., 2015), or data analyses (e.g., Nemec and Zapletal, 2015), on account that they do not use a simulation. When a study uses a simulation, it can still be excluded when the stimulation is not used to support a business decision, but, for example, studies water management (Lempert and Groves, 2010), battery thermal management (Kim and Lee, 2015), or air traffic management (Zhang et al., 2015). This reduces the number of reviewed documents to 209.

Indicators The conceptualisations of the studies that meet the selection criteria are reviewed by scoring them on a number of indicators. Those indicators are selected to indicate to what extent a conceptualisation meets the requirements to assess the indirect effects. As this thesis is concerned with internalising the environment's complexity in the assessment of an action, the indicators mainly focus on the focal company's environment: how the conceptualisation represents the environment, and how it captures the mutual influence between the company and its environment, and the environment's adaptation.

Level of analysis Even though all reviewed studies support business decisions, the decisions can relate to different elements of the industrial system. This means that the simulation studies can focus on different elements in the industrial system of which the performance is measured to assess the effect of a course of action: the study's focal entity. A study's level of analysis specifies the type of the study's focal entity. Extending the classification of Croom et al. (2000), we distinguishes four different levels: *department*, *company*, *supply chain*, and *network*. At the department level, a study focuses on the performance of a single department within a company (e.g., a single production line or a single warehouse). The company level entails that the performance of the entire company is studied, comprising multiple departments. At the supply chain level, the focus is further extended to the aggregated performance of multiple companies in a single supply chain. The network level combines multiple supply chains and assesses the performance of that network as a whole (e.g., the study of an entire industry).

Environment Each focal entity operates in an environment with which it interacts. In a business context, important entities in the (micro-)environment of companies are suppliers, competitors, and customers (Blythe, 2013), which can be generalised to the upstream, midstream, and downstream environment of the focal entity. The 'environment' indicator shows which aspects of the entity's environment are included in the conceptualisation and how those are represented. With regard to the representation of (an aspect of) the environment, we distinguish adaptive and non-adaptive representations. An adaptive representation entails that the entities in the environment can adapt to changes in the system, while a non-adaptive representation entails that this adaptation is not possible and the environment is specified outside the simulation. The upstream environment consists of the entities that cause material flows into the focal entity, which can be either adaptive *suppliers* or non-adaptive *shipments*. Midstream consists of the environment that is involved with the same activity as the focal entity and thus can be considered its competition. For the midstream environment, we distinguish between adaptive *competitors* and non-adaptive *market share*[2]. The downstream environment involves the entities that use the output of the focal entity, which can either be adaptive *customers* or non-adaptive *orders*.

Prices The 'prices' indicator specifies how the prices of goods are represented in the conceptualisation and to what extent they can change due to developments in the modelled system. For this indicator, we distinguish between studies with no prices (*none*), studies with prices specified *exogenously* from the system, and studies with *endogenously* emerging prices.

Volumes The 'volumes' indicator specifies how the volumes of goods between the focal entity and its environment are represented in the conceptualisation, and to what extent they can change due to developments in the modelled system. There can be no volumes (*none*) or, when there are volumes, they can be either *exogenously* specified or emerging *endogenously* in the system.

Relation formation The entities in a modelled system often have relations with each other, which may be formed during the simulation as a result of the interactions among two parties. The 'relation formation' indicates which of the interacting parties can influence the terms of a formed relation. When *none* of the parties has an influence, there is no relation formation and the relations are fixed. When relations are formed during the simulation, we distinguish between *single-sided* relation formation, when only one of the parties can influence the terms and the other has to accept those, and *double-sided*, when both parties can influence the terms – e.g., when they are negotiating with each other.

Performance measurement Each simulation study is performed to measure the performance of some aspects of the focal entity. The 'performance measurement' indicates what kind of performance is being measured in the study. Generally, the management literature distinguished between operational and

[2]We use the name market share, as in many conceptualisations non-adaptive competition is represented as the focal entity's market share.

financial performance (Yamin et al., 1999). We split the financial performance further, by distinguishing costs and total financial performance. The *costs* indicates the direct financial consequences of a certain action, such as the inventory costs, or logistics costs. The *financial* performance measures the financial consequences more comprehensively, such as the focal entity's profit or operating margin. The *operational* performance measures non-financial aspects, such as the focal entity's throughput, service level, or lead time.

2.4.2 Review outcomes

Scores on indicators

To get insights into the conceptualisations used in the simulation studies that support business decisions, we assess how those studies score on each of the indicators. Using those outcomes, we identify different types of conceptualisations (called approaches) and evaluate their ability to assess the indirect effects of an action. Figure 2.2 shows per indicator what percentage of studies conceptualise the system in a particular way. For some indicators the total score surpasses the 100 %, which is due to some studies matching multiple conceptualisations; for instance, a conceptualisation that measures the operational performance as well as the costs. In this section, we discuss those scores in further detail.

The *level of analysis* indicates that most of the reviewed studies focus on (a part of) a single company. In 74 % of the studies, either a company or a department is being analysed. In contrast, only 27 % of the studies analyse an entity that transcends a single company. This focus on a single company does not necessarily mean that those studies have an inward focus, as they still may represent the focal company's environment in detail with the ability to adapt to the company's actions.

In most of the studies, the *environment* (in Figure 2.2 grouped by indicators of an adaptive environment and a non-adaptive environment) is conceptualized deterministically. In 94 % of the studies aspects of a non-adaptive environment have been encountered, while aspects of an adaptive environment are present in 5 % of the studies. This entails that in most conceptualisations the environment is specified exogenously by the modellers and thus cannot adapt to developments during the simulation. The main contributor to the dominance of the non-adaptive environment is 'orders'. In 93 % of the studies, the environment is conceptualized as a set of orders that are to be processed by a focal entity that has no influence on those orders. Next to the non-adaptive nature of the environment, this indicates that most studies focus exclusively on the downstream environment of the entity (i.e., orders and customers), and have little attention for the upstream environment (i.e., suppliers and shipments) and the midstream environment (i.e., competitors and market share)

Only 8 % of the reviewed studies consider *prices* of the goods in the simulation. Of those studies, the majority of prices (6 % of the total) are exogenously imposed on the simulation, while only 2 % of the studies consider prices that emerge endogenously as a result of developments in the modelled system. With regard to the *volumes* of goods in a conceptualisation, 89 % of the studies specifies them exogenously, while only 8 % of the studies considers volumes that emerge endogenously in the modelled system. The remaining 2 % of the studies do not consider volumes of goods at all.

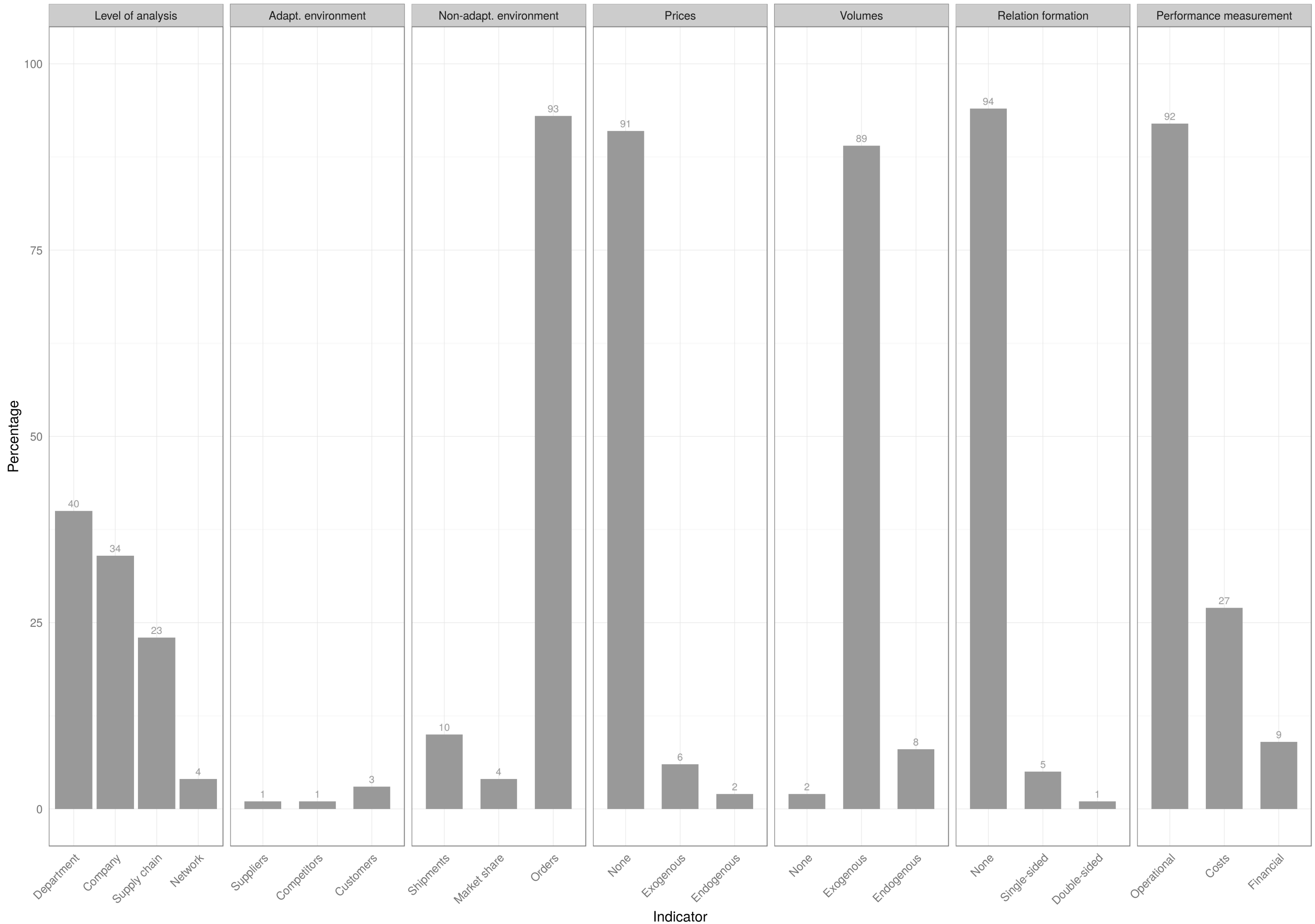

Figure 2.2: Conceptualisation of companies and their environment in the reviewed studies

The high percentage of exogenously specified volumes is related to our observation of the high percentage of orders, which exogenously specify the demand(ed quantity) for the focal company's products. This implies that, with regard the prices and volumes, the focus of the existing studies is mainly focused inward with little attention for developments outside the focal company.

The *formation of relations* between the focal entity and its environment is only considered in 6 % of the the reviewed studies. In the other 94 %, the relations are fixed in the modelled system's structure and cannot change during the simulation. In most of the studies with relation formation, the formation of the relations is single-sided. This entails that only one of the parties can decide on whether the relation is formed (generally, by selecting some of the received orders). There has been only one study in which both parties could decide the relation formations, which occurred through extensive negotiations. So, only in this study, both the focal entity and its environment can reflect their adaptation in the market interactions and the subsequently formed relations. In all other studies, maximally one of them can adapt, which prohibits the representation of the mutual influence between the focal entity and its environment.

With regard to the *performance measurement*, the operational performance is the dominant measure of the focal entity's performance. In 92 % of the studies, the operational performance is used as performance indicator, while the costs are measured in 27 %, and the total financial performance in only 9 % of the studies. The environment influences the focal entity for a large part via the entity's revenues. Therefore, by not measuring the total financial performance, most of the studies can only partially assess the indirect effects of an action.

Approaches used in existing simulations

Using the scores on the indicators, we can define some approaches (i.e., generic types of conceptualisations) that are used in the simulation studies that support business decisions. We distinguish three approaches: the non-adaptive approach, the partially adaptive approach, and the fully adaptive approach. Those three approaches mainly differ from each other regarding how they represent the focal entity's environment, the mutual influence between that entity and its environment, and the adaptation of the environment. In this section, we discuss those approaches in further detail and analyse to what extent the approaches can assess an action's indirect effects.

Non-adaptive approach When a system is conceptualised non-adaptively, the environment of the study's focal entity cannot adapt to any developments in the system. The volumes and prices that are included in the conceptualisation are specified exogenously, and there is no formation of relations. Hence, the relations – and thereby the system's structure – are also specified exogenously. The measurement of the performance is usually limited to the operational performance or the costs, although measurement of the total financial performance also occurs occasionally.

Of the 209 reviewed studies, 188 (89 %) use the non-adaptive approach. This entails that the large majority of studies focus on an entity (e.g., a company) that is to be analysed, with an environment that consists of a set of orders that need to be processed by that entity. The relations between the entity and its environment

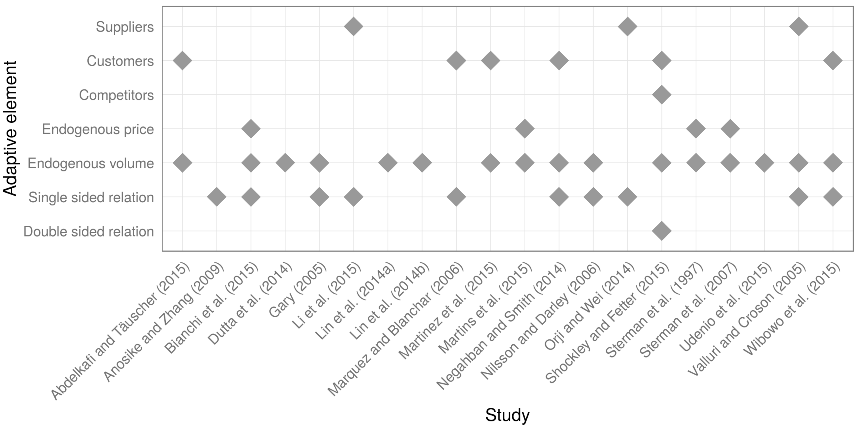

Figure 2.3: Adaptive elements in the conceptualisations of the reviewed studies

are specified exogenously by the modeller in the form of orders and shipments (with pre-set volumes and prices). This perspective concerns mainly the internal dynamics of the focal entity, which can be be justified by the focus of those studies on relatively short-term operational decisions that are only marginally influenced by the environment. Consequently, this approach does not meet any of the requirements to assess an action's indirect effects.

Partially adaptive approach Studies with a partially adaptive approach have some adaptive elements, but not all that are needed to meet the requirements to assess the indirect effects. Figure 2.3 shows for each study with a partially adaptive conceptualisation (x-axis) what adaptive elements (y-axis) they contain. The most common adaptive element is *endogenous volumes*, followed by *single sided relation formation* and *customers. Endogenous prices* occur only in 4 out of 20 studies and are always combined with endogenous volumes. Adaptive entities in the environment (i.e., *suppliers*, *customers*, or *competitors*) are found in 9 studies and are mainly combined with endogenous volume; however, they are never combined with endogenous prices. The *double-sided relation formation* is found in only one of the studies. This implies that there is no typical partially adaptive conceptualisation, but they have in common that the environment can adapt partially to changes in the system. This prevents them from assessing the indirect effects of an action.

With regard to the requirements, the partially adaptive approach only meets some of the requirements. In the studies where the volumes and prices can adapt, the behaviour of the entities in the environment cannot adapt; and in studies where the behaviour of the entities in the environment can adapt, the prices of the goods cannot adapt. During the identification of the requirements, we argued that both forms of adaptation are needed in a conceptualisation that can be used to assess the direct and indirect effects of an action on the focal entity's financial performance. So, as a consequence of the partial adaptation, the partially adaptive approach is not suited to assess the action's indirect effects.

Fully adaptive approach Out of the 209 reviewed studies, there is only 1 that matches all the requirements to assess an action's indirect effects. Arunachalam and Sadeh (2005) describes the use of the Trading Agent Competition Supply Chain Management (TAC SCM) to find pricing strategies that enable a company to maximise its financial performance, while negotiating with customers over the exchange of goods and competing with other companies. Over the years there have been multiple publications on TAC SCM that discuss the set-up of the competition (e.g., Arunachalam and Sadeh, 2004; Collins et al., 2010) or the functioning of participating companies in the competition (Benisch et al., 2004; Ketter et al., 2009; Pardoe and Stone, 2008, e.g.,). This competition has not only been used to find pricing strategies, but also strategies for other aspects of supply chain management, such as scheduling. This has provided considerable insights into strategies that are beneficial to the operation of companies.

In Arunachalam and Sadeh's study (but also the other TAC SCM-based studies), the entities in the system negotiate with each other to trade goods. The outcomes of those negotiations are transactions that specify the prices and quantity of the traded goods. When a company makes a certain decision, it changes the situation from which it enters into the negotiations, which may lead to changed market outcomes. This way, the environment of the focal entity can adapt to the decision, which then – via the market outcomes – can influence the focal entity. The prices and volumes in this study thus emerge endogenously from negotiations among the focal entity and its suppliers, competitors, and customers, all of which can adapt their behaviour to changes in the system. In those negotiations, both parties that are interacting can influence the formation of the relation, which thus is double-sided. This implies that this study meets all requirements and thus uses a fully adaptive approach.

Consequently, the fully adaptive approach is suited to assess the indirect effects of an action. However, the work in Arunachalam and Sadeh (2005) is based on the TAC SCM, which is a competition of intelligent agents in a generic industry with a focus on supply chain management decisions. The TAC SCM-based papers thus do not present the outcomes of simulations that are used to support business decision of an existing company in a real-world industry. This would require the translation of the used (fully adaptive) conceptualisation from a competition to a simulation of a real-world industrial system in which one (focal) company can implement a different actions. In other words, the conceptualisation needs to be further generalised in terms of the represented industrial system and in terms of the represented behaviour and decisions. Nonetheless, the market-based conceptualisation can form a basis for the development of this generalised conceptualisation.

2.5 Synthesis

In this chapter we reviewed the existing computer simulations that support business decisions and discussed their ability to assess the indirect effects of an action. The review focused on the conceptualisation of the simulation models. This provides insights into what aspects of the industrial system are captured, without being distracted by how those aspects are implemented. In total, we reviewed 209 studies that all used a computer simulation to support a business decision in industry.

We identified three approaches (i.e., generic types of conceptualisations): non-adaptive, partially adaptive, and fully adaptive. The non-adaptive approach (used in 89 % of the studies) represents the system as a company with pre-defined orders that need to be processed, which results in a certain performance. The partially adaptive approach (used in 9.5 % of the studies) enables only some aspects of the environment to adapt to changes in the system, but not enough to capture the environment's effect on the company's performance. This would require the fully adaptive approach, which was only used in one study. In that study, the interactions between the focal company and its environment are conceptualised as markets, which enables all elements of the environment to adapt to changes in the system and enables the relations between the entities to reflects this adaptation. Consequently, this meets all requirements to assess an action's indirect effects. However, this approach is based on the Trading Agent Competition Supply Chain Management, which is a competition of intelligent agents in a generic industry with a focus on supply chain management decisions. Therefore, the fully adaptive approach cannot be used directly to simulate the effects of a variety of actions in different industries. It thus needs to be generalised in terms of the represented industrial system, the represented behaviour, and the assessed actions. Only then it can act as a basis for computer simulations that can assess the direct and indirect effects of an action by using our system perspective.

These findings are in line with the observation of Ehlen et al. (2014), who say that there are no simulations that 'attempt to model the plant-level components and whole-system dynamics of large chemical supply chains'. Our study shows that this observation also applies more generally: there is no conceptualisation that can internalise the environment's complexity in the model (i.e., model the whole-system dynamics). This complexity is at the core of our problem and hence a new conceptualisation is needed to include them in a computer simulation that supports business decisions. In the following chapter, we develop the theoretical foundations for this conceptualisation, by analysing industrial systems from a variety of perspectives.

Chapter 3

Theoretical foundations

3.1 Introduction

Chapter 2 concluded that the existing approaches to simulate business decisions cannot assess both the direct and indirect effects of an action. Due to their predominantly inward focus, the approaches cannot account for the adaptation of the company's environment and the mutual influence between the focal company and the environment, which are driving the indirect effects of an action. The one approach that does capture the mutual influence needs to be generalised before it can be used in a computer simulation. Hence, there is need for a new conceptualisation that uses our system perspective to capture the mutual influence between the company and its environment, as well as the environment's adaptation.

The development of a new conceptualisation requires that we obtain a comprehensive understanding of different aspects of industrial systems. The main insight that we need concerns how the environment's adaptation and the mutual influence between the focal company and its environment are driving the indirect effects of an action. However, before we get to that, we need to get a better understanding of the behaviour of the industrial system. This behaviour materialises from the behaviour and interactions of the entities that form the system. A better understanding of the industrial system thus starts with insight into which entities the industrial system contains. For each of those entities, we also need insight into their individual behaviour and their interactions that cause the emergence of the system behaviour.

In this chapter, we obtain those insights that form the theoretical foundations for the system perspective by analysing the industrial system from a variety of theoretical perspectives. We start in section 3.2 with defining the system's entities, with a focus on defining the focal company and its environment. This requires a socio-technical system perspective, as the industrial system not only contains technical artefacts, but also social elements. The behaviour and interactions of those entities are studied in section 3.3 using a complex adaptive system perspective. This perspective also provides insight into how the interactions among individual entities cause the emergence of the system behaviour, which is fundamental to understand how the system develops. The interactions among entities in the industrial system are further explored in section 3.4. By perceiving the industrial system as a network of markets, we obtain insights into how the different entities influence each other and how the relevant industrial system should be delineated. Building upon this overview of the industrial system and its behaviour, section 3.5 discusses how the focal company and environment influence each other, how the environment adapts to the assessed action, and how those aspects are driving the indirect effects of the action. In this section, we use the competitive strategy perspective to analyse how the market interactions between two companies (e.g., the focal company and a customer) influence their financial performance. Section 3.6 combines the insights of the different perspectives into an integral view of the industrial system.

3.2 Socio-technical system perspective on industrial systems

3.2.1 The socio-technical system perspective

A socio-technical system (STS) is ‘a class of systems that span technical artifacts embedded in a social network, by which a large-scale, complex socio-technical artifact emerges’ (Nikolic, 2009, p. 11), like infrastructures (Ottens et al., 2006) and supply chains (Van Dam, 2009). Those systems do not only consist of technical artefacts, but also the actors that are involved with the management of the technical artefacts. Analysing a system from an STS perspective, therefore, entails the explicit description of the artefacts in the technical network, the actors in the social networks, and the connections within and between those networks.

The technical network consists of many physical artefacts that process, store, or transport materials, energy, or information; for instance, plants, machinery, datacentres, pipelines, or powerlines. Those artefacts are connected to each other and are often interdependent in multiple ways (Weijnen and Bouwmans, 2006). The interdependencies can take several forms, ranging from simple and linear to non-synchronous and non-linear, and are driving the complexity of the technical network (Holland, 1995). Most technical networks have evolved over time to their current state, representing considerable efforts and investments (Hughes, 1987), which makes them path-dependent and relatively reluctant to change (Ruttan, 1997).

The social network consists of autonomously operating actors with possibly conflicting interests. Those actors can be individuals or organisations, such as companies, governments, or non-governmental organisations. The actions of actors are driven by self-interest, but are steered by legislation and regulation, moral, and cultural codes (Herder et al., 2008). Interdependencies among the actors are caused by social interactions, which may have a collaborative or competitive nature. Through those interactions, the actors adapt their behaviour to each other and learn new behaviour over time (Borgatti and Cross, 2003), which may cause the social network to change. Like technical networks, social networks are path-dependent, which makes it difficult to change the social network fundamentally (Liebowitz and Margolis, 1995). The actors in the network are often large organisations that do not easily make large changes and the interactions are often established in institutions that also take time to evolve (Nelson, 1994).

In a socio-technical system, the technical and social network are tightly interwoven, which means that they mutually influence each other by causing developments in the other network or imposing conditions upon each other (Geels, 2004). For example, the sales of a manufacturing company depend on the availability of physical products available. Vice versa, the production rate of a plant and the destination to which a good is transported depend on the supply contracts that are agreed upon in the social network. Those mutual influences are dynamic and thus cannot be established once, but need to be considered as an integral part of the system's development. Consequently, the technical and social networks should not be studied in isolation, but as an integrated system, so that the interdependencies between the two networks can be considered and can change as the system develops.

3.2.2 Industrial systems as socio-technical systems

We use the STS perspective to get an overview of the entities in the industrial system and their relations, which we use as basis for the new conceptualisation. The STS perspective divides an industrial system into a technical and a social network. The technical network contains the physical artefacts that are involved with the physical handling of the goods that are used and produced in the industrial system; the social network mainly consists of the different companies that operate in the industrial system and supply goods to each other. Those two networks are connected through the companies that own and operate the technical artefacts to produce the goods that they supply to each other. Throughout this thesis, we use the term 'supply' to indicate the full process of one company providing a good to another company, which can be divided into the 'exchange' (i.e., the change of ownership) and the 'shipment' (i.e., the physical delivery) of the good. Figure 3.1 provides a graphical overview of the social-technical structure of an industrial system, which is discussed in more detail in the text.

Technical network The technical network of an industrial system revolves around the facilities[1] that convert raw materials into end-products. The production of an end-product from raw material usually takes multiple steps, which are performed by different specialised facilities (Van der Zee and Van der Vorst, 2005). All conversion steps are comparable to each other, in the sense that they use feedstock that is converted to products that are made available to the next conversion step(s) (Delfmann and Albers, 2000). The general structure of the facilities in each conversion step thus is comparable and we limit our discussion of the technical network to a single conversion step.

The main types facilities in the technical network are the plant and the distribution centre (Tsiakis and Papageorgiou, 2008). Each *plant* performs a production process – which consists of smaller unit manufacturing processes (Finnie, 1995) – that describes what feedstock is converted to what product, and how this conversion takes place. A *feedstock* is a good that is used by a particular plant, while a *product* is a good that is produced by that plant[2]. A *distribution centre (DC)* is

[1] We use the term 'facility' to indicate the superclass of artefacts in an industrial system. The different types of facilities (i.e., plants and distribution centres) are subclasses of the facility.

[2] The classification of a good as feedstock or product is relative to the plant from whom's perspective the good is observed. From the perspective of a supplying plant a good is a product,

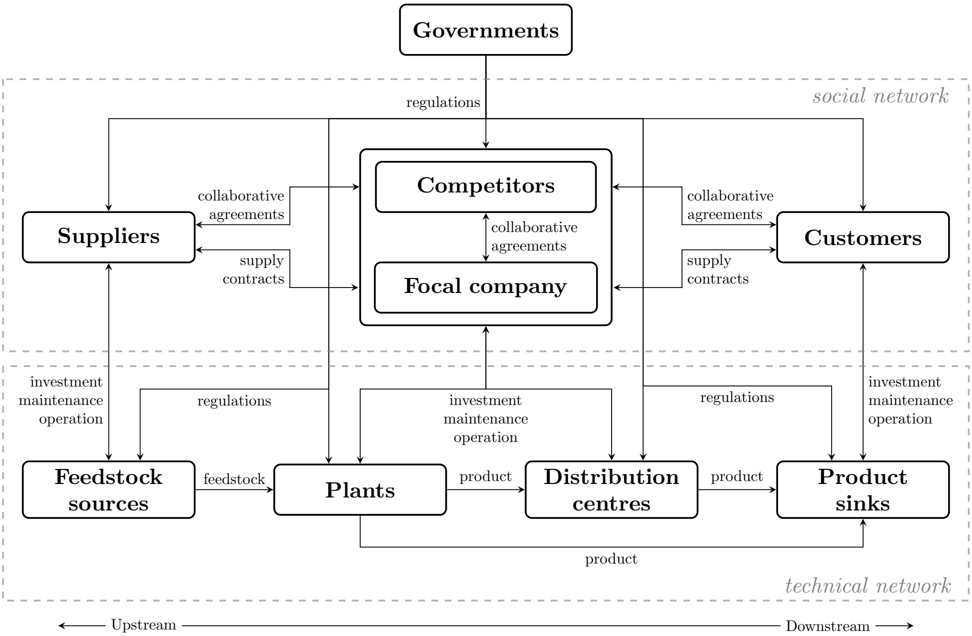

Figure 3.1: Socio-technical structure of an industrial system

a facility that distributes goods to customers in a certain region (Stock and Lambert, 2001). At a DC, shipments from a plant arrive and are processed in such a way that they can be shipped efficiently to customers. This processing may entail the temporary storage of goods, the repackaging of goods, or splitting or combining shipments (Baker, 2004). The DC usually does not physically or chemically change the product, but is concerned with changing its location, which we also consider a unit manufacturing process that contributes to the conversion of the feedstock to the product.

The feedstock that is used by a plant is shipped from a feedstock source. A *feedstock source* can be a plant that produces the feedstock, but also a DC that distributes the feedstock after it is produced by a more upstream plant. The feedstock source thus represents the facilities of a more upstream conversion step, which themselves also may have feedstock sources. The shipment of the feedstock from the feedstock source to the plant generally occurs via one, or a combination, of the available modes of transport: air, pipeline, marine, rail, or road (Kannegiesser, 2008).

The product that is produced by the plant is supplied to a product sink. Products do not only entail the desired main products, but also certain side-products, such as emissions like CO_2 and NO_x (Hao and Li, 2009), chemical residues (Christ, 2008), and waste water (Nasr et al., 2007). A *product sink* can be a more downstream plant that further processes the good into another good, but it can also be a retail outlet that supplies the good to consumers, or even the plant's physical surroundings (e.g., air, water, soil). Except for certain side-products, the product is generally

while from the perspective of the consuming plant that same good is a feedstock.

shipped via a selection of the available modes of transport. This shipment can occur directly from the plant to the product sink, but may also occur indirectly via a DC.

Social network The social network of an industrial system consists of companies that are connected via different relations (Choi et al., 2001). Considering the objective of this analysis, we divide the social network into two groups: the focal company and its environment. The *focal company* is the company for which the simulation is performed and whose business concerns the conversion of goods. The objective of the focal company is to maximise its profits by purchasing its feedstock at the lowest price possible and selling the products it produces at the highest price possible. The focal company's *environment* consists of all other companies in the industrial system and can be divided into three groups: suppliers, customers, and competitors (Lambert and Cooper, 2000). Like the focal company, *suppliers* are companies whose business entails the conversion of goods, but they produce and supply the feedstock that the focal company uses in its process. Similarly, the *customers* are companies that use the products that the focal company produces. Finally, the *competitors* are the companies that use the same feedstock and produce the same products as the focal company and thus compete with it over the supply of the suppliers and the demand of the customers (Delfmann and Albers, 2000).

As the companies in the social network aim to exchange goods, they are connected through relations that specify the exchange of goods. Generally, the exchange of goods – either feedstock or product – is arranged via supply contracts (Thorelli, 1986). A *supply contract* specifies what good is exchanged by two companies, what quantity of the good is exchanged and at what price (Anupindi and Bassok, 1999). Other important aspects of a supply contract are the due date at which the goods should be supplied and the quality of the good. Supply contracts may concern the one-time exchange of a good, but can also regard the recurring exchange of goods over a longer period of time (e.g., the weekly exchange of a good over a period of two years). In that case, the supply contract also specifies a duration and the multiple due dates at which the different shipments should be executed.

Besides a transactional relation through a supply contract, companies may also collaborate more extensively in, for example, joint ventures or strategic cooperative agreements (Chaharbaghi et al., 2005). Those collaborations are often used for research & developments activities (Roijakkers, 2003), but also to develop and produce a product together (e.g., Peek, 2010; Wilhelm and Kohlbacher, 2011). The *collaborative agreements* that the involved companies sign to start a collaboration specify the rules of the collaboration, for instance how the activities are distributed over the companies, how the companies collaborate, how profits are allocated, and how companies can enter or leave the collaboration (Reuer and Arino, 2007). Whereas supply contracts only connect companies that exchange goods to each other, collaborative agreements can also connect competing companies; for example, when two competing car manufacturers collaborate with each other on the development of a new car (Dagnino, 2009).

Regulations The behaviour of actors is bounded by regulations. Those regulations are imposed on the industrial system by governments that can be considered an integral part of the social network. However, as we are only interested in the effects of the regulations on the industrial system – and not in how they are put into effect – the governments are not included in the industrial system. The regulations are included in the system, to indicate their effect on the entities in the industrial system.

Regulations affect a wide variety of aspects of the production, handling and marketing of industrial goods. Next to the general regulations, such as the free movement of goods (articles 26 and 28-37 of Consolidated Version of the Treaty on the Functioning of the European Union, 2012), the most relevant regulations of industry in Europe[3] are the Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (European Parliament and Council of the European Union, 2006), the industrial emissions directive (European Parliament and Council of the European Union, 2010), the chemical agents directive (The Council of the European Union, 1998), and the energy efficiency directive (European Parliament and Council of the European Union, 2012). Those regulations can have a considerable influence on the companies and the supply contracts that materialise. For example, REACH determines which goods may be marketed within the European Union, which may influence the exchange of goods, if one of the involved companies is situated in the EU. Moreover, the regulations also influence the facilities – e.g., by controlling what emissions are allowed, where facilities can be located, and what safety measures are needed for the production of a good.

Socio-technical connection Next to the connections within the social and technical networks, there are also connections between the social network and the technical network. The companies in the social network invest in, operate, and maintain the facilities in the technical network, which creates connections between the social network and the technical network. As a result of those connections, the two networks influence each other, which cause essential dynamics in the industrial system.

The social network influences the technical network through the supply contracts and regulations that impose requirements and constraints on the technical artefacts. For instance, the supply contracts between companies determine which quantities of what goods are going to be shipped between facilities. The supply contracts also determine at which rate the plants have to produce, in order to be able to ship the sold goods. The other way around, the technical network also influences the social network by setting the conditions for the supply contracts. The properties of a company's facilities (e.g., capacity, cost structure, location) determine what supply contracts can materialise. A company cannot supply more of a good than its plants can produce or have in stock, nor will it purchase more feedstock than its plants can process or can keep in stock. Furthermore, the cost structure and location (via the transport costs) of the facilities influence for what price a company can exchange its product and what price it is willing pay for its feedstock.

Implications for the conceptualisation The industrial system thus consists of companies that own and operate facilities. Those companies are connected to each other via supply contracts (or collaborative agreements) through which they exchange goods, while the facilities are connected through shipments. This means

[3]For an extensive overview of the regulation of industry in Europe, the United States and Japan and the effect regulation has on the industry, one is referred to Rubim de Pinho Accioli Doria (2010).

that the focal company's environment consists of its suppliers, competitors, and customers, as well as their facilities. So, to internalise the environment's complexity in a model, those companies and facilities need to be captured in the conceptualisation, as well the supply contracts and shipments that connect them to the focal company.

3.3 Complex adaptive system perspective on industrial systems

Using the socio-technical system perspective, we now have a clear understanding of the entities in an industrial system and how they are connected to each other. However, this perspective has provided a static snapshot of the system, as it did not explicitly consider the dynamics that are driving the development of the industrial system. The complex adaptive system perspective complements the STS perspective, as it focuses on the micro-(inter)actions of the system's entities, and how those (inter)actions lead to the emergence of the system's macro-patterns. We use the complex adaptive system perspective to identify the dynamics in the industrial system and assess how those dynamics are driving the development of the system as a whole.

3.3.1 The complex adaptive system perspective

A complex adaptive system (CAS) is defined by John H. Holland (Waldrop, 1992) as:

> '. . . a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a complex adaptive systems tends to be highly dispersed and decentralised. If there is to be any coherent behaviour in the system, it has to arise from competition and cooperation among the agents themselves. The overall behaviour of the system is the result of a huge number of decisions made every moment by many individual agents.'

The (inter)actions of the system's autonomous entities (agents) are central in the CAS perspective, as those are driving the system's macro-behaviour (Holland, 1995; Kauffman and Johnsen, 1991; Newman, 2003). Hence, to understand the system's macro-behaviour, one needs to analyse the interactions in the system. Van der Lei et al. (2010) present a framework to describe CASs. This framework consists of three different levels: the agent level, the network level, and the system level. Each level describes a CAS at a different conceptual level and thus also concerns different properties of the CAS. Figure 3.2 presents an overview of the three levels (right column) and their properties (left column); the agent level is presented in the bottom row, with the network level above that, and the system level on top.

Agent level The agent level describes the individual entities (i.e., agents) of the CAS. Each agent has a *state* that defines the properties of the agent (Wooldridge and Jennings, 1995) and *rules* that specify how the agent behaves – i.e., translates

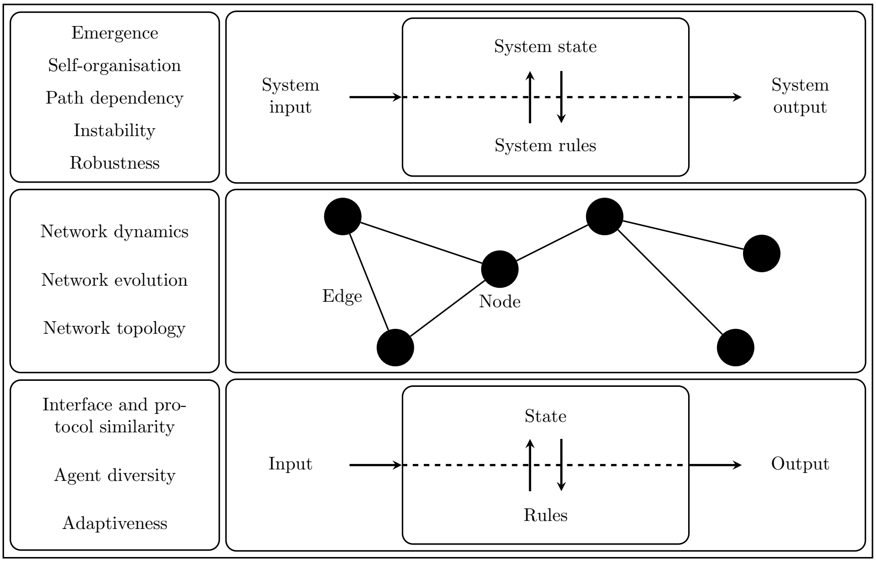

Figure 3.2: Conceptual framework of a complex adaptive system, with the three different levels in the right column (agent level at the bottom, network level in the middle, and system level on top) and their corresponding properties in the left column (Van der Lei et al., 2010).

the input and internal state to output and a new state (Holland, 1995). An agent is influenced by its environment (e.g., other agents) through its *input* and influences that environment through the *output* that materialises from its behaviour. The interaction between two agents thus entails the output of one agent that is the input of another agent. Important properties of the agent level are: interface and protocol similarity, agent diversity, and adaptiveness. *Interface and protocol similarity* ensures that the input and output of agents are aligned to each other, so that the agents 'understand' each other. *Agent diversity* is an important driver of the system behaviour (Kauffman, 1995, 2000; Waldrop, 1992). This concerns a variety of different agent types, as well as a variety of agents with different states (e.g., locations). *Adaptiveness* is the ability of agents to change their rules under the influence of changes in their inputs or internal state, in order to improve their 'fit' in the changed environment (Holland, 1995; Kauffman, 1993; Levin, 1998).

Network level The agents in a CAS are connected in a network through their interactions. Newman (2003, p. 2) describes a network as '. . . a set of items, which we will call vertices or sometimes nodes, with connections between them called edges.' In a CAS, the agents are the *nodes* and the *edges* are formed when agents interact. Those networks may be physical, with machinery as nodes and pipelines connecting them, but they can also be social, with organisations as nodes and social interactions connecting them. Each edge has a weight that indicates size of the flow across the edge or the edge's importance. Important properties of the network level are: network dynamics, network evolution, and network topology. *Network dynamics* entails the change of the edges' weights, as a result of changing flows through the network. *Network evolution* concerns the change of the network's structure, due to addition or removal of nodes and/or edges. *Network topology* regards the structure of the network, which determines its sensitivity to node or edge failure.

System level The system level regards the behaviour of the system as a whole that emerges from the networked interactions among individual agents. The system has a *system state* that often is the aggregated state of the components at the agent level and *system rules* that specify the system behaviour and are the aggregated rules of the agents. The system itself functions in an environment from which it receives *system input* and that it influences through the *system output* that materialises from the system behaviour. The system level has five important properties: emergence, self-organisation, path dependency, instability, and robustness. *Emergence* is the process whereby patterns at one system level arise from interactions at lower system levels (Crutchfield, 1994; Morin, 1999). Those patterns cannot be deconstructed solely into the actions at the lower levels (Jennings, 2000) and would not arise if the parts of the system were isolated (Morin, 1999). *Self-organisation* means that the system behaviour emerges spontaneously from the behaviour of individual agents without control by a central or outside authority (Kay, 2002; Prigogine and Stengers, 1984). *Path dependency* occurs when the past development of the system influences the (possible) behaviour of the system in the present (Vergne and Durand, 2010). *Instability* means that a system can suddenly switch to another attractor (Milnor, 1985) with minimal parameter changes (Gleick, 1997; Kellert, 1994). *Robustness* entails that the system behaviour ends up at the same attractor for a wide range of parameter values (Callaway et al., 2000).

3.3.2 Industrial systems as complex adaptive systems

It has been argued on multiple occasions that industrial systems are complex adaptive systems and thus can be observed from a CAS perspective (Choi et al., 2001; Pathak et al., 2007; Surana et al., 2005). In this section, we discuss the industrial system on basis of the three levels that were introduced in the previous section. At the agent level and the network level, we discuss the social and technical elements separately and explicitly remark how they are connected.

Agent level An industrial system consists of two types of entities: 'social' companies and 'technical' facilities. The companies are concerned with the business aspects of manufacturing and the exchange of goods, while the facilities handle the physical operations. The companies and facilities are connected through production orders that specify what operations the facility needs to perform.

Companies aim to maximise the returns on their invested capital by selling their product at the highest price, while buying their feedstock at the lowest (Koller et al., 2010). This requires the management of many different aspects of the company, which is described in the management literature (e.g., Porter, 1985; Stevenson, 2009). The *input* of a company is the demand for its product by potential customers, while its *output* consists of signed supply contracts with customers, demand for feedstock, and production orders assigned to its facilities. The *state* of a company involves those aspects that influence how it is managed, such as its price, cost structure, and financial position. How decisions are made regarding the management of company is specified by the *rules*. In the context of companies, *interface and protocol similarity* manifests itself through the standardisation of traded goods (Grey et al., 2005) or the use of common platforms where companies can interact (Gosain et al., 2003). *Agent diversity* materialises in the form of different sizes, product and geographic specialisations, or cultures. Companies *adapt* through reorganisations that aim to improve their profitability (Dekkers, 2005).

Facilities are the technical artefacts that handle, convert, and move the goods that are exchanged by their parent companies (e.g., Denn, 2011; Towler and Sinnott, 2013). The *input* of a facility concerns the production orders that it gets from its parent company, and the feedstock shipments that arrive from other facilities. The *output* of a facility is a shipment of product to another facility, which uses its as input. The facility's *state* mainly regards those properties that are related to the physical handling of goods, such as the production capacity, inventory of goods, and the available machinery and utilities. The *rules* of a facility specifies the production process that is used to convert the feedstock into product (e.g., Hess et al., 2007). Facilities have *interface and protocol similarity* in the form of the shipment of goods that occurs in standardised units, such as pallets, containers, or truckloads (Kemme, 2012). The *agent diversity* of facilities manifests itself through different locations, capacities, and production processes. The *adaptiveness* of facilities is seen through facilities that are upgraded over time to be competitive in the changing industrial system (e.g., Hounshell, 1985).

Network level At the network level, we distinguish the social network and the technical network. The social network concerns the companies that exchange goods with each other, while the technical network regards the facilities that ship goods to each other. The connection between the social and the technical network has been discussed in detail in section 3.2.

The **social network** consists of companies (*nodes*) that are connected via supply contracts (*edges*) (Borgatti and Li, 2009). A supply contract specifies the quantity of exchanged goods between two companies, which can also be 0. Hence, all companies that can exchange goods (i.e., the product of one company is feedstock of the other) are connected. The social network's structure thus indicates the potential to exchange goods, and the weights indicate the realised exchange of goods. The *network dynamics* of the social network concern the changing quantities of exchanged goods between companies, due to continuous negotiations between those companies (Helbing et al., 2004; Nagurney, 2006). The *network evolution* of the social network is the result of companies that are initiated or terminated, or that change their strategy to exchange different goods with other companies. Regarding the *network topology*, the social network consists of some large and diverse companies (i.e., conglomerates) that are connected to many companies and of many smaller and more specialised companies that are connected to fewer companies.

The **technical network** consists of facilities (*nodes*) that are connected via the shipments of goods (*edges*). The connection between two facilities indicates the ability to ship goods, while the weight of that connection indicates what quantity is actually shipped. Hence, the technical network's structure indicates the potential to ship goods, while the weights indicate the realised shipment of goods. The *network dynamics* of the technical network materialise as a consequence of shipments that change due to adjusted supply contracts or changed production rates of the facilities. The *network evolution* of the technical network is the result of the construction of new facilities and/or the closure of old facilities. The *network topology* of the technical network is fully connected, as (practically) all facilities are connected to the global transport system and thus can physically ship goods to each other.

System level The industrial system as a whole manufactures end-products (in multiple steps) from raw materials to meet the demand for end-products. This demand – as well as the shipments of raw materials – are the *system input*. As the demand for goods propagates upstream[4] (i.e., the demand of a particular good creates the demand for a more upstream good), the demand for the end-products is converted to demand for the raw materials. Likewise, the downstream propagation of the shipments of goods causes a conversion of the shipments of raw materials to the shipments of end-products. Both the demand for raw materials and the shipments of end-products are *system outputs*. The *system rules* are those rules that specify how the demand and the shipments propagate through the system. For the demand, this concerns the market protocols how goods are exchanged; for the shipments, the system rules concern the transport regulations that specify how goods can be transported. The *system state* involves the (aggregated) indicators of how the system develops as the demand and shipments of goods propagate through the system, such as the production rate of facilities, the quantities of shipped goods, and the price at which goods are exchanged.

The propagation of demand and shipments are the result of market interactions between agents (Gebert-Persson et al., 2014) and thus are *emergent* properties (Tesfatsion, 2002). Industrial systems have no central agency that allocates the work that needs to be done to meet the demand for the end-product, but the system *organises itself* via interactions between the agents (Choi et al., 2001). Both facilities and companies do not change easily, which implies that an industrial system is strongly influenced by decisions from the past and thus is *path dependent* (Arthur, 1994; Krugman, 1991; Mueller, 1997). Industrial systems can be *instable*, as relatively small events can have large consequences in industry systems. For instance, the 2000 fire at a Royal Philips Electronics factory is said to have resulted in Nokia – rather than Siemens – dominating the mobile phone industry in the decade that followed (Mukherjee, 2008). The focus of companies on stability and efficiency has caused the industrial system to become entrenched in its current mode of operating, which therefore makes it very *robust* to changes.

Holistic view on the industrial system As emphasised by Van der Lei et al. (2010), the three levels of the framework are merely conceptual. Those levels thus only are different ways of looking at the system and do not represent distinct parts of the system. This implies that changes at any conceptual level are changes of the whole system and thus also imply changes at the other levels. For instance, a changed supply contract (i.e., an agent's output) implies a change to the social network and a change to the propagation of demand through the system. Likewise, a changed shipment of raw materials (i.e., a system input) implies a changed shipment

[4]The upstream propagation of demand is a result of the companies whose input is the demand for their product and whose output is their own demand for their (more upstream) feedstock.

of feedstock to a facility and subsequently a changed technical network. Therefore, even though we discussed the different conceptual levels in isolation of each other, the developments in a complex adaptive system need to be assessed holistically, by considering all three levels and accounting for the fact that they are strongly related.

Implications for the conceptualisation The CAS perspective shows that the environment's complexity emerges from the interactions among companies over the supply of goods. The supply contracts and shipments that were identified in section 3.2 emerge from the market interactions among buyers and sellers of a particular good. This implies that – in order to internalise the environment's complexity – the conceptualisation should include the market interactions between the companies that form the industrial system.

3.4 Networked markets perspective on industrial systems

To further explore the propagation of demand and shipments through the industrial system, we analyse the industrial system from a networked market perspective. This perspective regards the industrial system as a network of coupled markets that influence each other and thereby cause the demand for goods to propagate through the system. We first discuss the market interactions of companies, which are fundamental to the markets and their coupling. Hereafter, we introduce the networked markets and discuss how this is driving the propagation of demand and shipments.

Market interactions Companies buy feedstock and sell the products that they produce using that feedstock. The supply contracts through which the companies exchange goods are the result of market interactions among the companies over the terms of the supply contract (Gebert-Persson et al., 2014). When two companies agree over those terms, they sign the supply contract and the demand of the buying company has been met. So, to sell its product, a manufacturing company interacts with potential customers to determine to which of those it should sell the product. Likewise, but to have its buy its feedstock, the company also interacts with potential suppliers to determine from which of those it should buy the feedstock. Simultaneously, the potential suppliers and customers have market interactions with multiple companies. They also interact with the focal company's competitors to determine to determine to whom they should sell the feedstock or from whom they should buy the product, respectively. This implies that, within an industrial system, a set of market interactions are conducted over the exchange of a certain good between multiple sellers and multiple buyers of that good. This set of market interactions leads to signed supply contracts, which connect the companies in the system's social network.

A set of market interactions over the exchange of a particular good, form a market for that good (Tesfatsion, 2006). We use the term 'market of a good' to indicate the set of companies that have market interactions over the exchange of that good. The market can take on many forms: a set of bilateral negotiations, a physical or digital platform where companies gather to exchange goods (such as the Aalsmeer flower auction), or brokerages that bring together buyers and sellers of a good. Depending on the number of buyers and sellers, the market can be a monopoly, an oligopoly, or can have perfect competition. So, by the term ‘market’, we mean the general concept of parties that engage in exchange and thus do not limit our discussion to a particular form or a level of competition.

Network of coupled markets Given that a company has market interactions to buy its feedstock and to sell its product, it participates in at least two markets: the market(s) for its feedstock and the market(s) for its products. By ‘participating in a market’, we mean that a company either uses or produces the good that is exchanged in that market and thus has market interactions over that good. When companies participate in multiple markets, their behaviour (e.g., price at which they want to sell their product) in one market is influenced by the outcomes of the other markets (Eckel and Neary, 2010). For instance, the price a company obtains for the product it produces influences the maximum price it is willing to pay for its feedstock. Next to that, when a company uses two types of feedstock and purchases one of them for a low price, it can pay a higher price for the other feedstock. In practice, we observe this as cross-subsidisation, where a company uses its strong position in one market to charge a higher price which it uses to lower its price in another market (Brennan, 1990). This implies that the participation of companies into multiple markets couples the development of those markets.

Industrial systems usually consist of a certain number of production processes that are needed to convert the raw materials to the end-product. Those processes are often performed by different companies that thus have to exchange a variety of intermediate goods with each other (Ehlen et al., 2014). This implies that an industrial system consists of a number of markets in which the different intermediate goods are exchanged. Given that companies in an industrial system participate in (at least) two markets and that the participation of a company in multiple markets couples those markets, the markets in an industrial system are coupled. Consequently an industrial system can be considered a network of coupled markets (Moyaux and McBurney, 2006). Figure 3.3 presents an example of an industrial system as a network of markets. The industrial system consists of three markets that are serially coupled. The raw material market consists of the suppliers that produce the raw material, the first-tier manufacturers that use the raw material, and their market interactions. The first-tier manufacturers use the raw material to produce an intermediate good and thus also participate in the intermediate good market. Consequently, they couple the raw material market to the intermediate good market. The same applies for the second-tier manufacturers that convert the intermediate good into the end-product, and thereby couple the intermediate good market to the end-product market.

The effects of coupled markets Moyaux et al. (2010) use the perspective of networked markets to represent supply chains and study the price dynamics throughout the supply chain. Their study concludes that the prices in the different markets are influenced by each other, and that the dynamics of those influences can be complicated. For an industrial system, this implies that the emerging supply contracts (and thereby the system behaviour) are not only the result of the market interactions over

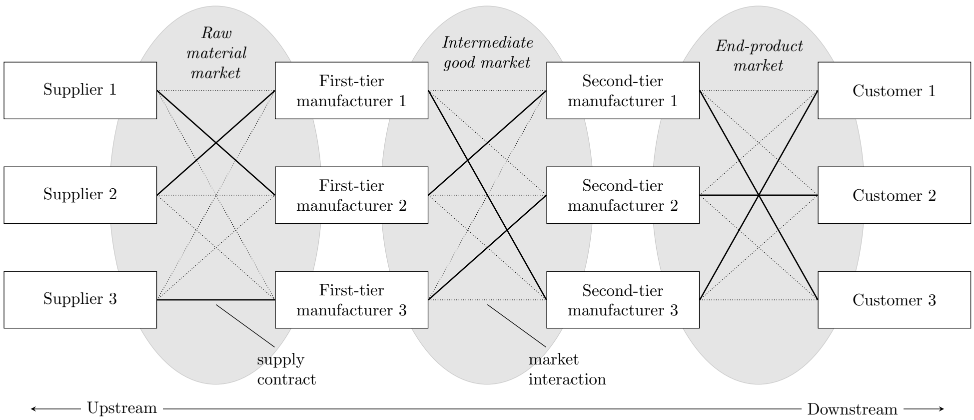

Figure 3.3: An industrial system conceptualised as a network of markets

the goods whose exchange they specify. The market interactions over other goods can also influence the terms of a particular supply contract. For instance, the prices of petroleum-based goods are to a large extent driven by the crude oil price and are only influenced partially by the market interactions over those goods (Nikkei Asian Review, 2014). Likewise, the supply contracts can also be influenced by the development of the market for an alternative good. For example, the price of natural gas used to be strongly connected to the crude oil price (Hartley et al., 2007).

As a consequence of those influences of the different markets on each other and the behaviour of the system as a whole, the entire relevant industrial system should be considered, even when only a part of that system (e.g., a single company) is assessed. By 'relevant industrial system', we mean all elements and interactions in the industrial system that have a substantial influence on the assessed part of the system and thereby on the outcomes of the assessment. So, when we assess a manufacturing company in an industrial system, we not only have to include its potential suppliers and customers, and its competitors, but we may also have to consider more upstream suppliers, more downstream customers, or companies that use or produce alternative goods. Which companies need to be included and which can be excluded should be determined by exploring their effect on the assessment outcomes and thus cannot be determined precisely on beforehand. However, by doing this multiple times, one can observe regularities and develop guidelines to identify the relevant industrial system.

Implications for the conceptualisation The networked markets perspective illustrates that the coupling of markets causes the market interactions of individual companies causes patterns at the system level – i.e., prices of goods, the propagation of demand, and the propagation of shipments through the system. Moreover, it also shows that the relevant industrial system may not be limited to the focal company and its suppliers, competitors, and customers. Other companies that are not directly coupled to the focal company can also influence the effects of an action. Therefore, the conceptualisation should not be limited to the focal company's direct environment, but needs to include all companies that can influence the system behaviour and thereby the outcome of the assessment.

3.5 Competitive strategy perspective on industrial systems

Now that we have an understanding of the elements in an industrial system and their (inter)actions, we can obtain insight into how a company's environment influences the effects of an action. Therefore, we analyse the industrial system from the competitive strategy perspective. Using this perspective, we identify the mutual influence between the focal company and its environment, how the environment adapts to the company's action, and how this affects the company's financial performance.

3.5.1 The competitive strategy perspective

Competitive strategy (also referred to as the value capture stream in strategy) is a sub-discipline of strategic management that researches the drivers of economic performance of companies in competitive markets (Brandenburger and Stuart, 1996, 2007; MacDonald and Ryall, 2004; Montez et al., 2013). Central notion in this perspective is that a company creates value for its customers, of which it can capture a part in the form of higher revenues (Grant, 2010). As we aim to assess the effects of an action on a company's financial performance, we limit our discussion to the financial value. How much of the created value the company can capture depends on the competition in the company's environment (Saloner et al., 2001). The revenues of a company thus are not considered to be a given, but can actively be influenced by the company, by capturing more of the created value.

Value creation A company creates value for its customers by enabling them to create more value for themselves using the goods (or services) supplied by the company. In general, companies create values for themselves by 'investing capital they raise from investors to generate future cash flows at rates of return exceeding the cost of capital' (Koller et al., 2010, p. 4). Hence, a company creates value for its customers if its goods enable the customers to generate larger cash flows. This can be done by supplying goods or services that decrease the costs of the customers or increase their revenues. For instance, a company that can supply goods to its customers with a shorter lead time, enables those customers to operate with less inventory, thereby reducing their holding costs (Silver et al., 1998). But also, by supplying higher quality goods, the customers may produce higher quality goods themselves that they can sell at a higher price.

Value capture If a company creates value for its customers, this only has a direct effect on the customers' financial performance. However, indirectly, the created value can affect the company's financial performance. This requires the company to capture a part of the created value for itself, by selling more of its product or by selling it at a higher price. When the company sells more of its product, it captures market share of its competitors and thus captures a part of their value; when the company sells its product at a higher price, it increases its revenues at the expense of higher costs for its customers and thus captures a part of their value.

How much of the created value can be captured by the company depends to a large extent on the structure and intensity of the competition in the market of the company's product (Saloner et al., 2001). In the previous section, we determined that the prices and quantities of exchanged goods emerge from the market interactions among companies. So, the focal company's captured value – and thereby its financial performance – depends to a large extent on the market interactions over the exchange of its products. For instance, due to the lower holding costs that follow from a shorter lead time, a company's customers are able to pay a higher price for the company's product. However, whether they actually will pay a higher price depends on whether the market interactions force them to do so, under the 'threat' of not being able to buy the product.

3.5.2 Effects of an action from a competitive strategy perspective

To define the mutual influence between a company and its environment and the adaptation of that environment, we analyse the effects of an action using the competitive strategy perspective. This implies that we study the consequences of an action in terms of value creation and value capturing.

Value creation The direct effect of an action is that it improves[5] the focal company's operations. For instance, a different production planning policy may enable the company to utilise its machinery more efficiently. For the company itself, the improved operations – due to lower costs or increased production – increases its net cash flows, thereby improves its financial performance, and thus creates value for it.

Next to the effect on its own net cash flows, the focal company's improved operations can also increase the net cash flows of its customers. As a result of the improved operations, the properties of the goods that the company produces may also become more attractive for the customers. For example, the more efficient use of machinery can cause better production conditions and the production of a higher quality good. Using the better good (i.e., the product with improved properties), the customers can improve their own operations, which can increase their net cash flows and thus creates value for them. For instance, when the customer uses the higher quality good as feedstock, it can produce more product per unit of the feedstock, which leads to higher revenues and thus larger net cash flows.

The focal company's improved operations can also cause it to capture a part of its competitor's market share. For instance, if the improved operations enable it to produce more of its product, the focal company may supply its product to customers that were initially supplied by its competitors. This implies that the focal company's improved operations may reduce the competitors' net cash flows and thus create negative value for them.

[5]In this discussion, we assume that a company only implements actions that improve its operations.

Value capture The changed net cash flows of the companies in the environment (i.e., competitors and customers) causes those companies to change their market behaviour. We use the term 'market behaviour' to indicate a company's outset that it uses as basic principles for the market interactions, which is driving its decisions during those interactions. For instance, when a company has larger net cash flows, it may be willing to pay a higher price for its feedstock. As the market behaviour of two interacting companies influences the outcomes of their market interactions (Li et al., 2003), the changed market behaviour of one company can substantially change the prices and volumes of exchanged goods. For instance, if one of the companies is willing to pay a higher price for the good, the price that emerges from the market interactions may be higher than it was initially. This entails that – depending on the level of competition – the created value for the customers can increase the focal company's revenues. However, competitors – whose value decreased – may respond by lowering the price they are willing to accept, thereby indirectly lowering the revenues of the focal company. Consequently, the changed market interactions can have different consequences for the focal company's net cash flows.

In response to the changed cash flows, the companies in the environment may also make more structural decisions. For instance, the smaller net cash flows of a competitor may force it to terminate its business. On the other hand, it may also decide to invest in a more competitive new facility in order to recapture its market share. All those structural changes influence the market behaviour of the companies, which – via the changed market interactions – affect the net cash flows of the focal company. For instance, as a consequence of its larger net cash flows, a customer may decide to increase the capacity of its facility. This increases its demand for the focal company's product, which leads to more competition over the product and possibly a higher price.

The changed revenues, which are the result of the captured (negative) value, change the net cash flows of the focal company. Those changed cash flows are an indirect effect of the action, since they materialise via the focal company's environment. However, together with the action's direct effects on the net cash flows, the indirectly changed cash flows can have a substantial influence on the focal company's financial performance. This means that, to assess the consequences of an action comprehensively, both the direct and indirect effects on the net cash flows should be considered.

Direct and indirect effects of an action Figure 3.4 presents an overview of the mechanisms that cause an action to influence the focal company's financial performance. This overview shows that an action affects the focal company's performance in two ways: directly and indirectly via the environment. The focal company influences its environment via the improved properties of its product and its increased production. This influence causes the environment to adapt to the action. The environment's adaptation has two aspects. First, the market dynamics in the form of companies in the environment that change their market behaviour in direct response to the changed net cash flows. Second, the market evolution in the form of structural changes in the environment that changes the market behaviour in the longer run. The changed market behaviour subsequently influences the net cash flows of the focal company via changed supply contracts. So, via the mutual influence be-

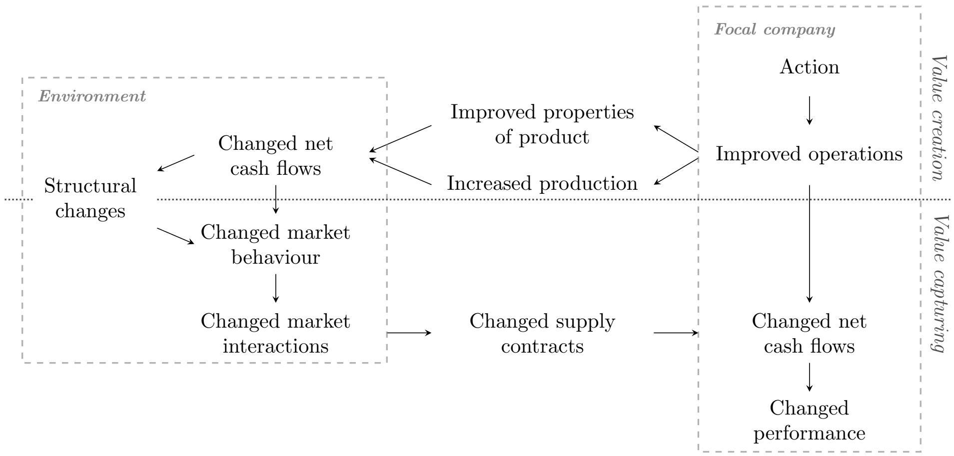

Figure 3.4: Overview of the mechanisms that cause the direct and indirect effects of an action

tween the focal company and its environment, an action indirectly affects the focal company's financial performance, which may substantially change the consequence of an action.

Implications for the conceptualisation This perspective shows that the indirect effects of an action materialise to a large extent from the market interactions between the focal company and its environment. Next to the market interactions, the response of the companies in the environment (i.e., changed market behaviour and structural changes) also contributes to the indirect effects. The conceptualisation thus should not only include the market interactions among the companies in the industrial system, but should also include the companies' considerations regarding their response to changes in the system.

3.6 Synthesis

In this chapter, we described the industrial system through four different lenses: the socio-technical system perspective, the complex adaptive system perspective, the networked markets perspective, and the competitive strategy perspective. Together, those perspectives gave a comprehensive overview of the industrial system and the mechanisms influencing the direct and indirect effects of an action.

The socio-technical system perspective showed that an industrial system consists of companies and facilities. The facilities handle and convert goods that are shipped between them with shipments. The companies, on the other hand, arrange the physical handling of goods by their facilities and are connected to each other via supply contracts and collaborative agreements. The focal company is the company (and its facilities) for which the simulation is executed, and its environment involve all other companies and facilities in the system.

The complex adaptive system perspective focused on the behaviour and interactions in the industrial system. It showed that the facilities interact with each other by shipping goods to each other. Hereby, they form a technical network that specifies how the different goods in the system are shipped. The companies interact with each other over the exchange of goods. Through those interactions, the companies form a social network that specifies how the goods are exchanged between companies and for what price. So, the market interactions among autonomous companies are driving the emergence of the complexity in the industrial system, and thus are central to the new conceptualisation.

Those market interactions were further analysed with the networked markets perspective. This perspective showed that the participation of companies in multiple markets to exchange goods couples those markets and makes the industrial system a network of markets. Through those coupled markets, the effects of an action can be influenced by parts of the system that are not directly related to the focal company. Hence, the relevant industrial system needs to be chosen to include those companies and facilities that may influence the performance of the assessed action.

Whereas the previous three perspectives focused on the composition of the industrial system, the competitive strategy perspective analysed how the industrial system can influence the effects of an action. This showed that an action has direct and indirect effects on the focal company's performance. The direct effects influence the focal company's net cash flows only through internal changes, such as cost reductions. The indirect effects, on the other hand, first influence the company's environment, which causes the environment to adapt. Those adaptations may occur in the form of operational changes (i.e., changed market behaviour) or topological changes (i.e., structural changes in the environment). Both types of adaptation influence the market interactions in the environment and between the environment and the focal company. Those changed market interactions then influence the focal company's net cash flows via the changed supply contracts that emerge from those interactions. This implies that the market interactions are essential for the assessment of an action's indirect effects, but that those effects are also influenced by how the environment adapts to the action.

All those insights into the composition and functioning of the industrial system form the foundation of the new conceptualisation. This means that those insights need to be combined into a comprehensive view on the industrial system. By implementing this view into a simulation model, it becomes possible to simulate the industrial system and assess the effects of the focal company's action. In the following five chapters, we develop and use simulation models that apply this new conceptualisation, with the purpose of assessing a variety of action that can enhance the focal company's resilience. Each case study implements the conceptualisation differently and consequently internalises other aspects of the environment's complexity.

Part II

Case studies

Chapter 4

Supply network reconfiguration

This chapter is based on Bas and Van der Lei (2015b)[1] and Bas et al. (In press 2017b)[2].

4.1 Introduction

In this chapter, building upon the theoretical foundations of chapter 3, we develop a simulation model to assess the consequences of reconfiguring a company's network of facilities. Industrial companies often operate multiple facilities, which are connected to each other via material, information, and monetary flows (Christopher, 2011). This supply network can be configured in a variety of ways. With their focus on efficiency, manufacturing companies generally use large plants that can supply a large region and operate a relatively centralised supply network. However, due to the development of small-scale production facilities, decentralised supply network configurations are expected to be considered more often (Bieringer et al., 2013). Therefore, insights are needed in the performance of decentralised supply networks in comparison to centralised supply networks.

Operating multiple smaller plants makes the company less vulnerable to disruptions in a single plant and to local disturbances. A decentralised network configuration thus increases the company's resilience to those kind of issues. However, this increased resilience comes at a price of higher investments and logistical costs. The network configuration influences the availability of the company's products as well as its market strategy and hence may have a considerable influence on the entire industrial system. Therefore, an assessment of the indirect effects of a supply network configuration on the company's financial performance could improve the decision-making regarding the configuration.

[1]Bas, G. and Van der Lei, T. (2015b). Simulating a global dynamic supply chain as a market of agents with adaptive bidding strategies. *Chemie Ingenieur Technik*, 87(9):1230–1239.

[2]Bas, G., Van der Linden, D., Nikolic, I., and Van der Lei, T. (In press 2017b). Integration of market and supply chain dynamics: Simulating the impact on business decisions. *Journal of Artificial Societies and Social Simulation.*

The model developed in this chapter is the first step in an iterative process of complex model development. The model involves a substantial extension to the existing models, as it internalises part of the focal company's environment's complexity into the model. The model's dimensions of complexity are as follows:

- *Diameter of the industrial system*: five tiers.
- *Possible market interactions*: focal company's current partners in its current market.
- *Types of changes caused by the focal company*: operational changes.
- *Types of changes caused by the environment*: operational changes.
- *Types of changes caused by the market interactions*: operational changes.
- *Detail of the environment's representation*: aggregated raw material suppliers.
- *Decision rules*: coupled single-sided auctions.
- *Considered features*: supply, demand, and location.

Besides assessing the effects of a supply network reconfiguration, we apply the model to demonstrate how the indirect effects influence the outcomes of the assessment. We evaluate this influence by assessing the focal company's performance (when operating decentralised) without enabling the environment to adapt and the focal company's performance with enabling the environment to adapt. The difference between the performance in those two situations is due to the indirect effects of the supply network configuration. The simulation and comparison of those two situations thus enables us to assess whether the used conceptualisation can account for the configuration's indirect effects and whether those influence the assessment's outcomes. However, before we get to that, we start in section 4.2 with an overview of the supply network configuration and the related literature. This is followed, in section 4.3, by a description of the model specifications. In section 4.4, we then present the experiments that are performed to assess the effect of supply network reconfiguration and to demonstrate the influence of the indirect effects. Hereafter, section 4.5 discusses the implications of the experimental outcomes with regard to two objectives of the experiments.

4.2 Supply network configuration

Network configuration We introduced in section 3.2 that each company owns, maintains, and operates a set of facilities, such as plants and distribution centres. Those facilities are interconnected via material, information and monetary flows and together form a network that the company uses to convert feedstock into products and supply those to its customers (Christopher, 2011). This *supply network* thus only consists of the facilities of a single company. In contrast, a supply chain is a sequence of autonomous companies (and their facilities) that supply goods or services to each other, with the purpose of making end-products available to end-consumers (Lambert and Cooper, 2000; Mentzer et al., 2001). A supply chain thus extends the scope beyond a single company and consists of multiple coupled supply networks.

Supply network design is the process that is involved with designing a supply network that can efficiently collect feedstock, convert them to products, and distribute those to the customers (Farahani et al., 2014). This may entail designing a network from scratch, but often concerns re-engineering an existing supply network by making improvements to the design. Depending on the scope of the supply network design, a company makes one or more decisions with regard to operational (e.g., provided service level), tactical (e.g., inventory volume and type in facilities), strategic (e.g., number and location of facilities) of the network design (e.g., Baghalian et al., 2013; Miranda and Garrido, 2004).

An important aspect of supply network design is the supply network configuration[3]. This is defined by Fleischmann et al. (2000, p. 660) as: 'the number of locations at which similar activities are carried out. In a centralised network each activity is installed at a few locations only, whereas in a decentralised network the same operation is carried out at several different locations in parallel'. The network configuration has two extreme forms: *1*) fully centralised configuration, whereby the company operates a single facility that produces all its products and distributes them to all its customers; and *2*) fully decentralised configuration, whereby the company operates a multitude of facilities that each are dedicated to the production and distribution of products for a single customer. Besides those extreme configurations, intermediate forms are also possible: for example, when the company operates one plant and then distributes its products via multiple distribution centres to its customers.

Next to this structural aspect, the network configuration also has a managerial aspect, which determines the autonomy of the facilities in setting their own policies, such as production planning (Saharidis et al., 2006), inventory replenishment (Chen and Chen, 2005), and pricing (Jørgensen and Kort, 2002). This managerial aspect has the same extremes as the structural aspect: fully centralised and fully decentralised. A managerially centralised supply network is controlled by the head office, which should lead to better coordination among the facilities. However, in a managerially decentralised supply network, each facility can set its own policy, which should lead to policies that are better aligned with the specific situation of each facility.

Network configuration literature Over the years there has been a considerable amount of research into the supply network configuration. In those studies, the issue of the supply network configuration has often been combined with the issue of facility location (Amiri, 2006). This combination of issues is natural, as they are closely connected: the number of facilities changes the optimal locations, and the available facility locations may change the optimal number of facilities (e.g., Mourtzis et al., 2012; Santoso et al., 2005; Wang et al., 2011). In recent years, a lot of network configuration research focused on closed loop supply chains (Aravendan and Panneerselvam, 2014; Clarke-Sather, 2009). Those studies are not only concerned with the number of facilities needed to efficiently handle the forward flow of goods, but also with the reverse flow of goods that closes the loop (Carter and Ellram, 1998). The reverse flow involves the collection of goods from many different locations, which makes the network design a fundamentally different issue than for regular linear supply chains (Fleischmann et al., 1997).

The methods used for network design (and network configuration, in particular) can be grouped into four distinct categories (Beamon, 1998): *1*) deterministic analytic models, *2*) stochastic analytic models, *3*) economic models, and *4*) simulation

[3]Although Fleischmann et al. (2000) uses the term 'network centralisation', we prefer 'network configuration' as it does not suggest a preference towards a centralised network.

models. Analytic models allow the 'optimal' network design to be found through approaches such as linear programming (e.g. Pishvaee et al., 2009), heuristics (e.g. Lee and Dong, 2008), and simulated annealing (e.g. Lee and Dong, 2009). However, they have some strict assumptions that are needed to ensure that they are analytically solvable. Deterministic analytic model are analytic models where all variables are known, whereas stochastic analytic model are analytical models where at least one variable is uncertain (Hritonenko and Yatsenko, 1999). The economic models use game theoretic frameworks to add behavioural components to the network design, such as cooperation or competition (Cachon and Zipkin, 1999). Simulations are generally not used to find the optimal design, but to test a possible design (optimised with an analytical model) in a richer representation of the system. The richer representation is possible in a simulation, because simulations can relax the strict assumptions of analytical models (Izquierdo et al., 2013).

The majority of the network design and network configuration studies limit their focus to a company's own supply network. Aspects outside this supply network are typically only considered in the form of exogenously specified sources of feedstock and sinks of product, while the role of market interactions with other organisations is generally disregarded completely (Farahani et al., 2014). Although there have been studies that consider competition between supply chains (e.g. Boyaci and Gallego, 2004; Xiao and Yang, 2008; Zhang, 2006), those studies assume a fixed network design and therefore have a limited ability to account for the adaptation of other organisations to a changed network design. As analysing network configurations inherently results in changing network designs, those studies thus have a limited use for designing and analysing network designs (Farahani et al., 2014). Hence, the existing network configuration models are not suited for a network design's assessment that accounts for the indirect effects of the design.

4.3 Model description

We implement the insights of chapter 3 into an agent-based model. The industrial system is thus represented as a set of autonomous companies that interact with each other through markets, enabling the supply contracts between companies to adapt as the focal company changes its supply network configuration. This section describes the model according to the overview, design concepts, and details (ODD) protocol (Grimm et al., 2006, 2010), which is suited to provide a complete and reliable account of agent-based social simulation models (Polhill et al., 2008).

Section 4.3.1 explicitly discusses the purpose of the model and provides an initial introduction of how the model achieves that purpose. In section 4.3.2, we identify the different entities in the model (i.e., agents and objects) and discuss the state variables that characterise them. An overview of the agents' behaviour and interactions is provided in section 4.3.3; this behaviour is discussed in more detail in appendix A. Hereafter, section 4.3.4 gives an overview of the design concepts that characterise the model through a discussion of how it implements different elements of complexity. To use the model for experiments with different supply network configurations, we need to initialise the agents and objects at the start of a simulation run. Section 4.3.5 discusses how the state variables of the agents and objects are initialised for each run.

4.3.1 Purpose of the model

The aim of the model is to assess the effect of different network configurations, while capturing the adaptation and complexity of the industrial system that surrounds the focal company. For that purpose, we simulate the industrial system as a complex adaptive system in which the market interactions among companies form a network of markets. The supply contracts, which have a substantial influence on the focal company's financial performance, emerge from those market interactions. Consequently, those supply contracts can adapt to changes in the market, such as a company that changes its supply network configuration. By including the adaptation of supply contracts in the assessment, we can obtain more comprehensive insights into the effects of the supply network reconfiguration, which may improve the decision-making.

4.3.2 Entities, state variables, and scales

The model consists of companies that are geographically dispersed and assumed to operate autonomously. The 'company' agents combine the companies and facilities that we discussed separately in chapter 3; separating them would only increase the model's complexity without providing additional insights. Each of those companies performs a certain production process, which specifies what feedstock is used and what products are produced. The goods are exchanged through supply contract that emerge from the market interactions among companies. The physical supply of goods occurs through shipments that execute the supply contracts.

Companies Companies buy feedstock from other companies, convert them to product, after which those are sold. Each company is located at a *site*, which specifies its location in the world. The kind of conversion performed by a company is defined by *my process*, while its *capacity* specifies how many times it can perform this conversion in a single time step. The percentage of feedstock that is actually converted to product is defined by the company's *efficiency*. Each time the company performs the conversion, it incurs *variable costs*; on the other hand, the *fixed costs* are incurred every time step, independent of how many times the conversion is performed. The company will sell its products if the net-price it receives per unit of product is higher than its *willingness to accept*, which equals the costs it has incurred to produce the product. The purchase of feedstock will only continue if the company can buy it at a gross price (i.e., net price paid to the seller + the costs of transporting the feedstock) that is lower than its *willingness to pay*. The willingness to pay is the amount of money that is left of the net price (at which the product is sold) after the costs of producing the product have been deducted.

Production processes Production processes define the type of conversions performed by the companies. Each process has an *input*, which specifies the type and quantity of good that are used as feedstock of the conversion. Similarly, the *output* specifies what type and quantity of good are produced by the conversion.

Supply contracts Supply contracts emerge from the market interactions between companies and represent the exchange of a good between a selling company (*origin*) and a buying company (*destination*). The *quantity* of a contract defines what quantity of a *good* is exchanged. The price paid by the destination for one unit of the good is specified in the order's *gross price*, of which the origin receives – after deduction of the transport costs – the *net price*. For this model, we assume that all supply contracts are spot contracts and thus cause the direct one-time supply of goods. Supply contracts for a longer time period are not considered to limit the complexity of the model and enable the market dynamics to emerge quickly.

Shipments Shipments represent the execution of supply contract (i.e., the physical transfer of goods) and thus have the same properties as those contracts.

Global variables The global variables are properties of the system that are not exclusive to a single agent, but are available to all agents. The *buyers* and *sellers* are catalogues of the companies that are respectively buying or selling any good. An overview of all traded goods is provided in *goods*, which is a list of goods ordered from most upstream to most downstream. The properties of transport are also considered to be commonly known. Those concist of the *transport expenses* and *transport duration*. Both those variables specify for all combinations of sites the expenses and duration of transporting a good between that specific combination of sites. That way, geographical differences, changes in the logistics market, and import tariffs can be included in the model.

Scales The model's spatial scale concerns the transport expenses and duration between companies, as those influence the companies' behaviour, while the physical distance is not directly of importance to them. The model has no limit to the maximum spatial scale and thus can represent global industries. As shipping of goods typically takes multiple days or even weeks and the ordering of goods often occurs at a weekly basis, the minimum time step in the model is set at a week. This entails that a time step in the model represents a single week and companies can interact each week with each other over the supply of goods. The behaviour of the agents is limited to an operational horizon, which implies that the insights of the model are only valid over a period of up to around two months. After that period, companies will display behaviour with a tactical or strategic horizon, which is likely to affect the model outcomes. As this behaviour is not captured in the model, simulation outcomes beyond two months are likely to deviate substantially.

4.3.3 Process overview and scheduling

The processes, which specify the behaviour of the agents, can be categorised into two phases: the negotiating phase and the shipping phase. In the negotiating phase, the companies negotiate with each other on the terms of their supply contracts. The markets for different goods are simulated successively, starting with the most downstream good and iteratively continuing more upstream. This allows the buyers of a good to update their willingness to pay and demand to reflect the sales of their (more downstream) product, which couples the markets. In the shipping phase,

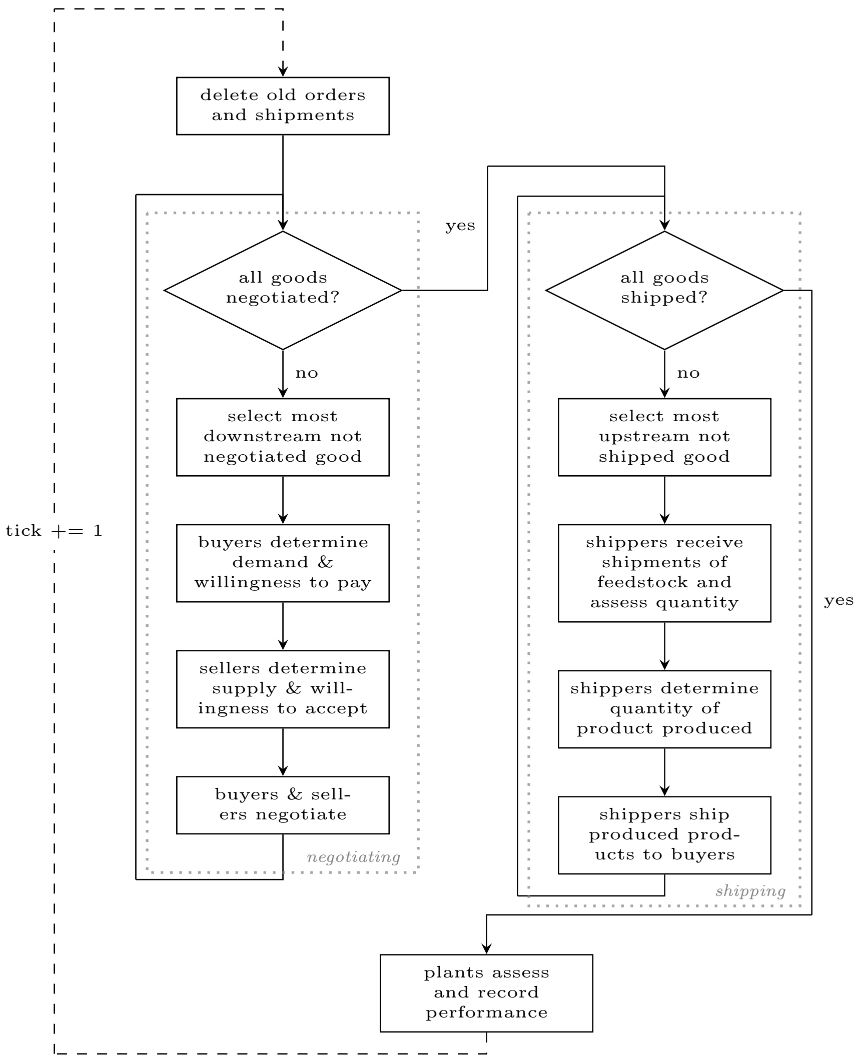

Figure 4.1: Process overview of the supply network reconfiguration model

the companies ship the ordered goods – to the extent possible – to each other. The quantity of product a company can supply depends on the quantity of (more upstream) feedstock it has received. Hence, in the shipping phase, the shipment of goods is also simulated successively; however, the shipping phase starts with the most upstream good and iteratively continues more downstream. An overview of the model's processes and their categorisation into the negotiation and the shipping phase is provided in Figure 4.1.

Negotiating phase A new time step start with *deleting the old contracts and shipments*, so that they do not interfere with the negotiations in the current time step. Subsequently, it is *decided if all goods have been negotiated* in this time step.

Unless this is the case, the *most downstream not yet negotiated good is selected*, so that iteratively more upstream goods are negotiated. The buyers that want to buy the selected good then *determine their demand for that good and their willingness to pay* (section A.1). Those are both based on the supply contracts that the buyer has received for the sale of its product. Hereafter, the sellers that can supply the selected good *determine the quantity they can supply and their willingness to accept* (section A.2). The seller assumes it can supply its entire capacity, and is willing to accept a net price that is higher than the costs of procuring its feedstock (in the previous time step) and the cost of converting that to the product. Once the demand and supply are determined, the *buyers and sellers negotiate* to establish the supply contracts for the selected good (section A.3). Those negotiations are conceptualised as a set of coupled single-sided auctions[4]. This conceptualisation allows the representation of a many-to-many negotiation (Wooldridge, 2009) with the ability to include transport costs in the negotiations.

Shipping phase The shipping phase follows upon the negotiating phase, and starts by *deciding if all goods have been shipped*. If this is not the case, the *most upstream not yet shipped good is selected*, so that iteratively more downstream goods are shipped. The shippers (i.e., the companies that can supply the selected good) first *receive shipments of their feedstock* (section A.4), after which they *determine the quantity of the selected good they can produce* from the received feedstock (section A.5). Subsequently, the shippers *ship the produced quantity to the buyers* by creating shipments (section A.6). The contracts with the highest net price are shipped first, followed by contracts with lower net prices. This ensures that, if the shipper can produce less product than anticipated, the buyer that paid the highest price has the biggest chance of obtaining the good. The shipment of goods is assumed to be executed within one week. However, the costs of the shipment duration are included the transport expenses.

Once all goods have been shipped, the companies *assess and record their performance*. In this model we record the operating margin of the company, which is computed by dividing a company's profits by its revenues. As both the profits and revenues of a company are based on its received and sent shipments and those shipments emerge indirectly from the market interactions, the performance of a company can thus be influenced considerably by those market interactions.

4.3.4 Design concepts

The design concepts of an agent-based model describe how different aspects of complexity have been implemented in the model. Grimm et al. (2010) define nine aspects that characterise the model: *1*) basic principles, *2*) emergence, *3*) adaptation, *4*) objectives, *5*) learning, *6*) sensing, *7*) interaction, *8*) stochasticity, and *9*) observation. A more detailed explanation of those concepts is provided in Grimm and Railsback (2013).

[4]Note that this is not the same as the coupled markets we discussed in section 3.4. The industrial system is represented as a set of coupled markets, and each market is conceptualised as a set of coupled single-sided auctions.

Basic principles: The core of this work entails that the assessment of supply network configuration can be improved by capturing the environment's adaptation as interacting companies. *Emergence:* Those interactions lead to the emergence of prices and flows of goods, which influence the financial performance of the companies. *Adaptation:* During the negotiations, buyers adapt their bidding strategy to the supply offered by the sellers; on the other hand, the sellers adapt their offering strategy to the price bid by buyers. *Objectives:* A company's primary goal during to the negotiations is to sell (buy) its entire supply (demand); only when this primary goal is fulfilled, it aims to maximise (minimise) the price of the negotiated good. *Learning:* The companies learn – albeit in a simple way – by changing their market behaviour in one market based on the outcomes of the other market in which they participate. *Sensing:* The companies are only aware of the information that is communicated to them during the negotiations (i.e., received offers and bids) and are ignorant of the other negotiations. *Interaction:* The companies interact through the bids and offers they make during the negotiations, the supply contracts that follow from those negotiations, and by the shipments of goods. *Stochasticity:* The stochasticity in the model is limited to the scheduling of the agents. *Observation:* The main outcomes of the model are the companies' operating margins, as an indication of how their financial performance is affected by the assessed supply network configuration. More general insights into the effect of the intervention on the development of the supply chain are obtained by measuring the prices and flows of goods.

4.3.5 Model initialisation

The entities and state variables in the model are initiated so that they represent a real-world polymers industry. This industry is involved with the production of the plastic casing that surround consumer electronics cables. The companies in this model thus represent the major companies that perform processes that directly and indirectly contribute to the production of those cables. The initialisation presents an overview of the production processes and the companies that form the industry. For reasons of confidentiality, the raw input data cannot be provided and the discussed values have been multiplied with a random factor.

Production processes The production of consumer electronics cables consists of five consecutive production processes, which are connected by four different goods. Consequently, the industrial system can be considered as a network of four serially coupled markets. Table 4.1 gives an overview of the sequence of production processes that are performed to produce the end-product, as well the type and (relative) quantity of goods used and produced by each of the processes. The production processes are coupled via their products, since one process produces the good that is used by another process.

Companies Each process is performed by a set of companies that are dispersed over the world, in three supranational regions: Europe, North America, and Asia-Pacific. Overall, the demand and supply of each good are roughly balanced. However, within the supranational regions, there are considerable differences between the demand and supply of the goods, so that shipments of goods between regions

Table 4.1: Sequence of processes in the polymers industry

Process	Feedstock Type	Feedstock Quantity	Product Type	Product Quantity
Monomer supply			Monomer	1.00
Polymer production	Monomer	1.00	Polymer	0.95
Compounding	Polymer	0.90	Compound	1.00
Cable production	Compound	0.50	Cable	1.00
Cable assembly	Cable	1.00		

Table 4.2: Distribution of companies over supranational regions in the polymers industry

	Europe		North America		Asia-Pacific	
Process	# com.	% cap.	# com.	% cap.	# com.	% cap.
Monomer supply	1	12%	1	44%	1	44%
Polymer production	2	28%	1	42%	2	30%
Compounding	3	41%	2	22%	3	37%
Cable production	2	36%	1	17%	3	47%
Cable assembly	1	15%	3	15%	6	70%

are needed. Table 4.2 provides, per process, an overview of how many companies (*# com.*) are located in each region and how the capacity of the companies (*% cap.*) is distributed over the three regions. The monomer suppliers have been aggregated into regional suppliers, even though in the real case there are many companies per region. To represent the large amount of monomer suppliers, we assume that each monomer suppliers is located at a distance of 100 km from the polymer producers in its region.

The monomer suppliers have a minimum price they are willing to accept for their goods of around €1,600/mt. At the downstream side of the industry, the cable assemblers are willing to pay around €23,000 for a metric tonne of cable. The efficiency of the companies differs slightly, ranging between 90 % and 95 %. The same applies for the fixed costs, which range from €1,500/mt to €1,600/mt (at full capacity). The variable costs differ per process: polymer producers, compounders, and cable assembler have variable costs of around €1,500/mt, while cable producers have variable costs of around €7,500/mt. In line with the real-world system, the production costs and efficiencies differ per company, which causes geographical differences in that regard.

With regard to the transport costs, we consider both the land-based (truck or train) transport costs and costs of deep-sea shipment. For the latter we used the market prices that applied at the time of the case study and processed them to allow realistic differences between regions. In practice, this resulted in intra-region transport costs between €20/mt and €1,000/mt (depending on the region and the distance) and inter-region transport costs between €1,200/mt and €2,500/mt (depending on the regions and the shipped good).

4.4 Assessing supply network configurations

Using the model, we perform a set of experiments to assess the effects of a decentralised supply network configuration and to demonstrate the influence of the supply network configuration's indirect effects on the simulation outcomes. For that purpose, we simulate the development of the industrial system for different supply network configurations of a focal company. The experiments are divided into three parts: *1*) simulating the industrial system to assess the performance of a centralised network configuration; *2*) computing the performance of a decentralised network configuration (i.e., replacing one large centralised plant of the focal company by multiple smaller plants with corresponding higher production costs) on basis of the supply contracts that materialised in the first experiment; and *3*) simulating the industrial system (with a changed structure due to the centralised plant that is replaced by the smaller plants) to assess the performance of a decentralised network configuration. As we use the shipments from the first experiment to compute the performance in the second experiment, the environment in the second experiment thus cannot adapt to the changed network configuration. In the third experiment, this adaptation is possible, as we simulate the industrial system with the decentralised network configuration and use those new shipments to determine the effects of the decentralised configuration. So, the second experiment does not assess the indirect effects of the changed network configuration, while those are assessed in the third experiment.

The simulations cover a period of 20 time steps, which in preliminary experiments has been found to be sufficient for the industrial system to reach a stable state. At the end of this period, we record the prices and volumes of goods between companies. To limit the effects of stochasticity, each simulation is repeated 100 times and the median outcomes are presented. The variability testing showed that, with a mean relative standard deviation of 3% for both prices and volumes, the model outcomes had little variability. However, due to the low run time (i.e., 1 minute per simulation run on a regular personal computer) and relatively simple experimental design a substantial number of repetitions could be selected.

4.4.1 Centralised supply network configuration

In this section, we assess the effects of the centralised supply network configuration of the focal company. Those effects are split into two categories: the overall development of the industrial system and the focal company's financial performance.

Industrial system development The prices and volumes of goods provide insights into the overall development of the industrial system. Figure 4.2 indicates per good the net prices obtained by the sellers and the gross prices paid by the buyers. Due to the incurred (fixed, variable, and transport) costs, the prices of more downstream goods are higher than the prices of the upstream goods. Next to the costs, the prices are also influenced by the ratio of demand and supply. For instance, the oversupply of cables in Europe depresses its price, which – based on the costs of monomers and the costs of processing them – should be higher than the prices in North America and Asia-Pacific.

The volumes of goods supplied between companies are presented in Figure 4.3,

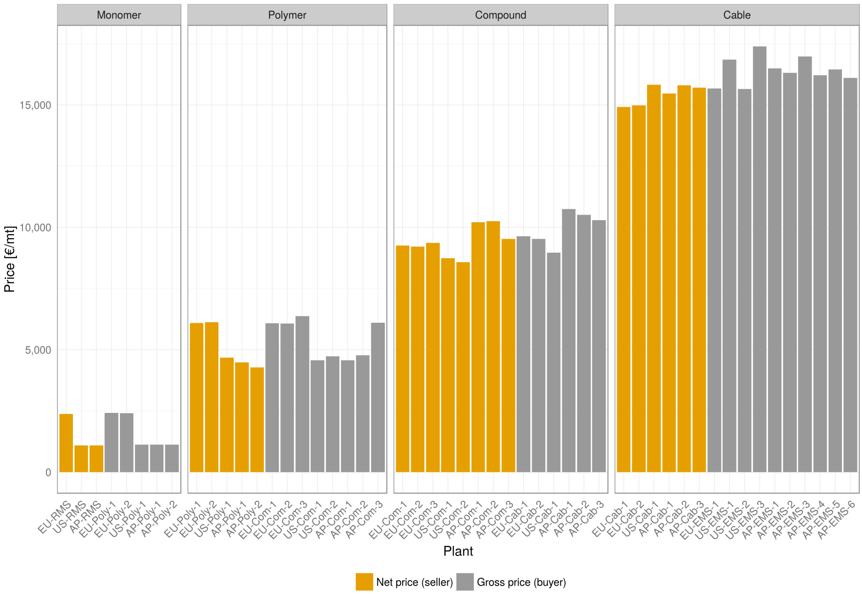

Figure 4.2: Simulated prices of goods with a centralised supply network configuration

which indicates that the majority of flows are within the regions, while only limited volumes are transported between regions. This pattern is in line with the expectations, as it is relatively expensive to transport goods between regions. Hence, a company will prefer to purchase feedstock from suppliers within the region. Both the prices and the flows of goods that emerges from the simulation have been compared to empirical data of the real-world industry. The prices had a mean absolute percentage error (MAPE) of 8 % (gross price) and 13 % (net price), and the MAPE of the flows of goods amounted to 22 %. Given the uncertainty with regard to the input data, these errors are relatively small and the model is considered an adequate representation of the modelled industry.

Focal company's financial performance The focal company of this study is a polymers producer in North America (*US-Poly-1*). Its supply network configuration is centralised: it operates a single plant from where it ships its goods to multiple geographically dispersed customers. Figure 4.3 indicates that US-Poly-1 obtains its monomers from the North American monomer supplier and that it sells its polymers to four compounders: two of which are situated in North America, one in Europe, and one in Asia-Pacific. Table 4.3 presents an overview of US-Poly-1's supply contracts, specifying the bought/sold quantities and the prices. The supply contracts to sell goods specify the revenues of US-Poly-1 and the contracts to buy goods specify its purchasing costs. Table 4.4 gives an overview of US-Poly-1's revenues and costs, including a specification of the costs into purchasing costs, fixed costs, and variable costs. With revenues of k€ 5,127/wk and total costs of k€ −4,729/wk, US-Poly-1 has a profit of k€ 398/wk and an operating margin of 8 %. This implies that per € 1 of sales, US-Poly-1 has a profit of € 0.08

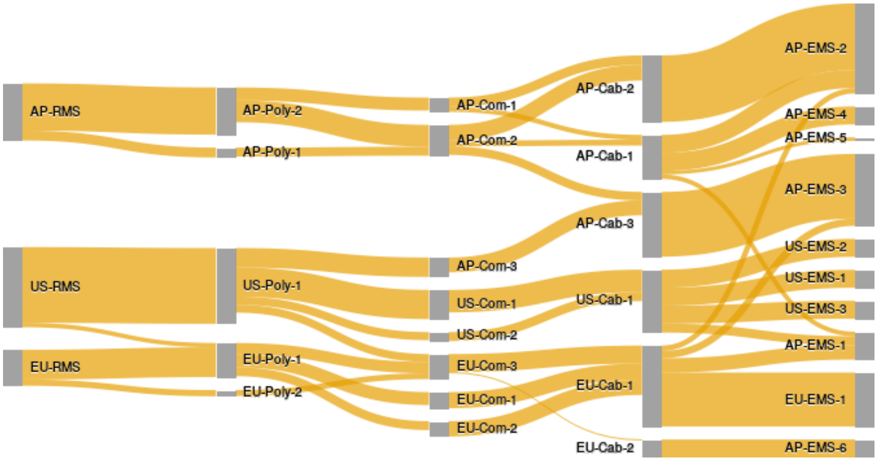

Figure 4.3: Volumes between companies with a centralised supply network configuration

Table 4.3: Simulated supply contracts of centralised US-Poly-1

Origin	Destination	Good	Quantity [mt/wk]	Net price [€/wk]	Gross price [€/wk]
US-RMS	US-Poly-1	Monomer	1,314	1,092	1,123
US-Poly-1	US-Com-1	Polymer	506	4,567	4,567
US-Poly-1	US-Com-2	Polymer	141	4,567	4,728
US-Poly-1	EU-Com-3	Polymer	137	4,583	6,240
US-Poly-1	AP-Com-3	Polymer	337	4,583	5,922

Table 4.4: Simulated revenues and costs of centralised US-Poly-1

Plant	Revenues [k€/wk]	Purchasing [k€/wk]	Fixed [k€/wk]	Variable [k€/wk]	Total [k€/wk]
US-Poly-1	5.127	−1,476	−1,558	−1,696	−4,729
Total	5,127				−4,729

4.4.2 Direct effects of decentralised supply network configuration

In the second experiment, we compute the performance of a decentralised network configuration, using the supply contracts from the first experiment. This implies that the supply contracts and the company's environment have not adapted to the changed supply network configuration, and that we only assess the network configuration's direct effects. A decentralised supply network configuration entails that US-Poly-1 replaces its large plants by four smaller plants that each are located at the site of a customer. Those plants have a smaller capacity, because they only have to produce goods for one customer instead of four. Due to the economies of scale, the smaller plants have higher (relative) costs than the large plant. Those costs are computed using the '0.6 rule', which is a guideline for the change of costs that follows from a change of capacity (Tribe and Alpine, 1986). Table 4.5 presents an

Table 4.5: Properties of the decentralised plants of US-Poly-1

Plant	Site	Capacity [mt/wk]	Fixed costs [€/mt]	Variable costs [€/mt]
US-Poly-1a	US-Com-1	506	1,791	2,171
US-Poly-1b	US-Com-2	141	2,985	3,619
US-Poly-1c	EU-Com-3	137	3,020	3,661
US-Poly-1d	AP-Com-3	337	2,107	2,554

Table 4.6: Computed revenues and costs of decentralised US-Poly-1 (direct effects)

Plant	Revenues [k€/wk]	Purchasing [k€/wk]	Fixed [k€/wk]	Variable [k€/wk]	Total [k€/wk]
US-Poly-1a	2,311	−599	−906	−1,099	−2,604
US-Poly-1b	667	−166	−421	−510	−1,097
US-Poly-1c	855	−350	−414	−502	−1,266
US-Poly-1d	1,996	−399	−710	−861	−1,970
Total	5,829				−6,937

overview of the locations, capacities, and costs of the decentralised plants.

As we use the same supply contracts as materialised in the first experiment, US-Poly-1 has the same supply contracts as listed in Table 4.3. Except for the change of the transport costs (due to the relocation of the plants), the revenues and purchasing costs thus are similar to when US-Poly-1 had a centralised network configuration. However, due to the smaller capacities of the decentralised plants, the fixed and variable costs have increased considerably compared to those of the centralised large plant. Table 4.6 specifies the revenues and costs of the four plants, as well as the revenues and costs of US-Poly-1 as a whole. The total revenues are k€ 5,829/wk the total costs increase to k€ −6,937/wk. The profit of US-Poly-1 thus decreases to k€ −1,108/wk and its operating margin amounts to −19 %.

4.4.3 Indirect effects of decentralised supply network configuration

To assess the indirect effects of a decentralised supply network configuration, we simulate the industrial system in which US-Poly-1 operates the four plants of Table 4.5 that operate as autonomous companies. In the simulation, the companies negotiate with each other, taking into account the reconfiguration of US-Poly-1's supply network. Hence, the prices and volumes of goods can adapt to the decentralised network configuration. This subsequently enables us to obtain more comprehensive insights into the effects of the decentralised supply network configuration.

Industrial system development Figure 4.4 shows for each company the relative price change in comparison to the prices in the first experiment. The price of polymers is affected the most, with an average price increase of around 75 %. US-Poly-1 needs to recover its higher costs, and therefore the compounders can only meet their polymer demand at a higher price, which increases the overall polymer

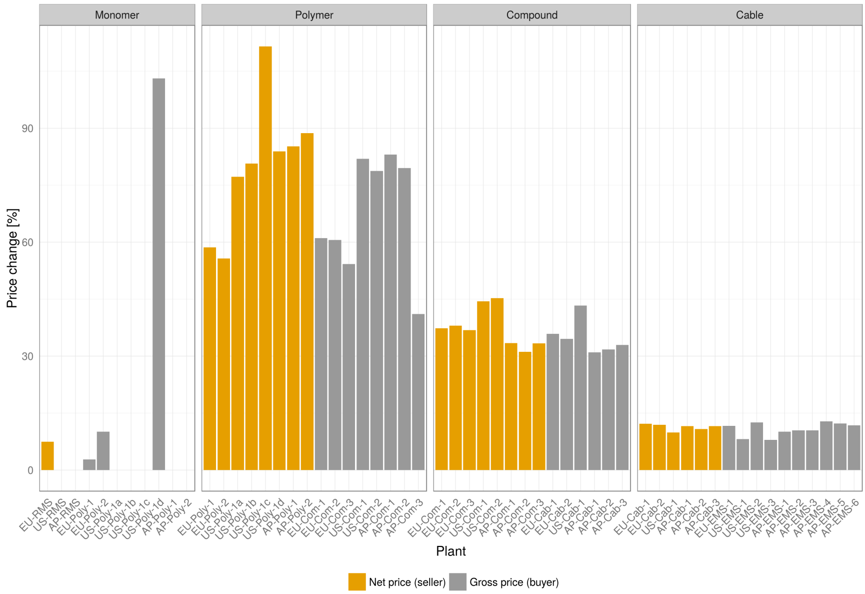

Figure 4.4: Price changes due the decentralised configuration compared to the centralised configuration

price. Consequently, the compounders need to sell their products at a higher price, which leads to an increase of around 30 % for the compounds. The same applies for the cable producers, but the price increase for cables is limited to around 10 %. So, the supply network reconfiguration of US-Poly-1 influences the development of the entire industrial system; vice versa, the industrial system sets limits to how much the polymer price can increase. The volumes of goods have not changed considerably compared to Figure 4.3 and thus are not discussed in further detail.

As a consequence of the changed prices, the operating margins of the companies changed considerably. The largest increase is for the polymer producers, whose operating margin increases from 5 % to 40 %. The increase for the compounders and cable producers is much smaller with an average increase of 1 %. This implies that, due to the scarcity in the market (i.e., US-Poly-1's capacity cannot be replaced by any of the other producers), all polymer producers benefit substantially from the supply network reconfiguration of US-Poly-1.

Focal company's financial performance Table 4.7 shows the supply contracts of US-Poly-1 that emerged in the simulation when its supply network was decentralised. Due to the environment's adaptation, those contracts have changed substantially compared to the contracts with the centralised network configuration (Table 4.3). Whereas US-Poly-1 received a mean price of €4,574/mt, it gets €8,519/mt with a decentralised network configuration.

Via those changed supply contracts, the environment's adaptation changes the revenues and costs of US-Poly-1. Table 4.8 specifies the revenues and costs of US-Poly-1 with a decentralised network configuration. Compared to the direct effects of

Table 4.7: Simulated supply contracts of decentralised US-Poly-1 (direct and indirect effects)

Origin	Destination	Good	Quantity [mt/wk]	Net price [€ /wk]	Gross price [€ /wk]
US-RMS	US-Poly-1a	Monomer	533	1,092	1,123
US-RMS	US-Poly-1b	Monomer	149	1,092	1,123
EU-RMS	US-Poly-1c	Monomer	90	2,497	2,528
AP-RMS	US-Poly-1d	Monomer	355	1,092	1,123
US-Poly-1a	US-Com-1	Polymer	506	8,289	8,289
US-Poly-1b	US-Com-2	Polymer	141	8,450	8,450
US-Poly-1c	EU-Com-3	Polymer	85	9,894	9,894
US-Poly-1d	AP-Com-3	Polymer	337	8,545	8,545

Table 4.8: Simulated revenues and costs of decentralised US-Poly-1 (direct and indirect effects)

Plant	Revenues [k€ /wk]	Purchasing [k€ /wk]	Fixed [k€ /wk]	Variable [k€ /wk]	Total [k€ /wk]
US-Poly-1a	4,194	−599	−906	−1,099	−2,604
US-Poly-1b	1,194	−167	−421	−510	−1,098
US-Poly-1c	841	−227	−414	−311	−952
US-Poly-1d	2,880	−399	−710	861	−1,970
Total	9,106				−6,624

the decentralised configuration, the changed revenues are the most noteworthy. Due to the higher prices – which are due to the environment's adaptation – the revenues increased from k€ 5,829/wk to k€ 9,106/wk. With total costs of k€ −6,624/wk, the profit of US-Poly-1 amounts to k€ 2,482/wk. This amounts to an operating margin of 27 %, which is not only considerably higher than the decentralised configuration's direct operating margin, but also higher than the margin of the centralised supply network configuration. However, it should be noted that this operating margin is lower than the industry average.

4.5 Discussion

Using the experimental outcomes, we can discuss the model's ability to internalise the environment's complexity and assess the indirect effects of the action. This discussion is broken down into three aspects: *1*) the model's ability to simulate the emergence of an industrial system from the market interactions in a set of coupled markets; *2*) the ability of the simulated industrial system to adapt to a changed network configuration of the focal company; and *3*) the influence of assessing those indirect effects on the outcomes of the assessment of the supply network configuration.

In the first experiment (section 4.4.1), we observed the prices and volumes of exchanged goods that emerged from market interactions among companies. Those prices and volumes were properties of supply contracts that connected the companies and together formed an industrial system. We assessed that, next to the physical connection through the volumes of exchanged goods, the prices were also connected. The price of a good was the result of the costs of producing that good and the ratio of demand and supply. Not only the prices of sequential goods were connected, but also the prices of a single good charged by competing companies. Given that the market interactions between companies gave rise to those connections between companies, the model could simulate the emergence of an industrial system from the market interactions between companies, without a structure being imposed by an outside or central agency. Compared to empirical data of the represented polymers industry, the prices and volumes of goods in the simulation deviated very little. This leads to conclude that, for the simulated industry, the model could simulate the emergence of an adequately representative industrial system.

The comparison of the industrial systems with a centralised configuration (section 4.4.1) and with a dencentralised configuration (section 4.4.3) indicated that US-Poly-1's supply network reconfiguration caused large price increases that propagated through the industrial system. This implies that the industrial system that emerged from the simulations could adapt to the higher costs that resulted from US-Poly-1's decentralised network configuration. As we discussed before on basis of theories, the market interactions among companies were essential for this adaptation, by allowing the changes in the system to be reflected in the prices and volumes of the exchanged goods. This case study thus shows that the theoretically expected behaviour actually materialises in the simulation.

The influence of the decentralisation's indirect effects is determined by comparing the assessment outcomes with only the direct effects (section 4.4.2) to the outcomes with both the direct and indirect effects (section 4.4.3). In section 4.4.3, the industrial system could adapt to the decentralised network configuration, which resulted in considerably higher prices. In the assessment that was limited to the reconfiguration's direct effects, the operating margin of US-Poly-1 was $-19\,\%$, while the margin was $27\,\%$ when we did assess the indirect effects. This implies that assessing the indirect effects in the assessment can have a substantial effect on the outcomes.

Nevertheless, we need to make two remarks to this conclusion. First, the operating margin of $27\,\%$ was relatively low compared to the average margin of $40\,\%$ of the other polymer producers. In that light, the decentralised network configuration does not seem a wise action. Second, the average operating margin of $40\,\%$ of the polymer producers is likely to attract additional (cheaper, centralised) polymer producing capacity that will replace the more expensive decentralised plants. Next to that, the higher price of the end-product may give rise to customers of cables to look for alternatives, which then will put pressure on the prices in the industrial system. As the decentralised plants are relatively expensive, their performance will be affected substantially by the lower prices. So, in the long run, the adaptation of the industrial system to the network configuration can have a detrimental effect. And thus, the adaptation in the long run can negatively influence the effects of a supply chain reconfiguration. Hence, those indirect effects should be captured over the full horizon of the reconfiguration decision.

4.6 Synthesis

In this chapter, we used an agent-based model to assess the direct and indirect effects of a supply network reconfiguration. The model conceptualised the industrial system as a set of autonomous, interacting companies that supply goods to each other. Those market interactions led to the emergence of prices and volumes of the exchanged goods in the system, which are important factors influencing the focal company's financial performance. The model was initialised to represent an industry involved with the production of consumer electronics cables. The reconfiguration of the focal company's supply network was not endogenously included in the model as a decision, but was imposed on the model in the form of a scenario.

We performed multiple experiments to assess different network configurations and the model's ability to account for the indirect effects. In the first experiment, the model was used to simulate the development of the industrial system in which the focal company operated a single plant as a centralised supply network. The focal company had an operating margin of 8 % in this experiment. The outcomes of this experiment indicated that the model could simulate the emergence of an industrial system as a result of market interactions among companies. Using the supply contracts that materialised in the first experiment, the second experiment involved the computation of a decentralised network configuration's performance. In this experiment, we thus did not assess the supply network configuration's indirect effects. By operating a decentralised supply network, the company's costs increased, which caused its operating margin to decrease to −19 %. In the third experiment, we also determined the performance of a decentralised network configuration, but in this experiment we simulated the industrial system again, so that we could assess the indirect effects. Due to the adaptation of the environment, the revenues of the focal company increased and its operating margin – despite the higher costs – amounted to 27 %. By contrasting the outcomes of the second and third experiment, it was demonstrated that the model could account for the reconfiguration's indirect effects, and that those effects can have a considerable influence on the outcomes of the assessment.

The presented model is a first step in the development of a conceptualisation with a system perspective that enables it to assess the indirect effects of an action. Although the experiments demonstrated the added value of assessing the indirect effects, further improvements are possible. We discussed that the adaptation of the environment, which enabled the improved performance of the decentralised network configuration, was unlikely to be sustainable over a longer period. In the long run, the high operating margins and the increased total system costs are going to cause adaptations in the form of additional competition or decreased demand. This would lead to substantially different outcomes than were observed in this chapter, which only consider the operational changes of the system. Hence, a substantial improvement would be to also account for the topological changes. In this specific case, that would entail adding decisions of companies to alter their production capacity. Those improvements will be made in the following two chapters. In the following chapter, we introduce the focal company's ability to cause structural changes to the system by relocation. The chapter that comes thereafter enables all companies in the system to cause structural changes by changing their production process.

Chapter 5

Transportable plants

This chapter is based on Bas and Van der Lei (2015a)[1].

5.1 Introduction

Generally, plants in industrial systems are realised at a location where they continue to operate during their entire lifetime. As a consequence, the investment assessment of such a plant only has to consider the expected costs and sales at one location. However, in recent years, transportable plants have been developed that can be relocated easily and thus may operate at multiple locations during their lifetime (e.g., Bieringer et al., 2013; Bramsiepe et al., 2012; Buchholz, 2010). This type of plants enables the company to adjust the location of its plants in response to changing local market conditions during the plant's lifetime. This reduces the company's vulnerability to those local market conditions and thus increases its resilience to geographical changes. Due to the possibility of being relocated, the investment decision for a transportable plant needs to consider the expected costs and sales at the possible locations, as well as the relocation decisions during the plant's operations. The costs, sales, and relocation decisions depend to a large extent on how the focal company's environment develops. In the previous chapter, we observed that this development can substantially be influenced by the focal company's decisions. For a transportable plant, those decisions concern the plant's relocation. Consequently, the investment assessment of a transportable plant needs to capture the indirect effects of the relocation decision (i.e., the adaptation of the environment in response to the relocation decision).

To assess the indirect effects of a relocation decision, the model used in this case study is an evolution of the previous model. Both the scope of the model and the behavioural richness are increased to internalise more of the system's complexity. The model's dimensions of complexity are as follows:

- *Diameter of the industrial system*: three tiers.

[1]Bas, G. and Van der Lei, T. (2015a). Dynamic investment appraisal: Economic analysis of mobile production concepts in the process industry. In *Proceedings of the 12th International Symposium on Process Systems Engineering and 25th European Symposium on Computer Aided Process Engineering*, pages 245–250.

- *Possible market interactions*: all potential partners in the focal company's current market.
- *Types of changes caused by the focal company*: operational and topological changes.
- *Types of changes caused by the environment*: operational changes.
- *Types of changes caused by the market interactions*: operational changes.
- *Detail of the environment's representation*: aggregated raw material suppliers.
- *Decision rules*: q-learning.
- *Considered features*: supply, demand, location, and market power.

The model's scope captures the market interactions between the focal company and all potential suppliers and customers in its current markets. Given the long time horizon of the investment decision, all those interactions are needed to allow the focal company to change its suppliers and/or customers and deploy its plant at any of the available sites. The relocation decision of the focal company causes structural changes in the system, which implies that the changes due to the focal company encompass both operational and topological changes. The modelled behaviour is enriched by using a reinforcement learning algorithm to implement the market interactions. Using this algorithm, the companies not only consider the supply, demand, and location of each other in their interactions, but also their market power.

In this chapter, we apply the developed model to assess the value of a transportable plant in comparison to a – otherwise identical – non-transportable plant. Section 5.2 introduces the concepts of facility (re)locations decisions, as well as the literature regarding those decisions. This provides a foundation for the relocation decisions that are captured in the model. In section 5.3, we describe the model, which includes the embedding of the relocation decisions within the operational market behaviour. Section 5.4 introduces the experiments that are performed to assess the value of a transportable plant and presents the outcomes of those experiments. The implications of those outcomes, for the transportable plants as well as the use of the model, are discussed in section 5.5.

5.2 Facility (re)location decisions

The facility relocation decision[2] has a substantial influence on the plant's value and therefore is essential for the assessment of transportable plants. The relocation decision determines to a large extent how well the transportable plant's parent company can benefit from the opportunities in the market. Consequently, the plant's value would be underestimated in comparison to what would be possible if the 'right' location was selected. In this section, we introduce important aspects of facility relocation decisions and discuss how the relocation decision is implemented in the investment assessment of a transportable plant.

[2] Even though we only consider the relocation of a plant, we use the term 'facility relocation decision' as this is the conventional term.

5.2.1 Facility location

Before we discuss facility relocation decisions, we first consider the more general facility location decisions. A facility location decision entails that a company decides where in the world it is going to deploy and operate a facility. Given the permanent nature of most location decisions, a location decision generally concerns the location of a new facility that is currently non-existing and thus has no costs to disassemble and remove from its current site. Despite that the location decision and the supply network configuration influence each other, facility location theory generally assumes that the network configuration (i.e., the number and size of facilities) has been determined and that, within that context, the facilities need to be located.

A typical facility location problem consists of a set of geographically dispersed customers and a set of facilities that need to be located to optimally serve those customers (e.g., Drezner and Hamacher, 2004; Nickel and Puerto, 2005). Regarding the possible locations for the facilities, we distinguish two types of problems: *1*) the continuous location problem, in which facilities can be located at any place; and *2*) the discrete location problem, in which facilities can be located at a finite number of locations (Melo et al., 2009). Both types of problems are addressed in the literature and are generally solved using different methods (Revelle et al., 2008). Given the distinguishing property of transportable plants to produce locally at the site of a customer (Bramsiepe et al., 2012), the focal company in this case study can choose from a finite number of locations and thus faces a discrete location problem.

Location problems can be further distinguished on basis of the number of layers, periods, and goods that are considered in the problem (Melo et al., 2009). The number of layers determines in how many echelons of the supply network the focal company needs to establish locations for its facilities (e.g., Hinojosa et al., 2000). As transportable plants operate at the site of the customer, there is no need for additional echelons to distribute the goods and the location decision thus is a single-layer problem. Regarding the number of periods, a distinction is made between single-period and multi-period models. In multi-period models, the location is optimised over multiple time periods during which parameters, such as demand, can change. The assessment of a transportable plant concerns a time interval during which the system can change substantially. To account for the system's changes, the location decision needs to consider multiple periods. For the number of goods that the facility handles and supplies to customers, the literature distinguishes between single-good problems and multi-good problems. Since we assess specialised transportable plants that produce one type of goods for a single customer, the location decision is a single-good problem.

Discrete location problems are often formulated as integer or mixed integer programming problems (Revelle et al., 2008). This means that the problem has an overall objective function, which generally regards the total distance or costs to meet the demand, that needs to be minimised. The optimisation methods locate the available facilities at the locations that minimise the objective function (Melo et al., 2006). Over the years, a variety of optimisation methods have been applied to this type of problems, for which the reader is referred to Klose and Drexl (2005) and Melo et al. (2009).

5.2.2 Facility relocation

Facility relocation decisions are a subset of facility location decisions (Pellenbarg et al., 2002). In a facility relocation decision, the facility is already located at a site, but it may be relocated to improve its performance. So, when making this decision, the focal company needs to consider the current location of the facility and how this influences the prospects of potential new locations. Except for this difference, location decisions and relocation decisions are very similar: both are establishing the location where a facility can maximise its performance. This implies that similar methods are used for both decisions, but that the problems are formulated differently.

Two types of factors influence a relocation decision, which subsequently can be divided in two parts along those lines: push factors and pull factors (Pellenbarg et al., 2002). The push factors concern those factors that drive a company to look for another location. Without this (relative) dissatisfaction, the company is unlikely to look for other locations, even though they may be more profitable. Due to capital inertia (Rodgers, 1952), companies are reluctant to relocate unless they have a very good reason. In other words, a company needs to overcome a certain threshold before it decides to relocate its facility. The pull factors concern those factors that attract a company to a certain location. This part of the relocation decision is comparable to the regular facility location problem. However, a difference is that the relocation decision has disassembly and relocation expenses, while the location decision does not have those expenses.

5.2.3 Competitive facility location

The large majority of facility location studies assumes that the focal company that decides on the location either is a price taker or monopolist (Karakitsiou, 2015). Consequently, the decision to select a location has no effect on the demand and price (and thus the potential revenues) at that particular location. However, the deployment of a facility at a particular location affects the competition between buyers and sellers of the facility's feedstock and product, which may lead to different prices, supply, and demand for that facility (Drezner, 2014). Therefore, competitive facility location relaxes the assumption of the focal company being a price taker or monopolist and explicitly considers the effect of the changed competition (Saidani et al., 2012). Like regular facility location problems, competitive facility location problems are solved using optimisation methods to find the optimal location for the facility. However, a competitive facility location problem is formulated to account for the effects of the competition on the location decision's objective function (e.g., Aboolian et al., 2007; Meng et al., 2009). This competition is represented through a game theoretic model of the market that changes in response to the parameters of the facility's location. This way, the mutual influence of the facility's location and the competition on each other is represented in the location problem.

The principles of competitive facility location decisions are close to the principles of the research presented in this thesis. In this research, we aim to capture the influence of the focal company's environment on the effects of a certain decision. Likewise, competitive facility location studies include the changes to the focal company's market environment due to a location decision. To align the principles of the relocation decision with principles of the investment assessment of a transportable plant (i.e., assess the indirect effects of an action), the facility relocation decision needs to account for how the environment may adapt to a proposed relocation. This means that the investment assessment of a transportable plant needs to account for the environment's adaptation at two levels: *1*) at the level of the assessment, where the adaptation to the chosen relocation influences the cash flows that are used to assess the transportable plant; and *2*) at the level of the relocation decision, where the expected adaptation to a proposed relocation is considered, which influences the chosen relocation.

5.2.4 Relocation decisions to assess a transportable plant

As we stated earlier, relocation decisions have a substantial influence on the value that materialises in the assessment of a transportable plant. Based on the previous discussion of different aspects of facility relocations, we can determine how the relocation decision should be implemented in the assessment.

The relocation decision consists of a push and a pull aspect. The push aspect is a threshold that should be overcome before the focal company decides to move away from its current location. The pull aspect concerns the problem of selecting the location that maximises the plant's performance. As we discussed, this problem is formulated as a one-layer, single-good, multi-period problem with a discrete set of possible locations (i.e., the customers' sites). Since the transportable plant is relocated from a particular site, the pull aspect of the relocation decision involves certain relocation expenses. Moreover, we determined that a relocation decision influences the company's environment. To align the relocation decision with the principles of the assessment's system perspective, the relocation decision has to account for the environment's adaptation to a proposed relocation. As in competitive facility location research, the expected adaptation to the possible relocation are considered in the relocation decision by including the market interactions and competition in the formulation of the relocation problem.

5.3 Model description

The model we use to assess the investment into a transportable plant is built upon the model we used in the previous chapter. The main changes to the model concern the altered implementation of the market interactions and the addition of the relocation decision of the focal company. To prevent unnecessary repetition, we discuss the changes in detail and explain how they fit with the other parts of the model. As in the previous chapter, the model description is presented according to the overview, design concepts, and details (ODD) protocol.

5.3.1 Purpose of the model

The objective of this model is to help a company decide about investing in a transportable plant. To enable a comprehensive assessment of a transportable plant, this model accounts for the complexity in the focal company's environment. As in the previous chapter, we conceptualise the industrial system as a set of autonomous companies that interact to supply goods. Through those interactions the industrial system can adapt to the focal company's relocation decision. This relocation decision is included in the model to study how the value of the transportable plant develops over time as it relocates. This value is computed based on the cash flows that emerge from the market interactions, which themselves are influenced by the relocation decision. That way, we expect to improve a more comprehensive understanding of the value of transportable plants.

5.3.2 Entities, state variables, and scales

As in the previous chapter, the model consists of companies that are geographically dispersed and operate autonomously at a particular site. Each plant performs a certain production process that converts feedstock into product. The goods in the system are exchanged via supply contracts and physically delivered via shipments. Compared to the previous model, only the companies have been changed to enable the relocation of plants and to facilitate the altered implementation of the market interactions. We therefore discuss the companies in further detail and refer to the previous chapter for the other entities. The time scale is also discussed in detail, as it has been changed to assess the value of a transportable plant during its entire lifetime.

Companies To allow the relocation of their plants, the companies are situated at a *site* that they can decide to change. As the transport expenses and the transport duration are defined as the costs and duration of shipping goods between sites, the relocation of one site to another automatically changes the plant's transport costs and duration. The companies that operate transportable plants are specified by the *transportable* variable, which thus indicates that those companies can decide to relocate. Whether they actually relocate depends on the outcomes of their relocation decision.

In this model, the market is not conceptualised as a set of coupled single-sided auctions, but as sellers that make a pricing decision and buyers that make a supplier selection decision. This implies that each company has *retail price* at which it sells its products to anyone that wants to buy those. To determine its retail price, each company has a *pricing strategy*, which specifies the perceived profitability of a set of prices and can be considered the company's perception of the current state of the market. To establish their pricing strategy, the companies perform price simulations in which they explore the attractiveness of a variety of prices. The company's *price simulation length* specifies what period is simulated to establish a pricing strategy. Next to that, the company has an *initial learning rate*, *initial exploration rate*, *learning rate decay*, and *exploration rate decay*, which it uses in the simulation to update its strategy and explore different prices. To include its capacity utilisation in the computation of a retail price's attractiveness, each company has a *required capacity utilisation* and a *importance capacity utilisation.*

For the relocation decision, the company considers the *relocation expenses* it incurs when it relocates. The plant decides to relocate only if the expected net present value of operating at a new site surpasses the net present value at the current site by more than the *relocation threshold.* The net present value of operating at a new site is determined through a relocation simulation. In this simulation, the company explores how the environment could adapt to the relocation and how this could influence its performance at the new site. The simulated period in the relocation simulation is specified by the *relocation simulation length* and the number of repetitions of the simulation, in order to reduce the effect of stochasticity, is specified by *relocation simulation repetitions*. Through this parameter, it is possible to set the company's level of bounded rationality.

Time scale As the value of a transportable plant materialises during its lifetime and can change substantially during that period, we need to simulate the performance of the plant's parent company over a period of time. Whereas the recorded performance in the previous chapter was a snapshot at the end of the simulation, in this chapter we record the company's performance each time step of the simulation and combine those measurements to indicate the value of the company's plant. The length of the simulated period has to cover the time that horizon of the investment decision, which typically amounts to 10 to 30 years.

5.3.3 Process overview and scheduling

The processes in the model can be divided into three categories: *1*) the market interactions, which have a similar structure as the processes in the previous chapter and consists of an ordering and a shipping phase; *2*) the pricing decision, in which the sellers determine their retail price; and *3*) the relocation decision, in which the companies with transportable plants decide about the best location to operate from. Figure 5.1 presents an overview of the processes in the model as well as the logic that connects them. In this section, the processes are discussed along the line of the three identified categories. The details of the sub-processes are presented in appendix B.

Market interactions The market in this model is conceptualized as buyers that select a supplier and sellers that learn which price to ask on basis of the orders they have received. The structure of the market interactions is comparable to the market behaviour in the previous chapter. However, the negotiations have been replaced by buyers that order feedstock and sellers that update their price. In the ordering phase, the buyers of the ordered good *order feedstock* for which they have a particular demand (section B.1.1). To create the supply contract that specifies the order, the buyer selects the seller(s) of the ordered good that can supply the good at the lowest gross price (net price + transport costs). This implies that the sellers that have set a competitive price will receive the most supply contracts, while sellers with too high a price will receive less or even no contracts. Once all goods have been ordered, the shipping commences, which is identical to the shipping phase in the previous chapter.

After all goods have been shipped, the second aspect of the market interactions is performed: the sellers *update their pricing strategy and set a new retail price*. To update its pricing strategy (section B.1.2), the seller uses a Q-learning algorithm to learn the reward of its current retail price based on the supply contracts it received in the ordering phase (e.g. Dogan and Güner, 2013; Tesauro and Kephart, 2002). Q-learning (Watkins and Dayan, 1992; Watkins, 1989) is a reinforcement learning technique, which means that the agent learns from the reward of 'good'

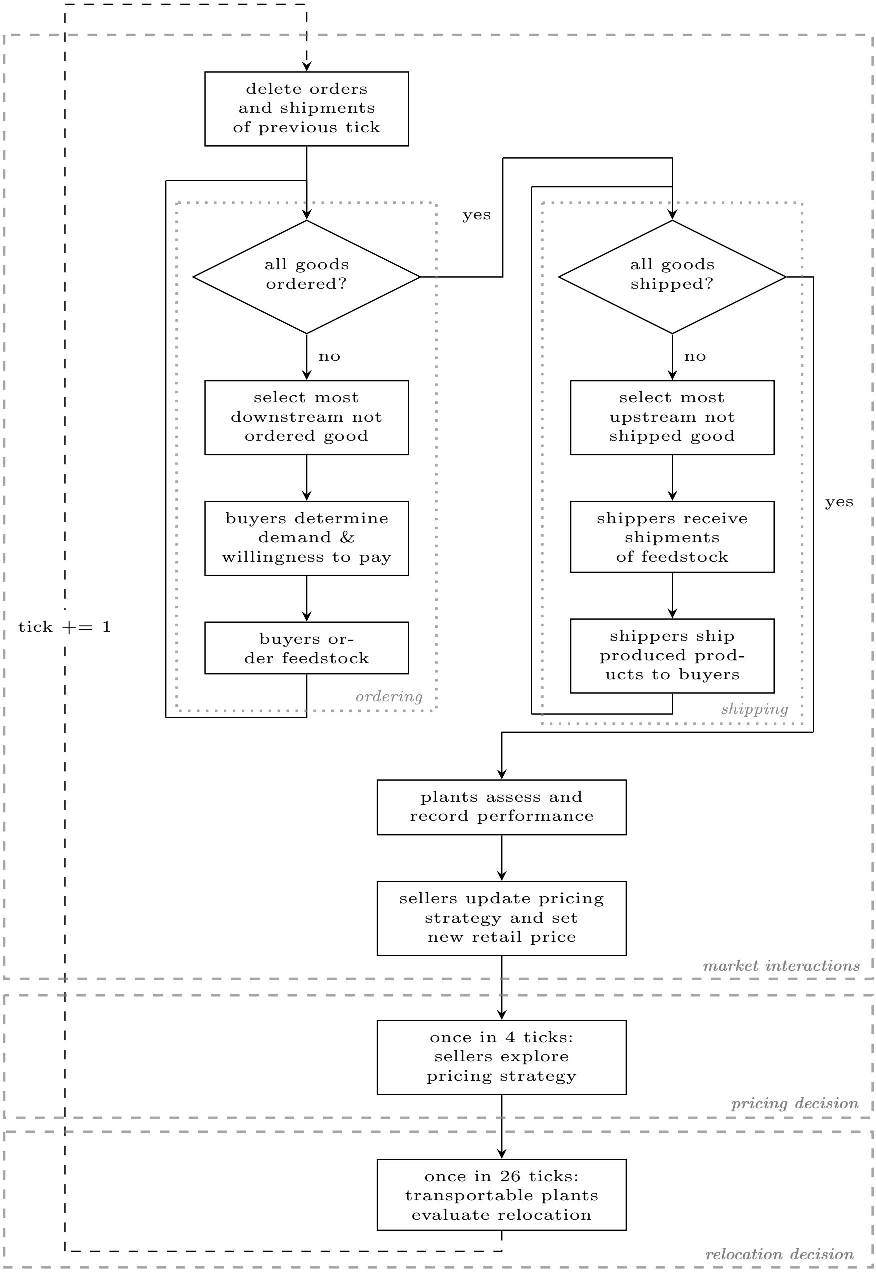

Figure 5.1: Process overview of the transportable plants model

actions and the punishment of 'bad' actions. Which actions are good and which are bad is determined by the reward function that the agent uses to learn. The perceived attractiveness of a particular action is stored in a Q-value. The learning occurs iteratively by choosing an action, determining the rewards, and updating the corresponding Q-value. The new Q-value $Q_{t+1}(a_t)$ of an action a_t (e.g., a certain retail price) is determined through[3]:

$$Q_{t+1}(a_t) = Q_t(a_t) + \alpha_t \left(R_{t+1}(a_t) - Q_t(a_t) \right), \tag{5.1}$$

where α_t is the learning rate of the agent that specifies to which extent the agent replaces the old Q-value with the obtained reward; $R_{t+1}(a_t)$ is the reward that the agent has received after selecting action a_t, which depends on the response of other agents to that decision; and $Q_t(a_t)$ is the old Q-value of a_t that gets updated using the reward.

As we apply the Q-learning algorithm to learn the perceived attractiveness of a retail price, the action for which the Q-value is computed entails a retail price. The reward of this retail price follows from the orders that the plant receives for the sale of its goods. The basis of this reward is the revenue that the plant receives from its sales (π_{t+1}). However, it is known that industrial companies often have to operate above a minimum capacity utilisation and need to shut down otherwise (Kallrath, 2002). As a result, companies do not merely aim to maximise their revenues, but also consider the achieved capacity utilisation (σ_{t+1}) as a part of their reward. Therefore, following Xiong et al. (2002), we combine the revenues and the capacity utilisation into a reward function to compute the reward ($R_{t+1}(a_t)$) of a certain action (a_t):

$$R_{t+1}(a_t) = \pi_{t+1} \left(\frac{\sigma_{t+1}}{\sigma^*} \right)^n, \tag{5.2}$$

where π_{t+1} is the revenue obtained by the agent in the period between setting the price (t) and updating the Q-value ($t+1$); σ_{t+1} is the realised capacity utilisation in that period; σ^* is the required capacity utilisation; and n is the strictness of complying to the required capacity utilisation.

Once the pricing strategy is updated, the seller sets its new retail price (section B.1.3). Typically, this entails that the seller select the retail price that has the highest perceived attractiveness in the pricing strategy. However, with a probability β_t, the seller selects a random price from the pricing strategy. This enables it to explore other prices than the (so-far) most attractive price. Therefore, β_t is generally referred to as the exploration rate.

Pricing decision The pricing decision consists of a simulation performed by a company (and not just the focal company) to *explore a new pricing strategy* (section B.2). Using this price simulation, the seller explores a range of possible retail

[3]Note that this is a simplified implementation of the original Q-learning equation. This equation does not consider the estimate of the optimal future and thus does not take into account the long term effects of an action. This is done because an action does not limit the future actions. Furthermore, to simplify the assessment of the pricing strategy, we do not consider the Q-value of a *state-action pair*, but the Q-value of only an *action*. This reduces the number of possible options that need to be learned, but has the drawback that it assumes that the action has the same Q-value in each state. This drawback is handled by updating the Q-values when the state has changed.

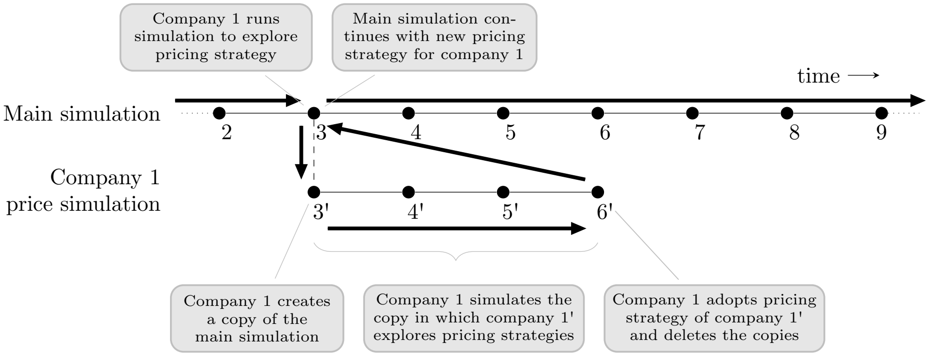

Figure 5.2: Timeline of a price simulation

prices and updates the pricing strategy based on the simulation outcomes. This enables the plant to quickly respond to sudden changes in the market, as well as overcome the exploration-exploitation dilemma through which it risks getting stuck at a local optimum or compromising its performance by selecting sub-optimal prices (Kaelbling et al., 1996). Following Darken et al. (1992), the exploration-exploitation dilemma is addressed by starting the simulation with a high α_t and β_t (0.4) and decrease them as the simulation progresses (to 0.03 at the end of the simulation). The company thus first explores a wide variety of prices and increasingly focuses on exploiting the more attractive prices.

The price simulation start with the simulating company (i.e., the company that explores a new pricing strategy) that creates a copy of all companies in the main simulation. It then simulates the market interactions of the simulated companies in the price simulation. So, just like in the main simulation, the simulated companies order and ship goods, but only the simulated self (i.e., the representation of the simulating company in the price simulation) updates its pricing strategy and sets its retail price. During the price simulation, the simulated self thus learns a pricing strategy that is best suited to the current market conditions in the main simulation (which are copied into the price simulation). At the end of the price simulation, the simulating company adopts the pricing strategy of the simulated self and deletes all the simulated companies.

Figure 5.2 presents an abstract overview of this process. The main simulation is considered a timeline, where the companies each time step perform the processes of the market interactions. When a company decides to perform a price simulation, it creates a new timeline with its own timekeeping (indicated by t') that explores how the market may develop in the future, while the time in the main simulation is on a hold. In this price simulation, copies of the companies in the main simulation (indicated by company') have market interactions without affecting the main simulation. At the end of the price simulation timeline, the simulating company adopts the pricing strategy of the simulated self and the timeline is removed. Hereafter, the time in the main simulation continues with the simulating company using a new pricing strategy.

Relocation decision As discussed in section 5.2, a decision to relocate causes the focal company's environment to adapt to the change system structure. To enable the consideration of this relocation effect, the relocation decision is supported by a simulation through which the company explores its potential performance at a new site. In this simulation, the environment can adapt to the relocation, by setting different prices or ordering from other suppliers.

The relocation decisions starts with a company (which operates a transportable plant) that *selects the site with the highest potential margin* (section B.3.1). In this initial selection, the company determines for each possible site the operating margin, using the current market prices and assuming it can exchange with the nearest companies. Of those sites, it selects the one with the highest margin. If it selects another site than its current site, the company explores the performance at that site in further detail. This starts with the company that *simulates the industry with itself at its current site* (section B.3.2). At the end of the simulation, the net present value of the simulated self is computed, as an indicator of the performance at the current site. Subsequently, the company *simulates the industry with itself at the selected new site* (section B.3.3). And again, the net present value of the simulated self is computed, including the relocation expenses, to indicate the performance at the new site. If the net present value of the new site surpasses the net present value of the current site by more than the relocation threshold, the company *relocates* by changing its site and incurring the relocation expenses. No costs of missed production during relocation are considered. However, those costs can be added easily and do not change the method presented in this chapter.

Figure 5.3 gives an overview of the relocation simulation and how it is related to the main and price simulation. The main simulation contains the focal company and its environment; the outcomes (cash flows) at this level are directly used to evaluate the focal company's plant. The relocation simulation is performed by the focal company to assess its performance on a potential new site; the outcomes at this level influence the focal company's operations in the main simulation and thus indirectly its evaluation. Like the price simulation in Figure 5.2, the relocation is performed while the main simulation is on a hold. To capture the environment's adaptation in the relocation decision, the companies in the relocation simulation update their pricing strategy by performing a price simulation, which thus introduces a third timeline. The outcomes of the price simulation influence the market interactions in the relocation simulation, and thus indirectly the relocation decision and the evaluation of the focal company's plant.

5.3.4 Design concepts

Basic principles: The main principle of this model entails that the assessment of investing into a transportable plant is influenced by the indirect effects of relocating the plant. *Emergence:* The interactions in the industrial system lead to the emergence of prices and volumes of exchanged goods, which are driving the focal company's cash flows and thereby the evaluation of the transportable plant. *Adaptation:* As buyer, a company adapts its ordering behaviour to the availability of goods; as seller, a company adapts its price to the received supply contracts. *Objectives:* A buyer's goal is to obtain its demand for a good at the lowest gross price;

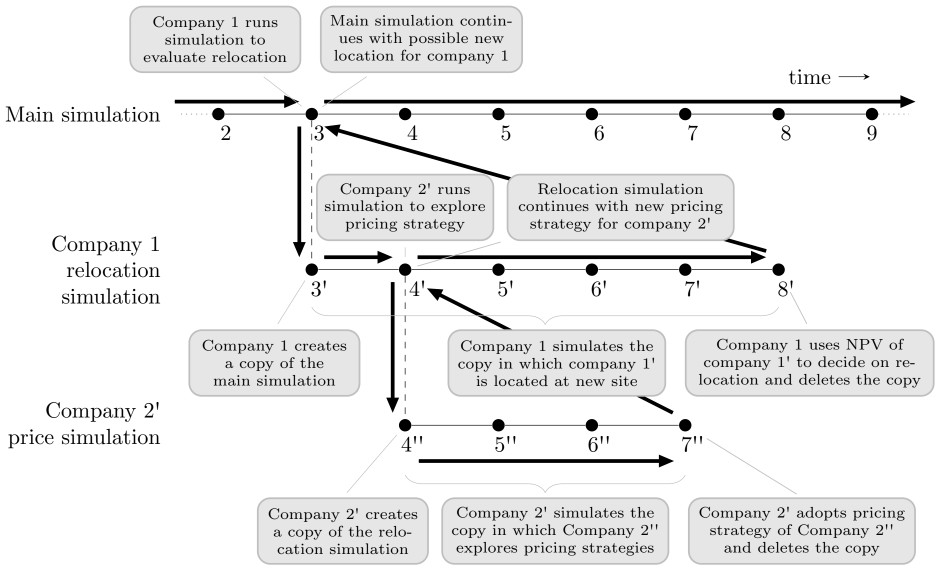

Figure 5.3: Timeline of a relocation simulation

a seller's goal is to maximise its revenues while also meeting its capacity utilisation requirements. A company that operates a transportable plant aims to maximise its value of operating at a certain site. *Learning:* The sellers use a Q-learning algorithm to learn which pricing strategy aligns the best with the current market conditions. *Prediction:* The companies use price simulations and relocation simulations in an attempt to predict the effects of setting a price and relocating to another site. *Sensing:* The sellers in a market are only aware of the supply contracts they receive; the buyers, on the other hand, know the prices set by the sellers and their available supply. *Interaction:* The buyers and sellers interact with each other by ordering goods and shipping those ordered goods. The buyers themselves do not have any direct interactions, but they influence each other indirectly via interactions wit the same sellers; the same applies to the sellers. *Stochasticity:* The stochasticity in the model follows from the order in which agents perform the processes, but also from the scheduling of the price simulation and the relocation simulation, and from the occasional selection of random prices in the price simulation. *Observation:* The transportable plant is assessed through the net present value that is computed on basis of the cash flows that its company collects in the simulation. Next to that, in order to improve our understanding of the effects of the transportable plant on the system as a whole, we also measure the site of the transportable plant throughout the simulations, as well as the development of the market prices.

5.3.5 Model initialisation

The model is initialised to represent a part of the polymers industry that was used in chapter 4. We limit the represented industry to the first three processes: monomer supply, polymer production, and compounding. Table 5.1 presents the number of companies and the capacity distribution in each of the supranational regions. Com-

Table 5.1: Distribution of companies over supranational regions in the polymers industry

Process	Europe		North America		Asia-Pacific	
	# com.	% cap.	# com.	% cap.	# com.	% cap.
Monomer supply	2	12%	3	44%	3	44%
Polymer production	2	28%	1	42%	2	30%
Compounding	3	41%	2	22%	3	37%

pared to the initialisation in the previous chapter, the number of monomer suppliers in each region has increased from one to two or three. The altered implementation of the market interactions introduces the notion of market power into the model, which implies that a single monomer supplier in a region acts as a monopolist. In the real polymers industry, there are numerous monomer producers, neither of which has the market power to act as a monopolist. Hence, multiple monomer suppliers are initialised per region to limit their market power. Due to the focus on the first three processes, the willingness to pay of the compounders is computed using the net prices they received in the previous chapter. On average, the compounders can pay around €9,000/mt.

To assess the value of a transportable plant, we focus the assessment to a polymer producer that is initially located in Asia-Pacific (*AP-Poly-1*). The capacity of this focal company is 156 mt/wk, which makes it a relatively small player in the polymers market. Its fixed and variable costs are both around €1,500/mt, which is relatively low compared to its competitors. However, due to its relatively low efficiency of around 90 %, the focal company has no advantage over its competitors.

All companies have a required capacity utilisation of 90 %, which has an importance factor of 0.5. Through experimentation, we found that, in general, this combination of parameters resulted in the most realistic prices and volumes of supplied goods. The initial learning rate and exploration rate are both set at 0.4, and their decay is set at 12,000. We found that with those parameters the agents learned relatively quick what price to set, while still setting a good price. Nevertheless, the price simulation length still has to be set at 400 ticks. The length of the relocation simulation is limited to 52 weeks as transportable plants can relocate relatively fast and companies thus are not bound to one site for a very long time. To limit the effect of stochasticity, the relocation simulations are performed 3 times and the mean outcome is selected.

For the assessment, we simulate a period of 10 years, which is at the lower end of an assessment period for a substantial investment. However, for the purpose of this chapter, this period suffices as it allows us to clearly demonstrate the difference between a transportable and non-transportable plant. During the simulated period, the demand for polymers changes geographically. Figure 5.4 shows the development scenario of the polymers demand in each of the three supranational regions. Between week 130 and week 390, the demand decreases in Asia-Pacific and is replaced by demand in North America. This implies that it becomes less attractive to be located in Asia-Pacific, while it becomes more favourable to be located in North America. A transportable plant may benefit from those geographical changes and thus becomes more valuable than a non-transportable plant.

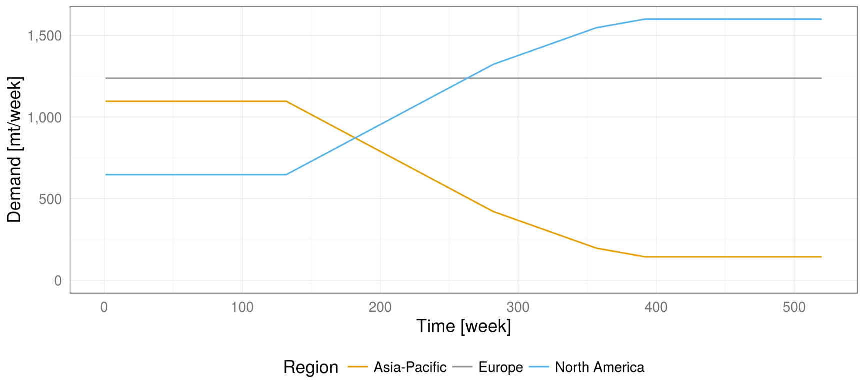

Figure 5.4: Devolopment scenario of the polymers demand in three supranational regions

5.4 Evaluation of a transportable plant

To evaluate a transportable plant, we use the developed model to perform one simulation study in which we assess three different aspects of the plant. In the first part of this study, we compare the value of a transportable plant to the value of a non-transportable plant, to determine by how much the value has increased due to the transportability. The second part regards the effects of relocating the transportable plant on the company's environment. The outcomes of this part can shed a light on the indirect effects of the relocation and their consequences for the plant's value. In the third part, we assess the effect of different relocation expenses and relocation thresholds on the value of the transportable plant. Hereby, we aim to improve our understanding of how the transportable plant can be deployed optimally.

In the experiment, we simulate a period of 10 years. Before the 10 year period starts, the simulation is run (i.e., warmed up) for 2 years, which we determined to be sufficient for the agents to learn about their environment and reasonable prices and volumes of goods to emerge. In the 10 year period, we record the cash flows of the focal company (AP-Poly-1), which we use to compute its net present value at the end of the simulation. This provides insights into the value of the focal company's plant for a considerable part of its lifetime. Next to that, we also measure the location where the focal company is situated and the prices of the different goods in each of the supranational regions. Those indicators provide additional insights into the effects of the transportable plant on its environment.

Although the use of the Q-learning algorithm leads to more variable prices and volumes of supplied goods, the experiments we performed indicated that this had little effect on the relocation decisions of companies and the net present value that materialised from the simulation. Combined with the substantial duration of a single run (30 minutes on a regular computer), we therefore decided to repeat each simulation 10 times to limit the effect of the stochasticity on the simulation outcomes. In the experiment, we present the median outcomes of those 10 runs. Due to this limited number of repetitions, we need to be cautious with discussing the simulation outcomes. However, in all analyses we found that the observed trends were stronger than the stochasticity-induced noise.

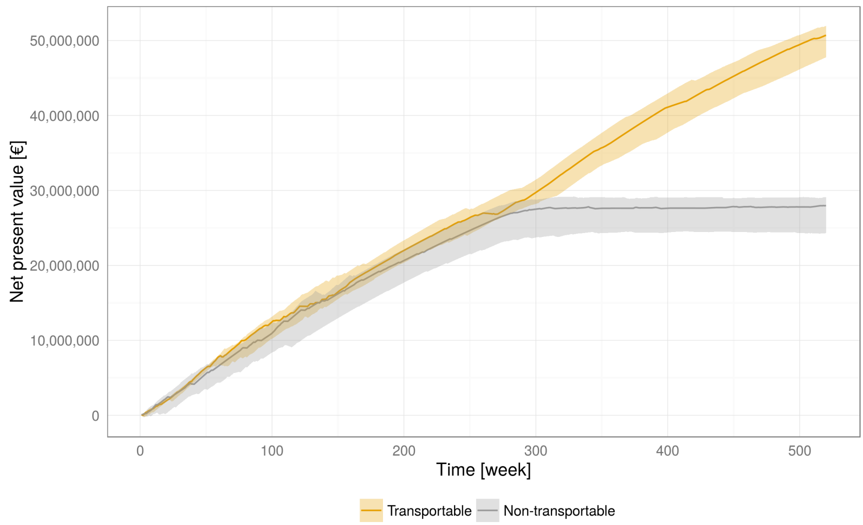

Figure 5.5: Net present value of a transportable plant and a non-transportable plant over time

5.4.1 The value of a transportable plant

The value of transportability is determined by comparing the value of a transportable plant (i.e., the value of the focal company that operates a transportable plant) to the value of a non-transportable plant. Figure 5.5 shows the net present values of a transportable and a (further identical) non-transportable plant during the simulation. The plotted lines indicate the median outcomes of the repetitions, and the bandwidth around each line indicates the interquartile range of the outcomes. Initially, the net present value of the two plants develops in a similar fashion. However, around week 300, the net present value of the non-transportable plant stalls, while the net present value of the transportable plant continues to develop as before. This results in a present value of the transportable plant that is 80 % higher than that of the non-transportable plant at the end of the simulation.

The difference between the value of the transportable and the non-transportable plant is caused by the possibility of the transportable plant to be relocated from Asia-Pacific to North America as the demand shifts from the former to the latter region. Figure 5.6 shows the modal location of the non-transportable and the transportable plant during the simulation. Initially, the transportable plant is relocated to a customer in Asia-Pacific, as this lowers the transport expenses and thus increases its profitability. The effect of this relocation on the net present value is only marginal. However, as the demand for polymers switches from Asia-Pacific to North America, it becomes more attractive to relocate to North America. This happens after 220 weeks, but does not directly lead to a (relative) increase of the transportable plant's value. Only after 300 weeks, the net present value of the transportable plant starts to deviate considerably from that of the non-transportable plant. Figure 5.7 indicates that around that time the polymers price in North America increases strongly, while the price decreases in Asia-Pacific. This leads us to conclude that the higher net present value of the transportable plant is the result of relocation from Asia-Pacific

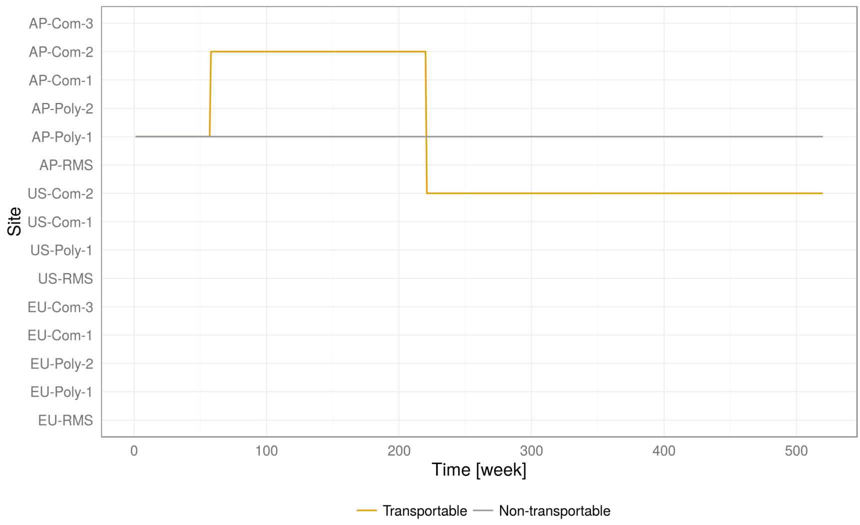

Figure 5.6: Location of the transportable plant and the non-transportable plant over time

to North America. The higher net present value of the transportable plant thus is attributable to its transportability.

5.4.2 The effects of a transportable plants on its environment

In this second part of the experiment, we set out to determine the effects of the transportable plant's relocations on the prices in the industrial system. To get insight into those effects, we compare the price developments of simulations where the focal company operated a transportable plant to the price developments of simulations where the focal company operated a non-transportable plant.

Figure 5.7 shows the development of the median polymer prices in each of the three supranational regions. The price development patterns are comparable when the plant of the focal company is transportable and when it is non-transportable. As the polymer demand switches from Asia-Pacific to North America (between week 130 and 390), the polymer price decreases in Asia-Pacific and increases in North America. Noteworthy is the price decrease in Europe, despite the stable demand in that region. This price decrease is caused by the abundance of cheap polymers from Asia-Pacific that need to find an outlet when the demand in Asia-Pacific decreases. Europe is a viable outlet due to its internal undersupply of polymers and its higher price than North America. The cheap Asian-Pacific polymers thus are supplied to Europe, where they lower the price. The European price stops decreasing when it equals the North American price, as both regions then are equally attractive to the Asian-Pacific polymer producers.

Despite their similarities, the price developments with and without a transportable plant differ at two points. First, between week 50 and week 150, the price in Asia-Pacific is higher when the focal company operates a transportable plant. This aligns with the period in which the transportable plant is located at the site of

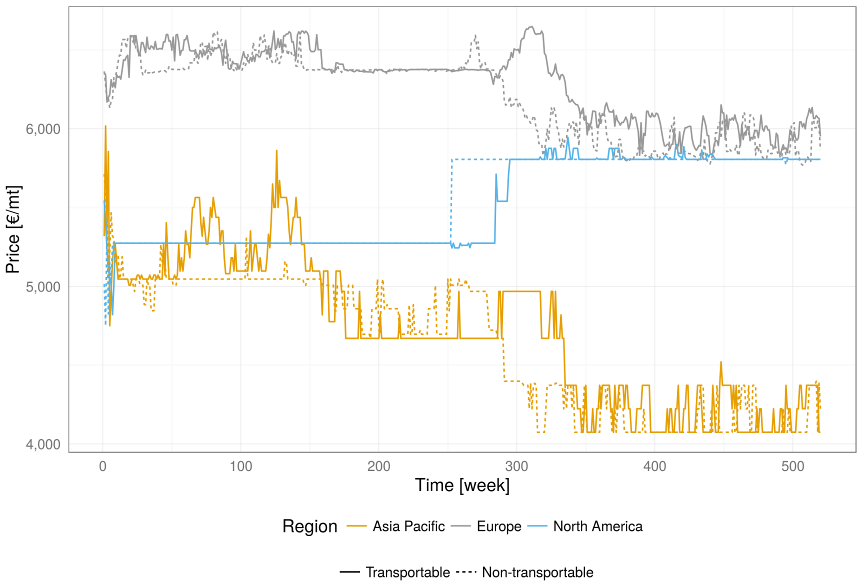

Figure 5.7: Development of the polymer prices in the three supranational regions with and without a transportable plant

a customer in Asia-Pacific (see Figure 5.6). Hence, the higher price is likely caused by the lower transport expenses that the focal company incurs to ship its products, which allows it to charge a higher retail price.

The second price deviation entails the period after the relocation of the transportable plant from Asia-Pacific to North America. When the focal company operates a non-transportable plant, we observe considerable price changes in each of the three regions around week 250 to week 300. However, when the focal company operates a transportable plant, those same changes are delayed by around 40 weeks. Hence, the relocation of the transportable plant appears to delay the price developments. To understand this delay, we start with the notion that the price increase in Asia-Pacific and price decrease in North America are caused by an oversupply of polymers in Asia-Pacific and an undersupply of polymers in North America. The relocation of the transportable plant temporarily lowers the oversupply in Asia-Pacific and the undersupply in North America. This suppresses the price change for a certain period of time. However, the change in demand more than the transportable plant can undo (i.e., more than the plant's capacity) and its relocation thus only delays the price developments.

5.4.3 Relocation decisions

In section 5.2, we stated that the relocation decision can have a substantial influence on the value of a transportable plant. This third part of the experiment aims to assess to what extent the relocation decision influences the transportable plant's value. In this part, we vary the relocation threshold (between €0 and €2,000,000) and the relocation expenses (between 0 % and 20 %), both of which are parameters

Table 5.2: Relative net present value of transportable plant at different relocation expenses and relocation thresholds

	Expenses [€]				
Threshold [%]	0	500,000	1,000,000	1,500,000	2,000,000
0	100.00	101.94	97.30	97.57	90.78
5	98.45	99.04	97.03	93.88	92.19
10	101.21	98.06	95.83	94.56	92.92
15	98.48	95.86	94.56	91.81	93.49
20	98.81	96.74	92.83	92.53	90.51

of the decision's push aspect. The relocation threshold concerns the relative performance improvement that is needed for the company to relocate its plant; and the relocation expenses concern the costs incurred by the company to disassemble its plant, remediate the old site, and ship the plant. The value of the transportable plant, which we use to assess the effect of the relocation decisions, is influenced both directly and indirectly by the relocation expenses. The relocation expenses influence the relocation decision and thereby indirectly the plant's value, but the incurred relocation expenses also directly influence the company's cash flows and thereby the plant's value.

Table 5.2 presents the median relative net present value (i.e., relative to the net present value at expenses of €0 and a threshold of 0 %) of the transportable plant at different relocation expenses and relocation thresholds. Although the number of repetitions was relatively low, the data suffices to distinguish a clear trend. However, it causes us to be cautious with the exact values found in this analysis. Not entirely surprising, it indicates that the net present value decreases as the expenses and the threshold increase. Nonetheless, even at the highest expenses and threshold, the net present value of the transportable plant is still 64 % higher than of the non-transportable plant. It appears that the expenses have more effect on the value than the threshold. Whereas the net present value difference between the highest and lowest threshold is never larger than 5 %, the difference between the highest and the lowest expenses is as high as 10 %. The fitted linear regression model confirms this idea: the net present value decreases with €1,000,000 when the expenses increase by €500,000 and decreases with €340,000 when the threshold increases by 5 %[4].

As we noted before, the relocation expenses both influence the relocation decision as well as the company's cash flows. To determine what part of the net present value change is attributable to the influence on the relocation decision, we exclude the cash flows of the relocation expenses from the net present value and determine the remaining effect of the relocation expenses on the net present value. Figure 5.6 indicates that the transportable plant relocates within Asia-Pacific around week 60 and from Asia-Pacific to North America around week 220. Combined with the number of relocations for each combination of expenses and threshold, this enables us to correct for the cash flows of the incurred relocation expenses and determine the

[4]The fitted linear regression model is $npv = 5.11 \times 10^7 - 2.12 * exp - 6.77 \times 10^4 * thres$, where npv is the transportable plant's net present value in €, exp is the relocation expenses in €, and $thres$ is the relocation threshold in %. Both the entire model as well as the individual parameters have been found statistically significant at $p = 0.05$.

Table 5.3: Relative net present value at different relocation expenses and relocation thresholds, corrected for the cash flows of incurred relocation expenses

	Expenses [€]				
Threshold [%]	0	500,000	1,000,000	1,500,000	2,000,000
0	100.00	103.35	100.13	101.82	93.05
5	98.45	100.45	99.86	98.13	97.86
10	101.21	99.47	98.66	98.80	95.19
15	98.48	97.27	97.39	93.52	99.15
20	98.81	98.15	95.67	94.23	92.78

effect of the relocation expenses on the relocation decision. Table 5.3 shows that, without the incurred relocation expenses, the differences between the relative net present values have decreased. The linear regression model fitted to this data tells a similar story, as the net present value decreases with only €500,000 when the expenses increase by €500,000 and decreases with €470,000 when the threshold increases by 5 %[5]. Hence, if we disregard the direct effect of the relocation expenses on the transportable plant's cash flows, both the relocation expenses and the relocation threshold have a significant effect on the relocation decision and thereby on the plant's value.

5.5 Dicussion

The outcomes of the experiment provide insights into the transportable plant itself as well as the model used to assess it. With regard to the transportable plant, the experimental outcomes improve our understanding of the investment into and the deployment of the plant. Regarding the model, the experimental outcomes provide insight into the model's ability to assess the indirect effects of relocating a plant and into the consequences of those effects for the assessment outcomes.

Investing and deploying a transportable plant The experiments in section 5.4.1 showed that, due to its ability to operate at the best locations, the transportable plant was more valuable than the non-transportable variant. This implies that transportable plant can successfully be deployed in markets with geographically different dynamics, so that the plant can benefit from those differences. How much value this creates for its parent company depends on the dynamics of the market and on the capabilities of the company to benefit from those dynamics. In our experiments, the local dynamics of the market changed clearly and gradually, which enabled the transportable plant to create 80 % more value. When it is less obvious that the dynamics are changing, it becomes less straightforward to benefit from them and the added value of transportability will be lower. However, this may be mitigated by competitors that also have more difficulties to benefit from the chang-

[5] The fitted linear regression model is $npv = 5.17 \times 10^7 - 1.02 * exp - 9.40 \times 10^4 * thres$, where npv is the transportable plant's net present value in €, exp is the relocation expenses in €, and $thres$ is the relocation threshold in %. Both the entire model as well as the individual parameters have been found statistically significant at $p = 0.01$.

ing market dynamics, leaving opportunities for the focal company. The competitors with transportable plants were not implemented in the model, which prevents us from analysing their effect on the value of transportability. To obtain a more comprehensive understanding of an action's effects, future models should include the system's topological changes caused by the focal company's environment.

Moreover, the experiment in section 5.4.3 demonstrated that the considerations in the relocation decision also had a significant influence on the value of the transportable plant. Both the relocation expenses and relocation threshold considered in the relocation decision influenced that decision to such an extent that it altered the net present value of the plant significantly. In this chapter's scenario, it proved better to be risk prone (i.e., have a low relocation threshold), as this allowed the plant to benefit optimally from the geographically changing demand. However, when the dynamics are more unpredictable, it may be beneficial to be more risk averse (i.e., have a higher relocation threshold) and identify the sustainability of the dynamics. Otherwise, the company risks to be continuously behind the curve. This results in a paradox, since unpredictable and swift development requires the company to limit its uncertainties, while it also requires it to act quickly, which limits the time available to reduce uncertainties. How the company balances those two requirements will probably differ per case and depends on the properties of the market and of the company.

Assessing the indirect effects of relocating a plant The main reason for evaluating a transportable plant through a simulation model is to include the adaptation of the company's environment to a relocation decision (i.e., the indirect effects). In section 5.4.2, we demonstrated that the plant's relocation substantially delayed the price developments throughout the industrial system. The relocation changed the market conditions, which caused the other companies to adapt their behaviour and interactions, which resulted in different prices. Hence, via the adaptation of the environment, the plant's relocation influenced the market developments. Together with the influence of the market developments on the focal company, this completes the mutual influence between the focal company and its environment that is central to this thesis.

An important effect of the environment's adaptation was the 40 week delay of the €600/mt price increase in North America (Figure 5.7). Since the transportable plant could produce 156 mt of polymers per week, this delay caused the plant to lose around €3,744,000 worth of revenues, with a present value of around €1,900,000 This amounts to around 4 % of the total net present value of the transportable plant. So, had we not considered the environment's adaptation, the computed net present value would have been overestimated by around 4 %.

In this particular case, an overestimation of 4 % has no real effect on the investment decision and most likely even lies within the margin of error. However, it should be noted that this 4 % error is caused by a single relocation over a period of five years. If the market dynamics would give reason for the plant to relocate more frequently, this error could build up to substantial proportions. Moreover, if there would be more transportable plants in the industrial system, the environment would adapt more often and possibly stronger. The effect of other transportable plants in the industrial system is not included in the current model, but thus could have substantial consequences for the evaluation of a transportable plant.

5.6 Synthesis

This chapter set out to assess the investment into a transportable plant. For that purpose, we built upon the model of chapter 4, which enabled us to assess the indirect effects of an action. In this chapter, the model's scope and behavioural richness were increased, which led to a more complex model that could be used to evaluate a transportable plant. The developed model was applied to evaluate a transportable plant in a polymers industry. The experiment was divided into three parts that each focused at different aspects of the plant's evaluation. The first part showed that geographical differences in a market enhance the value of a transportable plant. Since the transportable plant can be relocated, it can operate at the most attractive locations, whereas this is not possible for other plants. In the second part, we found that the plant also influenced the market developments: the relocation of the transportable plant temporarily neutralised the geographically changing demand and thereby caused a delay of the price developments. The third part demonstrated that the way a transportable plant decides about its relocation can have a significant effect on the its value. Both the relocation expenses and relocation threshold affected the relocation decision to such an extent that the net present value decreased by a maximum of 7 %.

Based on the experimental outcomes, we discussed their implications for the assessment of a transportable plant. With regard to the investment decision, the outcomes indicated that a transportable plant can be a profitable investment in a market with geographically differing dynamics. In markets with frequently differing dynamics, the relocation decision is important to reap the benefits from the dynamics. In those markets, the focal company needs to act quickly, but also needs to assess the dynamics thoroughly to identify the sustainable trends. Those two requirements are conflicting and consequently need to be balanced. Regarding the effect of the plant's relocation on its environment, we determined that the adapted market developments caused the plant's value to decrease by 4 %. However, when the market dynamics are more frequent and more plants become transportable, this error may build up to substantial properties. In industries with those dynamics, the evaluation of a transportable plant thus should assess the indirect effects of the plant's relocation. The experiments indicated that the developed model can assess those effects.

The used model does not capture the structural changes that are caused by the companies in the environment that operate transportable plants. We found in the discussion that those structural changes may have a substantial influence on the value of a transportable plant. Therefore, to comprehensively assess the indirect effects of an action, the structural changes caused by the environment need to be captured as well. In the following chapter, the model is extended to include those structural changes.

Chapter 6

Process flexibility

This chapter is based on Bas and Nikolic (2016)[1].

6.1 Introduction

In recent years, new production concepts have been developed that feature process flexibility (e.g., Bieringer et al., 2013; Bramsiepe et al., 2012; Seifert et al., 2014). Their modular design enables the fast replacement of equipment, which allows their production process to be changed. When a plant's process is changed, it can produce different products and/or use different types of feedstock, which entails that its company has to buy its feedstock and/or sell its products in different markets (Plambeck and Taylor, 2011). Consequently, process flexibility enables a company to protect itself against volatility in the markets for different goods, or even benefit from it (Christopher, 2000). This increases the company's resilience to changes between markets. To assess the investment into a flexible plant, a company needs to know to what extent the flexibility provides an advantage and how this influences the plant's value. This value depends on the dynamics of the markets in which the plant can be deployed, as those influence what process the plant is going to use, in what markets its company is going to participate, and thus what its cash flows are. Since a process change is not only influenced by the markets, but influences those markets as well, it is difficult to assess the development of the focal company's cash flows and thereby the flexible plant's value. So, to evaluate the investment into a flexible plant, there is need for a assessment method that accounts for the mutual influence between the plant and the markets in which it can operate.

The model used to assess the investment into a flexible plant builds upon the models developed in the previous chapters. To comprehensively assess the indirect effects of operating a flexible plant, more aspects of the environment's complexity are internalised into the model. The model's dimensions of complexity are hence as follows:

- *Diameter of the industrial system*: three tiers.

[1]Bas, G. and Nikolic, I. (2016). The value of process flexibility in a responsive market environment. In *Proceedings of the 5th International Engineering Systems Symposium - CESUN 2016.*

- *Possible market interactions*: all potential partners in all potential markets.
- *Types of changes caused by the focal company*: operational and topological changes.
- *Types of changes caused by the environment*: operational and topological changes.
- *Types of changes caused by the market interactions*: operational changes.
- *Detail of the environment's representation*: aggregated raw material suppliers and customers.
- *Decision rules*: q-learning.
- *Considered features*: supply, demand, location, and market power.

In section 6.2, we introduce the relevant concepts of process flexibility and the process selection decision. The insights into the process selection decision are implemented in the model, which is described in section 6.3. The experiments are introduced and analysed in section 6.4. Hereafter, section 6.5 discusses the implications of the experimental outcomes with regard to the investment into a flexible plant and the use of the model to assess such an investment.

6.2 Process selection

6.2.1 Production processes

A production process is the whole of operations performed by a facility that convert feedstock into a product (Kotler and Armstrong, 2010). For example, a plant may produce polyethylene using the Spherilene process (Covezzi, 1995), and a distribution centre may distribute goods using a cross-docking process (e.g., Gümüş and Bookbinder, 2004). In reality, a production process consists of multiple smaller unit manufacturing process or unit processes, such as casting, machining, and surface treatment. Each unit process specifies the used feedstock, the produced products, the required product and process data, and the needed resources, such as utilities, time, and equipment (Finnie, 1995). A production process is the aggregate of its unit processes and thus specifies the same aspects, but only at the scale of the entire facility.

As the production process performed by a plant specifies what types of feedstock it uses and what products it produces, it defines in which markets the plant's parent company participates. The type of used feedstock determines what feedstock the company needs to buy, which determines in which market it needs to participate. Equivalently, the process determines what type of product can be sold by the company and thus in which market it sells its product. Next to markets in which the company participates, the production process also influences the company's market behaviour. The production process specifies what (relative) quantity of feedstock is used, what (relative) quantity of product is produced, and the company's cost structure. Consequently, it influences how much feedstock the company needs to buy for what maximum price, and how much product it can sell at what minimum price.

6.2.2 Process flexibility

Process flexibility is a plant's ability to change the process it performs in response to developments in the industrial system (e.g., changing availability of feedstock or customer demand). Process flexibility actually is a single aspect of the broader concept of manufacturing flexibility. Manufacturing flexibility is defined as 'the ability [of a company] to produce a variety of products in the quantities that customers demand while maintaining high performance' (Zhang et al., 2003, p. 173). A common categorisation between types of manufacturing flexibility is the distinction of process flexibility, product flexibility, routing flexibility, volume flexibility, and expansion flexibility (Sethi and Sethi, 1990). Both process flexibility and production flexibility concern the ability of a company to change which process its plant performs. The other three types of manufacturing flexibility all concern changes to the operations that do not affect the process performed and/or the goods used or produced by the plant. The main difference between process flexibility and product flexibility is the set-up costs of changing the production process: process flexibility typically concerns relative small change with low costs, while product flexibility concerns the bigger changes with higher costs. In this chapter, we do not distinguish between process flexibility and product flexibility and only use the term process flexibility.

As a production process defines in which market(s) the company buys its feedstock and in which market(s) it sells its products, process flexibility implies that the company can change in which markets it participates. When a company changes its plant's process, it may change the used feedstock and/or the produced product. This causes the company to buy its feedstock and/or sell its products in another market. The company's entry into a new market changes the supply or demand in that market, which may lead to changed market interactions and subsequently changed prices and volumes of exchanged goods (Cai et al., 2010). Likewise, the exit from the old market causes opposing changes to the supply or demand in that market and to the market outcomes. So, as a consequence of switching between markets, the company may reduce the (price) difference between those markets. A similar phenomenon is observed in financial markets, where it is referred to as arbitrage (Brealey et al., 2011).

Performing a different production process typically requires the use of different equipment and utilities. Hence, if the plant wants to change its process within a certain time, the equipment and utilities should also be able to change within that period of time. This can be realised by designing the manufacturing system with a variety of (parallel) processes in mind, but also by designing the system to be reconfigured easily. Likewise, different processes also need different process data and product data to function (optimally), and a flexible plant thus requires an information system that can account for changing data streams. The novel production concepts that have been developed recently are aimed at flexibility and therefore have a modular design (Seifert et al., 2012). This entails that pieces of equipment can easily be replaced by other pieces of equipment that are connected to a common information backbone (Buchholz, 2010). Consequently, those production concepts can be easily reconfigured to perform a different process.

6.2.3 Process selection decisions

The process selection decision is the decision of a company concerning which process its (flexible) plant should use. This decision is typically driven by developments outside the company (Gerwin, 1993): often developments in the markets in which the company participates or in which it may participate. For instance, if the demand for the company's current product decreases, it may become more attractive to produce another product and thus change its plant's production process. The company thus changes its plant's process because there is a difference between two markets: the expected profitability of participating in one market is higher than the expected profitability of participating in another market.

To date, there has been very little research with regard to the considerations in a process selection decision. Only some fundamental research into strategies for choosing between competitive marketplaces (Miller and Niu, 2012). Therefore, we cannot directly derive a conceptualisation of the process selection decision from the existing literature, like we did for the relocation decision. However, there are strong resemblances between the process selection decision and the production planning decision for a batch operation: in both cases, the company needs to decide what process to use (i.e., what product to produce). Production planning concerns the planning of production activities to convert feedstock to product in order to meet customer demand (Johnson and Montgomery, 1974). In the literature, a variety of approaches are used to plan the production activities, but the analytical approach is the most commonly used (Mula et al., 2006). This approach uses optimisation tools to maximise the customer satisfaction, while limiting the company's costs. A generic production planning problem involves a company that has a variety of products for which there is a certain demand from its customers. For those products, the company has to determine which products it is going to produce and in which order. This means that it considers the availability of resources, the revenues of the sale of each product, the production and inventory costs, and the set-up costs incurred to prepare the equipment to produce another product (Pochet and Wolsey, 2006).

Like the production planning decision, the process selection decision also concerns what products to produce (and what feedstock to use) to meet customer demand. However, as a process change involves the entry into one market and the exit from another market, the process selection decision is likely to cover a longer time horizon than a production planning decision. Consequently, the process selection decision does not determine the order of producing products, but selects only one production process from possible processes. The objective of this selection is to maximise the value that the selected process generates for the company. This value is computed on basis of the costs and revenues that the company expects to realise using the process. The costs of a process concern the fixed costs, the variable costs, the set-up costs, and the costs of purchasing feedstock. The revenues are the result of the company's sales in the market for its products. Since we aim to include the adaptation of the environment in the assessment of business decisions, we also consider this adaptation in the process selection decision. The company thus explores how the markets in the environment could adapt to its changed processes and how this influences its costs and revenues. Using those insights, it subsequently determines which process is expected to generate the most value in the coming period and thus should be used by its plant.

6.3 Model description

The model we use in this chapter is a continued development of the model we used in chapter 5. The main difference compared to the previous model is that the process selection decision replaces the relocation decision. Related to that, we change the plants to enable them to perform different processes. In this section, we limit the model description to those aspects that have been changed compared to the previous model. For the other aspects of the model, the reader is referred to the model descriptions in chapters 4 and 5.

6.3.1 Purpose

The purpose of this model is to support companies with their decision to invest in a flexible plant. To account for the indirect effects of this decision, the model captures the entire relevant industrial system in which the focal company operates. The industrial system is conceptualised as a set of companies that interact with each other in markets over the exchange of a variety of goods. The prices and volumes of exchanged goods that materialise from those interactions are driving the cash flows of the focal company and thereby the value of its flexible plant. Using this conceptualisation, the environment can adapt to any process change of flexible plants, which then influences the plant's value. All companies in the model are allowed to change their (flexible) plants' process, which improves the model's representation of how the system may develop during a flexible plant's lifetime.

6.3.2 Entities, state variables, and scales

Like in the previous two chapters, the model consists of companies (with integrated plants) that perform a particular production process to convert feedstock into a product. The plants operate at geographically dispersed sites, from where they exchange and ship goods through orders and shipments. Compared to the previous model, the companies and processes are changed to accommodate process flexibility and the process selection decisions.

Companies In the previous two models, the fixed and variable costs were properties of the company. This makes sense, when the process performed by a company does not change throughout the simulation; the process – and its related costs – then form an integral part of the company. However, when the company can change its process, its costs do not only depend on its own properties, but also on the properties of the process that it performs. Therefore, the fixed and variable costs are split into a company-specific aspect and a process-specific aspect. The company-specific aspect specifies how its costs relate to the costs of other companies, and thus represents its cost-efficiency. This is implemented in the model by giving the plants *fixed-costs-efficiency* and *variable-costs-efficiency* variables. The company computes the fixed costs and variable costs that it incurs by multiplying its cost-efficiency with the process-costs of the process that it performs. However, by splitting the costs like this into a company-specific and the process-specific aspect, we assume that the company is equally cost-efficient for each of the processes.

The ability of a company to change its process is indicated with its *flexible* variable. To decide about changing its process, the company makes a process selection decision. A company only decides to change its process if the value of the new process surpasses the value of the current process by more than the *process-change-threshold*. If a company decide to change its process, it incurs *process-change-expenses*. To decide about its process-change, the company performs a process selection simulation in which it simulates how its environment may adapt to the process-change. The duration of the process selection simulation is specified by the company's *process-selection-simulation-horizon*. To reduce the effect of stochasticity on the simulation outcomes, the company repeats the process selection simulation a number of times, which is specified by its *process-selection-simulation-repetitions*.

Production processes The process-specific aspect of the costs concerns the costs that an averagely cost-efficient plant would incur. So, a plant with a cost-efficiency of 100 % would incur exactly the process-specific aspect of the costs. The process-specific aspect is implemented as the *process-fixed-costs* and *process-variable-costs* variable of the production process.

6.3.3 Process overview and scheduling

As in chapter 5, the model's processes are divided into three categories: *1*) the market interactions, *2*) the pricing decision, and *3*) the process selection decision. The logic connecting the processes is identical to the logic presented in Figure 5.1, but the relocation decision is replaced by the process selection decision. We first discuss the initial two categories of processes in general terms, after which we discuss the process selection decision in greater detail. The full details of the process selection decision are discussed in appendix C.1.

Market interactions The market interactions between the companies are conceptualised as sellers that learn what price to set and buyers that select the best seller(s) to purchase their feedstock. The sellers learn which price to set on basis of the orders they received, while each buyer selects the supplier(s) of its feedstock that can meet its demand at the lowest gross price. This operational behaviour – consisting of buying feedstock, converting it, and selling the produced product – has two phases: an ordering and a shipping phase. The ordering of goods in the ordering phase occurs incrementally: first the most downstream good is ordered, followed by increasingly more upstream goods. In the shipping phase, this sequence is reversed: first, the most upstream good is shipped, which is then followed by increasingly more downstream goods. After the shipping phase, each sellers uses the orders it received to update the expected attractiveness of its current retail price and set a new retail price. Hereafter, the performance metrics of the companies in the current time period are recorded.

Pricing decision Through their pricing decision, the companies update their pricing strategy, so that it aligns with the current market conditions. The company updates its pricing strategy by performing a price simulation in which it explores the attractiveness of a variety of prices. By using a simulation, the pricing decision accounts for the adaptation of the market to the explored prices. The company uses the obtained insights of the price simulation to set its retail price in the main simulation.

Process selection decision The process selection decision is a decision with tactical horizon that is performed with average intervals of half a year. We discussed in section 6.2 that a changed production process influences the market that the company enters, as well as the market that it exits. The process selection decision accounts for those influences by simulating the company's operations with the changed process, while accounting for the adaptation of its environment. To capture this adaptation in the process selection simulation, the companies in that simulation update their pricing strategies by performing a price simulation. As explained in section 5.3 and illustrated in Figure 5.3, this entails that the model then consists of three alternative timelines at different levels. The outcomes of the price simulation (i.e., the deepest level) influence the market developments in the process selection simulation (i.e., the middle level). And the outcomes of the process selection simulation influence the process used by the (flexible) company in the main simulation (i.e., the top level).

The process selection decision starts by *selecting the process with the highest potential margin* (section C.1.1). In this initial selection, the company computes the potential operating margin for each of the available processes. To compute a process's operating margin, the company first determines what revenues it expects to obtain and what costs it expects to incur with the process. Since, we consider processes that produce the same product, the revenues can be determined by multiplying the plant's current retail price by the quantity of product it can produce in a single time period. The costs consists of the fixed costs, variable costs, and costs of purchasing feedstock. For the fixed costs, the plant multiplies the process's process-fixed-costs with its own fixed-costs-efficiency and its capacity. The variable costs are computed similarly, only using the process-variable-costs and the variable-costs-efficiency. And for the purchasing costs, the plant multiplies the minimum gross price for which it can purchase feedstock with the quantity of feedstock needed to operate at full capacity. The operating margin of the process is subsequently computed by subtracting the costs from the revenues, leaving the profits, and dividing this by the revenues.

If the process with the highest potential margin is another one that the company's current process, the company explores the value of that process in greater detail. Hereto, it first *simulates the industry while performing its current process* (section C.1.2). Throughout the process selection simulation, the company records the cash flows that it obtains from its operations in the simulation. It uses those cash flows at the end of the simulation to compute the net present value of its current process. Herafter, the plant *simulates the industry while performing the new process* (section C.1.3). Again, the cash flows are recorded, but this time they account for the environment's adaptation (in the process selection simulation) to the changed process. Those cash flows are used at the end of the simulation to compute the net present value of the new process. If the net present value of the new process surpasses the net present value of the current process by more than the process-change-threshold, the company changes its current process to the new process (in the main simulation) and incurs the process-change-expenses. Otherwise, the company keeps performing its current process and has no additional expenses.

6.3.4 Design concepts

Because the model developed in this chapter is a continued development of the model in chapter 5, the design concepts of this model are nearly identical to those of previous chapter's model. The *prediction* is the only design concept that has changed. Whereas, in the previous model, the prediction concerned the relocation decision, prediction is included in this model through the process selection decision. This decision is made on basis of a simulation performed by the company, in which it attempts to predict its performance if it were to perform another process. The outcome of this prediction influences which process it is going to use and subsequently in which markets it participates. Consequently, the prediction may have an impact on how the markets in the main simulation develop and the net present value of the flexible plant.

6.3.5 Model initialisation

The model is initialised to represent a fictional industry that is based on the real-world caprolactam industry. Caprolactam (CPL) is an organic compound with the formula $(CH_2)_5C(O)NH$ that is used for the production of Nylon-6 polymers (Davis et al., 2014). We have selected the caprolactam industry to initialise the model, because CPL can be produced via a variety of processes using different types of feedstock; the use of this case does not say anything about the technical feasibility of flexible plants that produce CPL. A flexible plant could switch between processes to produce CPL, depending on which feedstock is more attractive. Consequently, this industry is well-suited to assess the value of a flexible plant. In this section, we discuss the initialisation of the production processes and companies to represent the caprolactam industry. A more detailed description of the companies and processes is provided in appendix C.2.

Production processes Caprolactam (CPL) can be produced via a number of different processes that either use benzene (Bz), phenol (Ph), or toluene as feedstock (Davis et al., 2014). However, the toluene-based process is rarely used commercially and thus is not included in the model. Both the Bz-based processes and the Ph-based processes produce CPL by first producing cyclohexanone. Since the production of cyclohexanone and CPL is often integrated at a site, we combine them in a single process. For the sake of simplicity, the different Bz-based processes are aggregated in a single process; the same applies for the different Ph-based processes.

Figure 6.1 gives an overview of the production processes represented in the model and how they are connected to each other via different goods. It shows the two separate 'routes' that can be used for the production of CPL, which is subsequently used for the production of nylon-6. The companies that supply Bz and those that use Bz in the production of CPL together form the market for Bz. Likewise, the companies that supply Ph and those that use Ph in the production of CPL together form the market for Ph. As those two goods are both used to produce CPL, those two

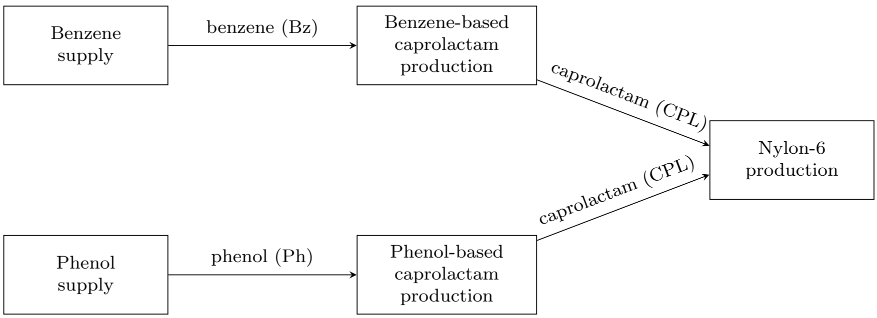

Figure 6.1: Overview of processes and goods in the process flexibility model

markets are both coupled with the CPL market. Consequently, the Bz and the Ph market are indirectly connected. Through this indirect connection, those two markets may influence each other, which can affect their development and subsequently may influence the value of a flexible plant.

For both caprolactam production processes, we assume 100 % efficiency, so that 1 unit of Bz or Ph is converted to 1 unit of CPL. With regard to the costs, we assume for both processes process-fixed-costs of € 200/mt at full capacity and process-variable-costs of € 400/mt. Depending on the cost-efficiency of the plant, the actual variable and fixed costs can differ considerably.

Companies The companies that perform the processes are divided over three supranational regions. Each region accommodates two benzene (Bz) suppliers and two phenol (Ph) suppliers. As in the previous models, those suppliers represent a large variety of suppliers and are assumed to be situated at 100 km from any CPL producer in the region. In total, the Bz suppliers, as well as the Ph suppliers can supply feedstock for 75 % of the CPL production capacity. So, together, the Bz and Ph suppliers can supply 150 % of the maximally needed quantity of feedstock. The minimum price that the Bz and Ph suppliers are willing to accept is drawn from a normal distribution with a mean value of € 700/mt and a standard deviation of € 150/mt.

The 20 caprolactam (CPL) producers are randomly divided over the three regions. Ten of those companies produce CPL using Bz and the ten other companies use Ph. The capacity of each CPL producer is drawn from a normal distribution with a mean value of 325 mt/wk and a standard deviation of 100 mt/wk. This gives a total capacity that is comparable to the capacity observed in the real-world caprolactam industry. The fixed-costs-efficiency of all plants is set at 100%; however, the variable-costs-efficiency of each plant is drawn from a normal distribution with a mean value of 100 % and a standard deviation of 10 %. The price simulation parameters of the plants (i.e., learning rate, exploration rate, and length of simulation) are equal to those in the previous chapter.

Each region accommodates three nylon-6 producers that use the produced CPL in their production. Each of the three nylon-6 producers in a region produces a different variant of nylon-6: fibres, films, or compounds. As a consequence, the willingness to pay of each nylon-6 producer is slightly different. On average, the fibre producers are willing to pay € 2,300/mt, the film producers € 2,400/mt, and the compounds producers €2,500/mt. The total demand of the nylon-6 producers is around 90 % of the total production capacity of the CPL producers. So, as in the real-world caprolactam industry, there is an oversupply of CPL.

The costs of transporting goods depends on the distance between two plants. Within a region, goods can be transported via truck or via rail. The costs of transport via truck are €0.09/(km mt), and the costs of transport via rail are €0.03/(km mt) plus a fixed cost of €48/mt. The used mode of transport is selected on basis of which mode is the cheapest. The costs of transport between regions consists of three components: *1*) plant to port, *2*) port to port, and *3*) port to plant. The costs of plant to port and the costs of port to plant are computed as the intra-region costs. The costs of port to port transport are in line with market prices around 2015 and range between €20/mt and €190/mt. The inter-region costs can subsequently be computed by adding the costs of those three components.

6.4 Evaluation of flexible plants

We use the developed model to evaluate a flexible plant. To obtain a comprehensive understanding of the value of a flexible plant, we perform two experiments. In the first experiment, we explore the added value of process flexibility for a company and what factors cause this added value. In this experiment, the focal company thus is the only company that operates a flexible plant. The second experiment looks beyond the focal company and considers how the environment influences the added value of flexibility. In this experiment, the focal company and other companies can operate flexible plants. Together those experiments provide a comprehensive understanding of the investment into a flexible plant, covering a variety of aspects and conditions of the investment decision.

For each experiment, we simulate the caprolactam industry for a period of 260 weeks (i.e., 5 years). In that period, the companies are manufacturing, exchanging, and shipping goods, while the companies with flexible plants make process selection decisions. In the experiments, we focus on the performance of a focal company that initially performs the Ph-based process. However, when it is flexible, the focal company can change its process and thus may decide to use Bz as feedstock. To demonstrate the use of the model and assess the value of process flexibility, we introduce changes in the Bz and Ph markets. After 1.5 year (week 78), the costs of Ph double, which is implemented as an increase of the willingness to accept of the Ph suppliers. Two years later (week 182), the costs of Ph return to their normal levels and the costs of Bz double. Due to those cost changes, the attractiveness of the different types of feedstock changes over time, providing opportunities for a flexible company to benefit from the possible price differences. This makes it a suitable scenario to assess the value of a flexible plant.

The variability tests of the model showed that the process selection decision has relatively little variability. Combined with our earlier insights into the relatively low variability of the market behaviour, we repeat each simulation 10 times and – where possible – discuss the median outcomes. For the outcomes, where the variability played a substantial role, we also present the distribution of the outcomes. The sensitivity analysis showed that above minimum threshold the process selection decision was hardly influenced by the process selection parameters. There-

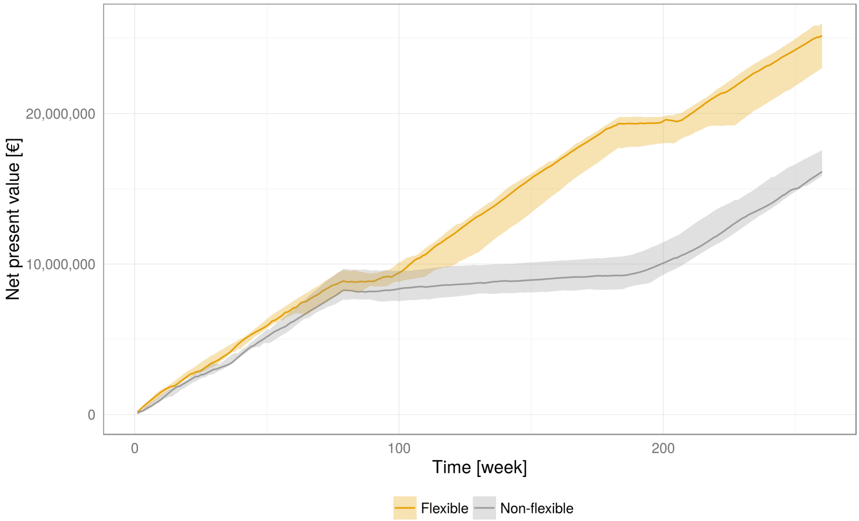

Figure 6.2: Comparison of a flexible company's value and a non-flexible company's value

fore, those parameters are set at values that resulted in relatively stable outcomes. The process-simulation-horizon is 26 weeks, the process-change-threshold is set at 0 %, the process-change-expenses are set at €0, the process-selection-frequency at 26 weeks, and the process-selection-simulation-repetitions are set at 2.

6.4.1 The added value of process flexibility

To assess the added value of process flexibility, we compare the flexible company's (i.e., the focal company that uses a flexible plant) net present value to the net present value – determined in other simulation runs – of the further identical non-flexible company. Figure 6.2 presents the development of the net present value of those two companies over time. At the end of the simulation, the median net present value of the flexible company is 56% higher than the net present value of the non-flexible company. The difference between the flexible and non-flexible company is mainly made in the period between week 100 and week 180. This corresponds to the period in which the price of Ph was doubled. As the focal company initially uses Ph, it had to pay the high price when it was non-flexible. However, when the focal company was flexible, it could switch to using the cheaper benzene. Consequently, the net present value of the flexible company continued to increase during that period, despite the high price of Ph. The two periods where the flexible company's value increase levelled off were caused by the (on average) 26 week interval between process selection decisions. Due to this 'sluggish' response, the company continued to use the expensive feedstock for a period of time, which caused its net present value to stop increasing for that period.

In Figure 6.3, we see that the process flexibility resulted in a very small change of the Bz price development in the period between week 100 and week 180. Although the difference is small and may be attributes to variability, it seems to indicate that

Table 6.1: Correlations between phenol and benzene prices with and without a flexible company, for five different time periods

	[0,78)	[78,130)	[130,182)	[182,221)	[221,260]
Non-flexible	1.00	0.20	0.23	−0.14	0.33
Flexible	0.99	0.28	0.36	−0.15	0.32

the switch of the flexible company from Ph to Bz causes the demand and price of Bz to increase. We argued before that the ability of a company to change its production process and switch between markets would couple the prices of those markets. Although the observed small increase of the Bz price is the indirect result of the increased Ph price, it would be an exaggeration to call this a coupling of those markets. To quantify the extent to which the two markets are coupled, we compute the Pearson correlation of the Ph and the Bz prices. The price developments can be divided into five different periods:

1. Before week 78 ([0,78)) when the costs of Ph and Bz were at their normal level.
2. Between weeks 78 and 130 ([78,130)) when the markets were adapting to the doubled costs of Ph.
3. Between weeks 130 and 182 ([130,182)) when the markets had adapted to the doubled costs of Ph.
4. Between weeks 182 and 221 ([182,221)) when the market were adapting to the normal costs of Ph and the doubled costs of Bz.
5. After week 221 ([221,260]) when the markets had adapted to the doubled costs of Bz.

Table 6.1 shows the correlation of the Ph and the Bz prices for each of those five periods, to assess the coupling of the two markets in each of those periods. The correlation in the periods right after the costs changes (i.e., periods [78,130) and [182,221)) indicate how fast the markets adapt to the changed costs. On the other hand, the correlation in the periods after those adaptation phases (when the markets had adapted – i.e., periods [130,182) and [221,260]) indicate to what extent the markets were coupled. Overall, the correlation increased as a result of the process flexibility. Despite still being weak correlations (Evans, 1996), the increase of 0.23 to 0.36 (with a one-tailed p-value of 0.03) after the doubling of the Ph costs ([130,182)) indicates that the markets became more coupled due to the introduction process flexibility. The adaptation of the markets was relatively slow, as indicated by the low correlations in the period right after the costs changes. Nonetheless, the introduction of process flexibility appears to slightly increase the speed at which the markets adapt.

6.4.2 Effects of the environment on a flexible plant

In the previous section, we observed that the added value of process flexibility was the result of the price differences of alternative goods. Furthermore, by comparing the price developments, we noted that the deployment of a flexible plant slightly decreased the price differences, by coupling the markets of the alternative goods. Following this reasoning, we expect the added value of process flexibility to decrease as more flexible plants are deployed in the industrial system. Therefore we explore

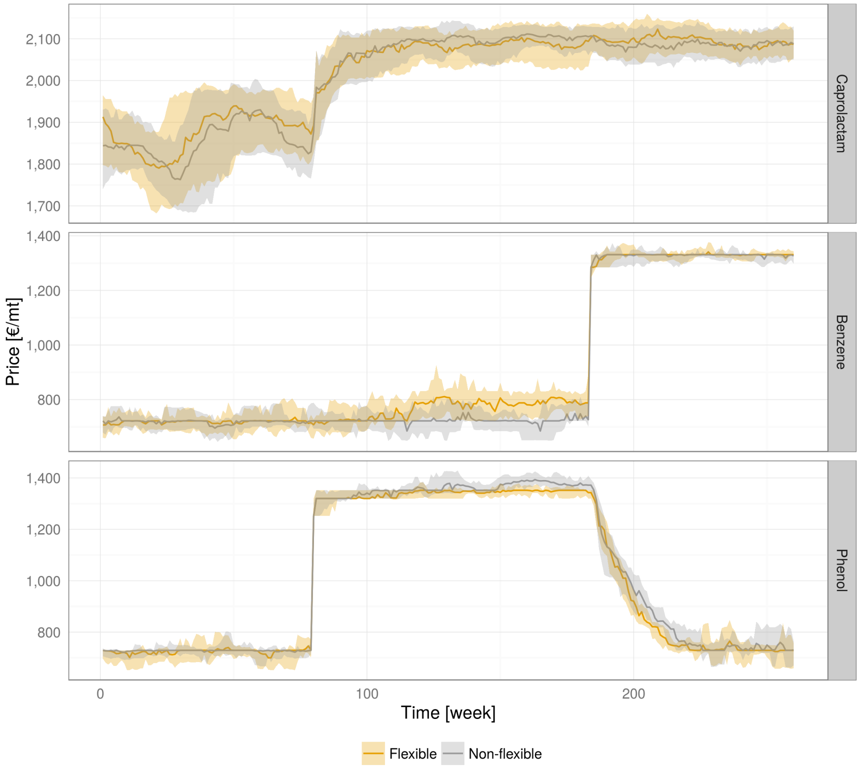

Figure 6.3: Price developments due to cost changes, with and without a flexible company

the net present value of the flexible focal company for different levels of flexibility adoption (i.e., percentage of all CPL producers that is flexible) in the industrial system.

Figure 6.4 shows the net present values of the flexible focal company at the end of the simulation, for different levels of flexibility adoption. Although the spread of outcomes is relatively large, increasing flexibility adoption appears to lower the focal company's net present value. The figure also displays the linear regression, which indicates that an increase of the flexibility adoption by 1 % causes the net present value to decrease by around € 100,000 [2]. Even though the linear regression only explains 50 % of the variance of the outcomes, it clearly demonstrates that an increased flexibility adoption leads to a decreased net present value of the focal company.

The decreased added value of flexibility can be explained by the reduced price difference between Ph and Bz. Figure 6.5 shows that at higher flexibility adoptions, the costs increase of Ph not only causes the price of Ph to increase, but also the price of Bz. The higher the level of flexibility adoption, the smaller the difference

[2] The fitted linear regression is $npv = 23{,}867{,}533 - 104{,}064 * fa$, where npv is the flexible plant's net present value at the end of the simulation and fa is the level of flexibility adoption in the industrial system. Both the entire model as well as the individual parameters have been found statistically significant at $p < 2 \times 10^{-16}$

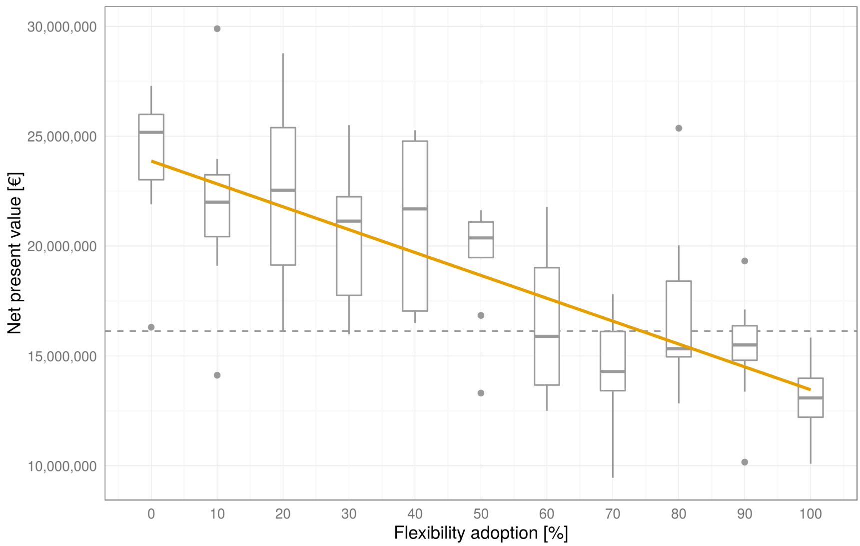

Figure 6.4: The net present value of a flexible company for different levels of flexibility adoption

between the Ph price and the Bz price. A comparable pattern is observed when the costs of Ph revert to normal levels and the costs of Bz double. In that situation, the price difference is also smaller for the higher levels of flexibility adoption. Table 6.2 quantifies the correlation between the Ph and Bz prices for the different levels of flexibility adoption. This confirms the insights of Figure 6.5: as the flexibility adoption increases, the correlation increases as well. Interesting to note is that for flexibility adoption levels above 50 % the market coupling does not increase substantially. The higher correlation in the period between week 221 and 260 is not caused by a tighter coupling but by faster adaptation of the markets. At 100 % flexibility adoption, the markets are coupled with a correlation of 0.97 and 0.89 Those are considered very strong correlations, indicating a tight coupling of the markets, especially compared to real-world correlations of goods. For example, the prices of crude oil and natural gas, which are generally considered tightly linked (Hartley et al., 2007), have a mean correlation of 0.4 and a maximum of around 0.8 (Aegent Energy Advisors, 2014).

Figure 6.6 illustrates that the decrease of the price difference coincides with the number of companies that switch their feedstock. When companies switch from the costly feedstock (i.e., the feedstock for which the costs increased) to the non-costly feedstock (i.e., the feedstock for which the costs did not increase), the demand for the non-costly feedstock increases. The increased demand for the non-costly feedstock increases its price, which consequently causes the price difference to decrease. Due to this smaller price difference, a flexible company can benefit less from its process flexibility, which therefore has a lower added value.

It is interesting to note that, even though the price difference does not decrease when the flexibility adoption is higher than 50 %, the number of companies that switch their process does increase. This explains why the focal company's net present value decreases to levels below the value of the non-flexible plant (Figure 6.4). The large number of companies that want to use the non-costly feedstock causes a short-

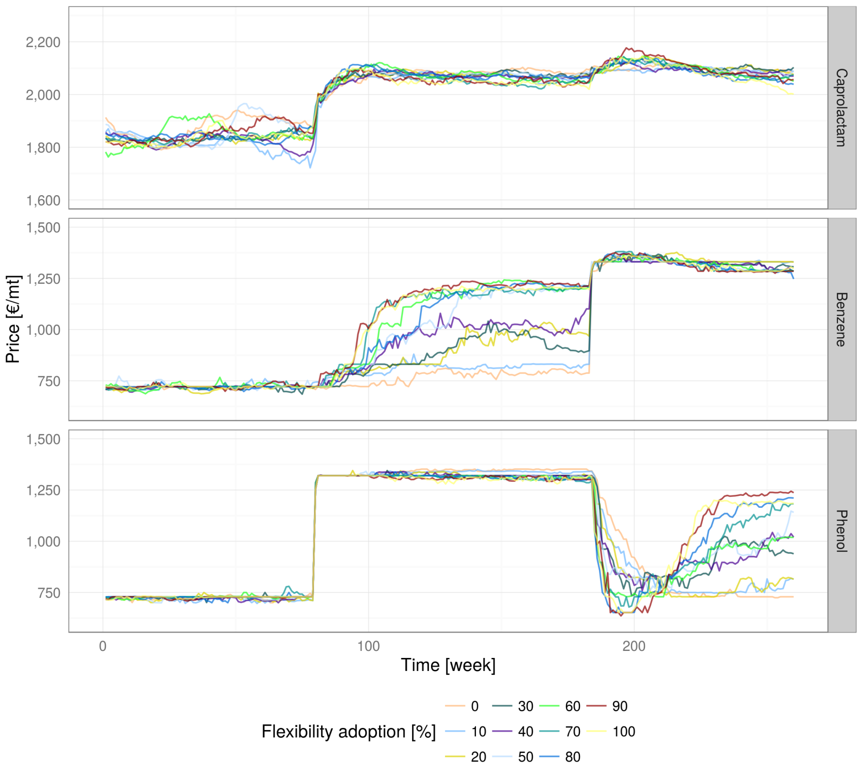

Figure 6.5: Price developments for different levels of flexibility adoption

Table 6.2: Correlations between phenol and benzene prices for different levels of flexibility adoption and different time periods

	[0,78)	[78,130)	[130,182)	[182,221)	[221,260]
0 %	0.99	0.28	0.36	−0.15	0.32
10 %	0.98	0.37	0.42	−0.15	0.35
20 %	0.98	0.39	0.63	−0.14	0.35
30 %	0.99	0.37	0.60	−0.18	0.52
40 %	0.99	0.41	0.74	0.03	0.50
50 %	0.98	0.43	0.88	0.11	0.54
60 %	0.99	0.39	0.93	0.03	0.57
70 %	0.99	0.42	0.95	0.00	0.53
80 %	0.99	0.39	0.94	−0.03	0.57
90 %	0.99	0.42	0.97	−0.05	0.77
100 %	0.99	0.38	0.97	0.00	0.86

age of that feedstock, which is not resolved through the price. Consequently, not all companies can obtain their needed quantity of feedstock and thus cannot utilise their full capacity. This lower capacity utilisation reduces the companies' revenues and thus lowers the net present value. Hence, the added value of process flexibility is

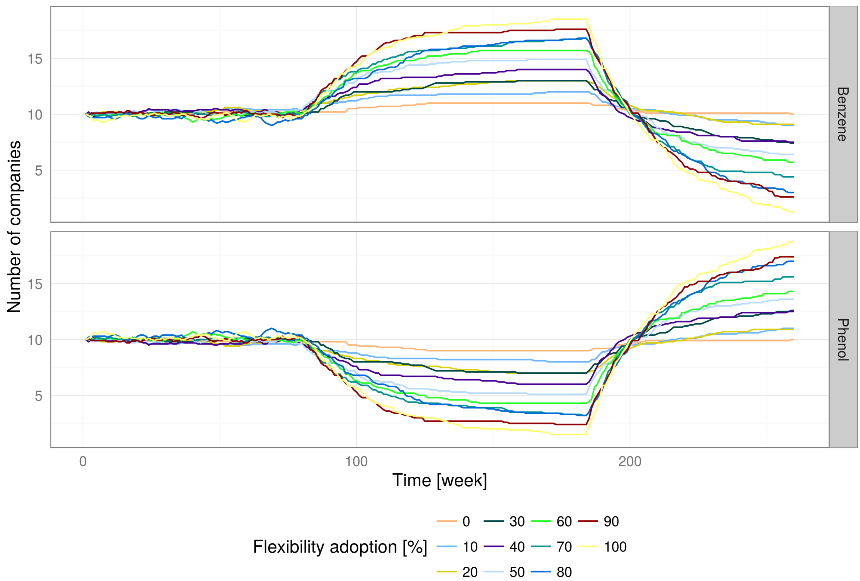

Figure 6.6: Usage of the available types of feedstock under different levels of flexibility adoption

not only influenced by the price developments, but also by the physical availability of goods.

6.5 Discussion

We use the experimental outcomes to discuss the considerations for a company that thinks of investing in a flexible plant. This not only concerns whether to invest in a flexible plant, but also the conditions under which the investment into a flexible plant is recommended. Furthermore, we also use the outcomes to discuss the ability of the model to capture the adaptation in the environment and how this influences the evaluation of a flexible plant.

Investing into a flexible plant With regard to the investment into a flexible plant, the experiments showed that a flexible plant can be more valuable than a non-flexible plant. The company that used a flexible plant was able to benefit from the changing price difference of the possible types of feedstock. This implies that a company only should invest in a flexible plant if the differences between the prices of the goods it can use/produce are changing over time. Otherwise, it would be better of to invest in a plant that always uses the cheaper feedstock.

However, the added value of process flexibility is likely to persuade other companies to invest in a flexible plant. The experiments demonstrated that increased flexibility adoption caused the added value of the process flexibility to decrease substantially. The companies using flexible plants could all switch from one feedstock to the other feedstock, thereby decreasing the difference between the prices of the two types of feedstock. This implies that a company should only invest in a flexible plant if it expects that the level of flexibility adoption remains low, so that process flexibility still adds value. For instance, when the other companies recently invested in non-flexible plants and thus are unlikely to replace them for flexible plants, or when the focal company controls the technology needed for the flexible plant. This is in line with financial markets, where we observe this phenomenon as arbitrage. The new insight that emerges from these experiments is that this phenomenon can also occur in industrial systems, where the companies need more time to respond to developments, and that it can be simulated to study in more detail.

Effects of capturing the environment's adaptation We assessed the investment into a flexible plant using a simulation model, because we expected that this model would be able to capture three important aspects: *1*) the mutual influence between the focal company and its environment; *2*) the indirect influence between the markets for alternative goods; and *3*) the environment's topological changes. In this paragraph, we discuss whether the experimental outcomes indicate that the model actually captured those aspects.

In our analysis of the experimental outcomes, we argued that the net present value of a flexible plant materialised from the price differences of alternative goods. This implies that the focal company (and its plant) is influenced by (price) developments in its environment. Vice versa, the price developments, presented in Figure 6.5, showed that the decision of companies to change their production process influenced the prices of the two types of feedstock substantially. Therefore, the experimental outcomes demonstrate that the model can capture the mutual influence between the focal company and its environment, and that those influences can substantially affect the outcomes of the assessment.

In the experiments, the scenario-induced price increase of one type of feedstock had the focal company to change its production process. This caused the price of the other type of feedstock to increase as well. The correlation of the prices of those two types of feedstock indicated that, as the flexibility adoption increased, the two markets become increasingly coupled. This implies that the model can account for the indirect influence between the markets for alternative goods. However, it also shows that this influence is not static, but changes as the industrial system develops.

By enabling companies in the environment to operate flexible plants and make process selection decisions, the environment could change structurally. The experimental outcomes indicated that, as the flexibility adoption increased, the focal company's net present value decreased. This demonstrates that the model can capture the environment's topological changes. Moreover, it also demonstrates that – as we claimed in the previous case studies – this adaptation can have a considerable influence on the outcomes of the model and thereby the evaluation of a flexible plant.

6.6 Synthesis

In this chapter, we aimed to support companies to decide about investing in flexible plants that can change the feedstock they use and/or the product they produce. We extended the model of chapter 5 to capture the process flexibility and the process selection decision. This extended the delineation of the modelled system to include the market interactions between the focal company and the suppliers and customers in all markets it could participate, which effectively coupled those markets. Using this model, we performed experiments to determine the added value of process flexibility and to assess the effect of topological changes of the environment on the value of a flexible plant. The first experiment demonstrated that process flexibility can improve the value of a plant substantially, as it enables the company to benefit from the changing price differences of alternative goods. In the second experiment, the coupling of markets for alternative goods was explored further for different levels of flexibility adoption (i.e., the percentage of companies operating a flexible plant. As the flexibility adoption increased, the differences between the prices of the alternative goods decreased, which caused the added value of process flexibility to decrease.

Using the experimental outcomes, we argued that a company should invest in a flexible plant if the price differences of alternative goods change over time. However, the additional value of flexibility will attract more flexible plants to the industry, which decreases the company's profitability. Therefore, a flexible plant can only be a sustainable investment if there are limits for other companies to deploy flexible plants in the industry. This shows that this effect is not only limited to financial markets, but also applies in industrial systems in which the companies can only respond with some delay.

With regard to the effects of accounting for the environment's adaptation, the experiments showed that the model was able to capture three important aspects.

1. *The mutual influence between the focal company and its environment.* The focal company's decisions were influenced by the price differences (of alternative goods), but also influenced those differences by changing its production process.
2. *The indirect influence between the markets for alternative goods.* As the flexibility adoption increased, the prices of the alternative goods became more correlated, which indicates that those markets influenced each other.
3. *The ability of the environment to cause structural changes in the system.* During the simulation, the companies in the environment changed the production processes, thereby changing the structure of the markets. This had a substantial influence on the focal company and subsequently on the value of its flexible plant.

Chapter 7

Collaboration in networks

This chapter is based on Bas and Van der Lei (2014)[1].

7.1 Introduction

In real-world industrial systems, companies are increasingly becoming aware that they can benefit mutually by collaborating (Camarinha-Matos et al., 2009). Fundamentally, collaborating entails that companies exchange goods for a longer period and thus do not have to interact each time step. It has been argued that collaborating companies can benefit from improved agility and resilience, which is essential in industrial systems that are changing quickly (Tukamuhabwa et al., 2015). By collaborating, the companies are less influenced by market developments, such as changing prices, which makes them more resilient to changes in the markets. However, collaborating is not necessarily beneficial under all circumstances, and companies thus need to carefully assess their possibilities for collaboration. This assessment is not straightforward, as the benefits of a collaboration depend on the interactions at both the company and network level of the industrial system. At the company-level, market interactions over the sale of goods; at the network-level, the interactions among collaborative networks over the participation of companies in those networks; and between those levels, companies that select the collaborative network they want to join. All those interactions influence the revenues and costs of the collaborative networks and of the (collaborating and non-collaborating) companies. Therefore, the assessment of the possibilities for collaboration needs to account for all those interactions and the different levels of the system.

To assess the possibilities for collaboration, we need to extend the simulation models with network-level interactions and connections between the company-level and the network-level. Therefore, the model's dimensions of complexity are as follows:

- *Diameter of the industrial system*: eight tiers.

[1]Bas, G. and Van der Lei, T. (2014). Analysis of profit allocation strategies for competing networks by applying cooperative game theory within an agent-based model. In *Proceedings of the 4th International Engineering Systems Symposium - CESUN 2014*.

- *Possible market interactions*: all potential partners in the focal company's current market.
- *Types of changes caused by the focal company*: operational and topological changes.
- *Types of changes caused by the environment*: operational and topological changes.
- *Types of changes caused by the market interactions*: operational and topological changes.
- *Detail of the environment's representation*: no aggregation.
- *Decision rules*: double-sided auctions.
- *Considered features*: supply and demand.

In this chapter, we assess the development of collaborations in an industrial system under a variety of conditions. Section 7.2 introduces collaborative networks in greater detail with a focus on the interactions at the company-level and the network-level, and the interlinkages between those two levels. In section 7.3, we describe the model that is used to study collaboration in an industrial system. Hereafter, in section 7.4, we use the model to perform a number of experiments aimed at different aspects of the decision to collaborate. We use the insights of those experiments in section 7.5 to discuss the implications for the decision to collaborate and the use of the developed model to study this decision.

7.2 Collaboration in collaborative networks

As a basis for the model, this section elaborates on the concepts that were introduced in the introduction. We start by defining the most important aspects of collaboration and collaborative networks. Building on those concepts, we discuss the interactions at – and between – the company-level and the network-level, which gives us the insights needed to capture the collaborative interactions in the model.

7.2.1 Collaboration

Joint endeavours of companies occur in a variety of forms, often differing with regard to the degree to which the collaborating companies are integrated. Some joint endeavours only involve the sharing of information between companies, while other require companies to hand over control over some of their operations, or even create a new separate joint organisation (Parmigiani and Rivera-Santos, 2011). Collaboration is a form of a joint endeavour and is defined as 'a process in which entities share information, resources and responsibilities to jointly plan, implement, and evaluate a program of activities to achieve a common goal' (Camarinha-matos and Afsarmanesh, 2006, pp. 28–29). A collaboration thus is an *activity that causes the companies to operate as a single entity.* This implies that collaborating companies are handing over some of their autonomy in order to achieve the common goal, which makes it one of the most profound joint endeavours.

Collaborations can be vertical, horizontal, or diagonal (Thoben and Jagdev, 2001). Vertical collaboration concerns the collaboration among two or more companies that perform successive steps in a supply chain and thus would normally exchange goods via market interactions. The purpose of vertical collaboration is to 'plan and execute supply chain operations with greater success than when acting in isolation' (Simatupang and Sridharan, 2002). For example, the supplier of a good that manages the inventory (at the site) of a retailer (Waller et al., 1999). Horizontal collaboration is a collaboration of two or more companies that are involved in comparable activities (Bahinipati et al., 2009). This type of collaboration creates value through the effective deployment and sharing of resources. For example, car manufacturers that collaborate with each other on the development of a new car (Dagnino, 2009). A diagonal collaboration is a collaboration between companies that are active in different sectors (Villa, 2011). Despite their apparent differences, those companies can benefit from a collaboration when they have similar needs or interests. For instance, the sharing of waste water, steam, and cooling water by a refinery and a power plant at an eco-industrial park (Jacobsen, 2006).

7.2.2 Collaborative networks

Companies that collaborate with each other, together form a collaborative network (CN). Whereas a collaboration is the activity of operating together, the collaborative network is the *collection of organisations and artefacts* that are involved in the collaboration. This collection can be a set of collaborating companies and their facilities, a separate (legal and/or physical) entity created especially for the collaboration, or anything in between. A variety of CN classes have been identified, such as industrial clusters, extended enterprises, dynamic supply chains, and virtual organisations (Camarinha-Matos et al., 2009). Despite their differences, those classes have some common characteristics: *1*) they are networks composed of largely autonomous organisations that are heterogeneous in terms of their operating environment, culture, social capital, and goals; and *2*) those organisations collaborate to (better) achieve common or compatible goals (Camarinha-Matos and Afsarmanesh, 2005).

To achieve their common goal, the companies put a part of their operations into service of the CN. Consequently, they lose some of their revenues, for which the revenues of the CN will have to make up. The CN's revenues depend to a large extent on which other companies participate in the CN (i.e., with whom the company collaborates). Due to this interdependence, the collaborating companies need to agree on a set of rules regarding the operations and the management of the CN. Those rules are formalised in collaborative agreements that specify the rights and obligations of the participants and typically covers the establishment, operations, and dissolvement of the CN (Romero et al., 2008).

The management of a CN concerns the coordination of the collaborating companies' efforts to deliver network outcomes (Grandori and Soda, 1995). This management can be arranged in a variety of ways that differ in how they allocate the power to control the CN (Jansson et al., 2008). In a participative management model, the CN is managed through the companies that need to reach common consent (Vurro et al., 2009). This model is often applied when the CN has no central company that can control the CN and the trust among the participants is high. When there is a single central company that can impose its will on the other participations, the CN is often managed by that company, which is referred to as the dictatorial model (Vurro et al., 2009). However, when trust is lacking and there is no central company, a CN can also be controlled by an independent network orchestrator (Vervest et al.,

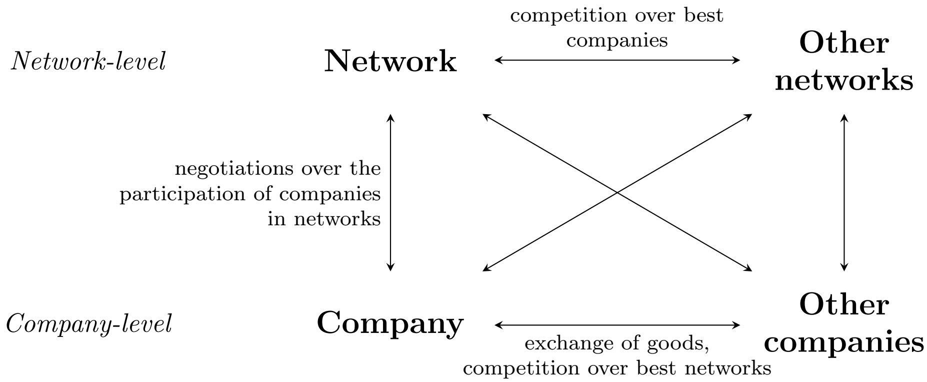

Figure 7.1: Collaborative interactions at the company-level and the network-level

2008). This independent network orchestrator is a neutral company that does not participate in the CN, but is hired by the collaborating companies to manage the CN. Apart from the chosen management model, we consider the management as separated from the collaborating companies. The companies execute operations, as coordinated by the management, to contribute to the common objective and are reimbursed for their effort as specified in the collaborative agreements.

7.2.3 Collaborative interactions

Collaborative network theorists typically distinguish two levels of entities: the company-level and the network-level (Galaskiewicz and Wasserman, 1994; Kilduff and Tsai, 2003). The company-level comprises the individual companies that may or may not collaborate; and the network-level consists of the different CNs in which the companies collaborate. At both levels, there are interactions between the entities, while the entities at different levels interact as well (Bergenholtz and Waldstrøm, 2011; Provan et al., 2007; Zaheer et al., 2010). Figure 7.1 gives an overview of the two levels and the interactions at those levels and between them.

At the company-level, the individual companies interact with each other over the exchange of goods that they use or produce in their operations. Those interactions comprise the market interactions that have been simulated in the previous three chapters, but also the supply of goods among collaborating companies. Moreover, the companies also interact with each other over participation in the best networks. Only a limited number of them can participate in a network, so the companies have to compete with each other to be invited to join the best networks (i.e., the networks with the best performance). At the network-level, the different networks are competing with each other to attract the best performing companies and thereby maximise the network's performance. The interactions between the company-level and the network-level concern the negotiations between networks and companies over the participation of the companies in the networks. The companies compare the expected payoff of participating in the networks to the payoff of trading in the market. The networks, on the other hand, compare the expected added value of the different companies, in order to determine which companies they want to attract.

Through the interactions at the different levels, the companies and the networks form a market in which they interact over the participation of companies in the network. In stead of negotiating over the exchange of goods, the entities negotiate over the exchange of the companies' services. The companies are the sellers and the networks are the buyers. This market exists next to the markets in which the goods are exchanged, and those two markets can influence each other. The prices of goods that emerge from the 'goods markets' are used by the companies to evaluate the attractiveness of collaborating, and thus influence their market behaviour in the 'collaboration market'. The other way around, the participation of companies in a network (i.e., the outcomes of the 'collaboration market') withdraws them from the 'goods markets', which – as we demonstrated in the previous chapter – can have substantial influences on how those markets develop.

7.3 Model description

As in the previous chapters, the model consists of companies that interact over the exchange of goods, which causes the modelled system to adapt and indirectly influences the performance of the companies. In this model, we add the possibility for companies to collaborate in a CN and thus supply goods without having to interact every time step. The collaboration emerges from market interactions between networks and companies over the participation of the companies in the CNs. For this, we add (on top of the 'goods markets') an additional layer of markets in which the service of companies are exchanged between selling companies and buying networks.

7.3.1 Purpose of the model

This model aims to provide the insights needed for a company to assess its possibilities for collaboration. In contrast to the previous models, we do not evaluate a focal company, but assess the patterns in the performance of all companies and networks in the industrial system. Those patterns emerge from the interactions in different layers of markets: the 'goods markets' and the 'collaboration markets'. Using the emerged patterns, we can make inferences about what this means for a company's decision on whether and how it should collaborate.

7.3.2 Entities, state variables, and scales

The model consists of three types of agents: companies, networks, and markets. The company agents represent the companies and facilities that use and produce goods that they exchange with each other, or supply to companies they collaborate with. The networks can be thought of as the management of the collaborative network that aims to maximise the CN's performance. The CNs' management principles thus are pre-specified in the network agents, but their structure and performance emerge from the companies that collaborate in the CNs. This collaboration is formalised through a collaborative agreement between the company and the network. The companies that participate in the same network, collaborate with each other by automatically supplying goods to each other. The companies that do not collaborate – or could not supply all their goods in their CN – have to exchange their goods in the markets.

The market for each good is conceptualised as a double-sided auction, which means that those markets are centralised and cleared by an auctioneer – i.e., the market agent (Parsons et al., 2006). The exchange of goods (emerging from the markets) is specified in supply contracts, which become shipments when the goods are shipped to the buyer.

Companies Companies are the agents that use a certain feedstock and convert it to a product that is supplied to another company. The type of conversion executed by the company is defined by *my process*, which thereby also specifies the feedstock it uses and the product it produces. The company's capacity defines the number of times it can execute the conversion in a single time step and thus how much product it can produce in that time. Each time the production process is executed, the company incurs certain *variable costs*. The *fixed costs*, on the other hand, are independent of the number of time the company performs its process. Depending on the costs of purchasing feedstock and its (fixed an variable) costs, the company has a minimum *willingness to accept* for the good that it sells. Likewise, the company has a *willingness to pay* for the good that it wants to buy. If the company collaborates with other companies, it keeps a record of the network in which it participates in *my network*. The most recent financial performance – either due to collaborating or the exchange of goods in the market – is recorded by the company's *expenses* and *revenues*. Those state variables serve as basis for the indicators that together are used to study the performance patterns in the industrial system.

Networks Networks represent the management of a collaborative network that together with the collaborating companies form the CN. Networks are entities that exists even when there are no companies that want to collaborate. They can be thought of as the backbone of the CN to which the companies can 'connect' to collaborate with each other. Each network has a certain set of *positions* available that specify the processes that it aims to (have its companies) perform. The network records which companies participate in the network (i.e., whose collaboration it manages) in *my companies*. Combined with the positions, this gives insight into the kind of companies that could still join the network. Furthermore, each network has some preferences regarding how to manage the collaborating companies. It has an *allocation strategy* that specifies how it allocates the network profits over the participating companies; it has a *preferred participation duration* that specifies for how long each company should participate in the network; and it has a *preferred fine* that specifies the fine paid by either the network or the company, if one of them terminates the collaborative agreement before the agreement's end date. Like the companies, a network also has two accounts to record the CN's most recent financial performance: *network expenses* and *network revenues*, which are also used to study the performance patterns in the industrial system.

Markets The market agents represent the markets for the exchange of goods, which are conceptualised as double-sided auctions and thus are explicitly represented in the model. The 'collaboration market' emerges from the interactions of the companies and networks (like the markets in the previous chapters) and thus is not represented explicitly. Each market agent administers one market for a particular *good*. The market agent acts as an intermediary between the buyers and sellers of that good and thus receives and sends both orders and shipments. This implies that the market also has revenues and expenses of trading those goods, which (as we consider no margin for the market) should add up to zero.

Supply contracts Supply contracts represent the exchange of *goods* between a seller (*origin*) and a buyer (*destination*). A supply contract can emerge from market interactions, but can also be the consequence of collaborating companies. When the supply contract emerges from market interactions, a market agent (as intermediary) always acts as either the origin or destination and a company takes the other position; when the supply contract is the consequence of collaborating companies, both positions are taken by companies. A supply contract has a *quantity* that specifies what amount of the good is exchanged between the origin and destination. The price paid (per unit of the good) by the destination is recorded in the order's *gross price*, while *net price* entails the amount of money received by the origin.

Shipments Shipments are the execution of supply contracts, by physically delivering the exchanged goods, and thus have the same properties as orders.

Collaborative agreements A collaborative agreement couples a *company* to a *network* and specifies under which terms the company participates in the network. So, the companies that have a collaborative agreement with the same network are collaborating with each other. The *end date* of the agreement concerns the date after which the agreement is automatically terminated and the company is no longer a part of the network (but may decide to renew its participation). If the agreement is terminated before that date, the terminating party has to pay a *fine*. Both the end date and the fine are set on basis of the preferred participation duration and the preferred fine of the network agent. The *allocated percentage* specifies what percentage of the network profit is allocated to the company, which is computed on basis of the network agent's allocation strategy and the other companies that participate in the network. The most recent amount of money that is actually allocated to the company is specified by the *allocated payoff*, which thus can be considered a sort of paycheck.

Scales Since the markets for trading goods are conceptualised as double-sided auctions, the plants cannot account for transport expenses in their bidding strategy. Consequently, the geographical component does not play a role in this model, and the geographical scale of the model thus is limited to a single point at which all plants are assumed to be located. Each time step in the model represents a period of a week. The behaviour of the agents concerns both operational and tactical horizons. This implies that the maximum time period that the model can represent (without other (non-modelled) dynamics comping into play) spans around two years.

7.3.3 Process overview and scheduling

The performance due to a collaboration is influenced by market interactions at two levels: market interactions for the supply of goods, and market interactions for the participation in networks. Consequently, the processes in the model are categorised into two categories: *1*) the exchange interactions through which companies exchange goods with each other; and *2*) the collaboration interactions through which CNs emerge. The exchange interactions have an operational horizon and thus are executed each time step, while the collaboration interactions have a tactical horizon and thus are executed with longer intervals. Figure 7.2 presents an overview of the processes. In this section, we discuss those processes and the logic connection them. The details of the processes themselves are discuss in greater detail in appendix D.

Exchange interactions As in the previous models (where they were named market interactions), the exchange interactions consist of rounds in which succeeding goods are traded; starting with the most downstream good and iteratively continuing more upstream. The structure of those interactions is comparable to the structure that was introduced in Figure 4.1, consisting of a negotiation phase and a shipping phase. The exchange interactions mainly take place at the company-level (Figure 7.1), and the processes thus are mainly executed by companies.

The negotiation phase starts with the buyers of the negotiated good that *determine their demand* along with their willingness to pay for that good. Both their demand and their willingness to pay depend on the sales of their product in a more downstream market, or on the supply of their product to a collaborating company. This is followed by the sellers of the traded good that *determine their supply* and their willingness to accept. For the supply, the seller assumes that it can supply its full capacity, while its willingness to accept depends on the price it has paid for its feedstock in the previous time step (either the market price or the costs that a collaborating company incurred to produce the good). Hereafter, the buyers that collaborate with a seller *order the good from the network*, which entails that they order goods without any market interactions. The supply contract's net price equals the buyer's willingness to pay and the gross price equals the seller's willingness to accept, so that collaborating companies only 'pay' the costs of the good. The buyers with remaining demand *bid in the market*, which means that they send a supply contract to the market for the traded good, in which they communicate their demand and their willingness to pay. The sellers with remaining supply then *offer in the market*, which means that they send a supply contract to the market for the good, in which they communicate their supply and their willingness to accept. Based on the received orders, the market then *clears the markets* by determining at what price the supply and demand match and updating the prices and quantities of the supply contracts according to the market outcomes.

Once all negotiations are finished, the exchanged goods are shipped. This also occurs sequentially, but this time starting with the most upstream good and continuing with iteratively more downstream goods. First, the shippers (i.e., the companies that can ship the good) *ship the goods to its collaborating buyers*, followed by *shipping the goods to the market.* The market receives those goods and pays the shippers, after which it *transfers the goods* by shipping them to the buyers that ordered those

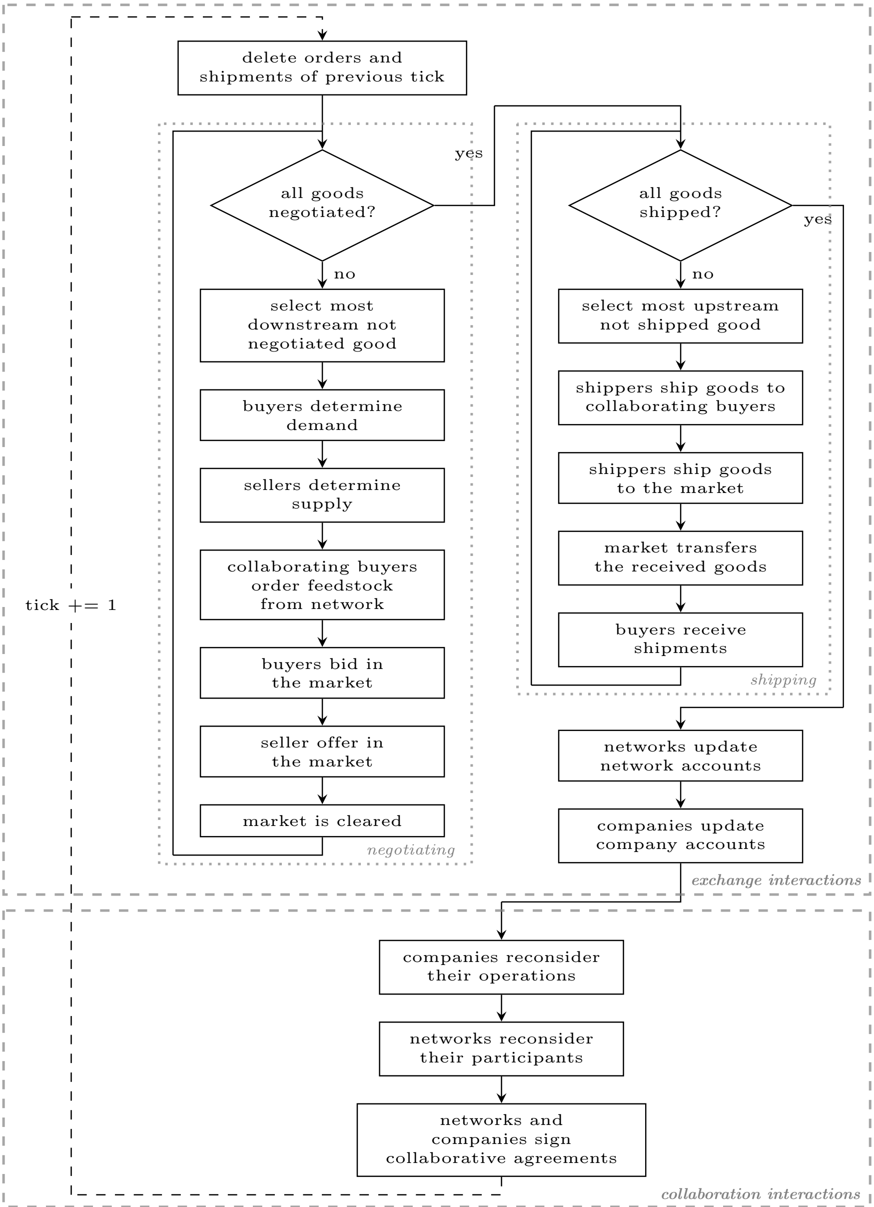

Figure 7.2: Process overview of the collaboration model

from the market. Finally, the buyers *receive the shipments*, either from a collaborating plant or from the market. They pay the origin of the shipment and determine how much product they can produce using the received quantity of goods.

After the shipment of goods is completed, the networks and companies update their financial accounts. When a network *updates its network accounts*, it receives the revenues and expenses of its companies, which are the result of the supply of goods. Next to this, it also determines the variable and fixed costs of its companies and lowers those, where applicable, to account for synergies between collaborating companies. As a third item, it determines the expenses that it incurs to coordinate the network. It sums all those items to compute the network profits. The network then allocates those profits to its companies, as specified by the allocated percentage of each collaborative agreement. Subsequently, the companies *update their company accounts*. Companies that do not collaborate add their fixed and variable costs to their (feedstock purchasing) expenses. The companies that do collaborate replace their revenues with the allocated network profits and set their expenses to zero. The initial expenses and revenues of selling and buying goods have already been included in the allocated network profits and thus should not be accounted for twice.

Collaboration interactions The collaboration interactions entail those processes through which companies and networks establish which company is going to participate in which network. As these interactions connect the network-level and the company-level (Figure 7.1) the processes are executed by companies and by networks.

The formation of networks starts with companies that, randomly or when their collaborative agreement ends, *reconsider their operations*. This reconsideration entails that the company assesses whether it wants to collaborate or operate independently. For this, it computes the net present value of *1*) operating independently, *2*) participating in one of the networks with an open position, or (if applicable) *3*) continue participating in its current network. In those computations, the company assumes that the prices of the exchanged goods do not change, so that it can project what revenues and expenses it can expect and what payoff the network may allocate. From those three options, the company selects the one with the highest net present value. If it has selected a new network (option 2) or it wants to renew its agreement (option 3, provided that its current agreement ended), the company sends an offer to the network it has selected, indicating its intent to participate in the network.

This is followed by the networks that *reconsider their participants*, either at random intervals or when they have an open position. So, a network starts looking for new participants to improve its performance. First, the network determines which position is reconsidered and (if this position is taken) also which (reconsidered) company it may remove from the network. For the reconsideration of its participants, the networks computes its net present value when *1*) operating with the reconsidered position open, *2*) operating with the reconsidered position occupied by the reconsidered company, or *3*) operating with the reconsidered position occupied by another available company. The network then selects the option with the highest net present value, and sends an offer to the company (if any) it wants to involve in the network. If the network had no open position and the reconsidered company is not selected, the collaborative agreement with that company is terminated and the fine is paid.

Once the companies and networks have reconsidered their operations and participants, the offers are compared and *collaborative agreements are signed*. For this purpose, the offer with the highest added-value (i.e., additional network profit due to the company joining the network) is selected. This allows the best combinations of companies and networks to have the greatest probability of 'finding' each other. The company of the selected offer first determines whether the expected payoff of the offer is higher than that of its other offers and its current operations. If the company agrees with the offer, the incumbent companies of the network determine whether the participation of the new company improves their expected payoff. If the expected payoff of all incumbent companies improves, the new company joins the network. This entails that a collaborative agreement is signed that ends after the network's preferred participation duration and has a fine that equals the network's preferred fine. The allocated percentage of all the network's collaborative agreements is then recomputed, as the participation of the new company is likely to alter the payoff of all companies. Hereafter, this process is repeated – but this time for the offer with the next-highest added value – until there are no offers left.

7.3.4 Design concepts

Basic principles: The main underlying principle of this work is that the emergence of collaborative networks is influenced by the market interactions at two levels: interactions at the company-level over the exchange of goods, and interactions at the network-level over the collaboration of companies in a collaborative network (CN). *Emergence:* At both levels, the market interactions cause emergent phenomena: the prices and volumes of exchanged goods at the company-level, and the composition of CNs at the network-level. *Adaptation:* Developments at one level of the market cause the agents to adapt their behaviour and interactions at the other level of the market. *Objectives:* Networks aim to maximise the network profit by attracting the best performing companies, while each company endeavours to operate in the way that maximises its individual profits. *Prediction:* Both the companies and networks attempt to predict how their performance is going to change if they alter their operations or their participants. *Sensing:* To exchange goods, the companies only consider their own state (e.g., received orders, supply/demand) and do not sense their environment. However, for the formation of CNs, both the companies and networks consider the state and behaviour of other networks and companies. *Interaction:* Companies interact with each other via markets or directly when they are collaborating. Companies and networks interact directly when they send offers to each other. *Stochasticity:* The stochasticity in this model mainly comes from the scheduling of the agents, but also from the timing of the collaboration interactions. *Observation:* The observations are also split in a network-level and a company-level. At the network-level, we observe what kind of companies collaborate and how the CNs perform; and at the company-level, we observe the financial performance of individual companies, either collaborating or operating individually.

Table 7.1: Sequence of production processes represented in the collaboration model

	Feedstock		Product	
Process	Type	Quantity	Type	Quantity
Process-1			Good-1	1.00
Process-2	Good-1	1.00	Good-2	1.00
Process-3	Good-2	1.00	Good-3	1.00
Process-4	Good-3	1.00	Good-4	1.00
Process-5	Good-4	1.00	Good-5	1.00
Process-6	Good-5	1.00	Good-6	1.00
Process-7	Good-6	1.00	Good-7	1.00
Process-8	Good-7	1.00		

7.3.5 Model initialisation

To demonstrate its use, the model is initialised as an abstract case that is designed for the study of collaborations. Unlike the previous chapters, this case represents a non-existing industrial system. The companies in this model perform sequential production processes, and the different goods in the model are traded in markets that are coupled serially. Each network has – per process – room for one company, which implies that the collaboration is vertical. In this section, we discuss the initialisation of the production processes, companies, and networks.

Production processes The industry that we represent in this model consists of eight different consecutive production processes that are connected via the used and produced goods and together form a non-branched chain. Each process uses one unit of a particular good and produces exactly one unit of another good. Table 7.1 specifies for each process what feedstock it uses and what product it produces.

Companies The model has a total of 640 companies, that each perform one of the eight production processes and have a production capacity of 1,000 units per time step. Each company has fixed costs and variable costs that are randomly drawn from a uniform distribution with a minimum of €75/unit and a maximum of €125/unit. The willingness to accept of the good-1 suppliers (i.e., companies that perform process-1) is randomly drawn from a normal distribution with a mean of €250/unit and a standard deviation of €50/unit. The willingness to pay of the good-7 customers (i.e., companies that perform process-8) is chosen so that the willingness to pay of 15 % of the buyers and the willingness to accept of 15 % of the sellers overlaps. So, for each good in the industry, around 15 % of the sellers and 15 % of the buyers are not competitive and thus cannot exchange goods. We have chosen for this initialisation as this enables us to study how the markets change in response to the collaborations of companies. In practice, this implies that the willingness to pay of the good-7 customers ranges between €1,200/unit and €1,600/unit.

Networks The networks in the model can take in exactly one company per production process (i.e., process-2 up till process-7) and thus allow the collaboration of six companies. With a total of 60 networks, not all companies can collaborate and thus have to compete with each other. However, depending on the conditions, not all companies may want to collaborate, causing the networks to compete with each other. The preferred participation duration of each network is randomly drawn from a uniform distribution with a minimum of 1 time step and a maximum of 80 time steps. Likewise, the preferred fine (for terminating a collaborative agreement) of a network is drawn from a uniform distribution with a minimum of €100,000 and a maximum of €1,000,000

Each network uses one of three allocation strategies: 'Evenly', 'Shapley', and 'Gately'. The 20 networks that use the Evenly strategy give each participating company an equal share of the network profit, independent of their added value to the network. Both the Shapley and Gately strategies are based on cooperative game theoretical solution concepts. Those solution concepts can be thought of as guidelines for the allocation of a coalition's worth (i.e., network profit) and are generally based on believes of fairness or expected rational behaviour (Osborne and Rubinstein, 1994). The 20 networks that use the Shapley strategy compute the Shapley value (Shapley, 1953) for each of their companies. The Shapley value of a company represents that part of the network's value that is caused by the company. The allocated percentage of each company is computed by determining its share in the summed Shapley value of the network. The 20 remaining networks use the Gately strategy and thus compute the Gately value (Gately, 1970) for each of their companies. Like the Shapley value, the Gately value of a company represents that part of the network's value that can be attributed to the company. However, the computation of the Gately value is different, which therefore results in a different allocation of the network profit.

The effect of the initialisation assumptions on the assessment outcomes has been tested through a sensitivity analysis. We found that the assumptions had no substantial effect on the relative performance of collaborating and individual companies or the relative performance of different companies. The costs influenced only the absolute (network and company) profitability and market prices, while the overlap of willingness to pay and willingness to accept only had a very small effect on the price developments.

7.4 Assessing the possibilities for collaboration

To assess a company's possibilities for collaboration, we perform three experiments that focus on different aspects of collaborating. The first experiment assesses what kind of collaborative networks (CNs) materialise in industries with different coordination costs and collaborative costs savings. In the second experiment, we study the profitability of different modes of operation (i.e., individually or collaborating) under those conditions. Together, those two experiments can provide insights into the conditions under which the company should collaborate and when it is better to operate individually. The third experiment assesses how the company should collaborate, by studying the effect of three aspects of network management on the network profit: the allocation strategy, the participation duration, and the fine for leaving the network prematurely.

To limit the effects of stochasticity on the experimental outcomes, each experiment is repeated 15 times. The sensitivity analysis indicated that the stochasticity had relatively little effect on the trends that emerged from the model, which allowed us to limit the number of repetitions. Nonetheless, we consider the variability in our discussion of the experimental outcomes.

7.4.1 When to collaborate

Materialised collaborative networks To determine whether a company should collaborate, we explore the types of CNs that materialise under different conditions. Those conditions are varied along two dimensions: *1*) the coordination costs, which are defined as the costs incurred by the network to coordinate one unit of production capacity; and *2*) the collaborative cost savings, which is the relative decrease of a company's variable costs when it can collaborate with a direct preceding or succeeding company. What types of CNs materialise is measured by the number of companies participating in the CNs and the difference between the variable costs of collaborating plants and those of individually operating plants. Those two indicators combined provide insights into the number and the kind of companies that collaborate.

Figure 7.3 shows, for different coordination costs and collaborative cost savings, a distribution of the companies per network. As expected, a combination of high collaborative cost savings and low coordination costs makes it attractive for companies to collaborate, which results in many networks with the maximum number of companies. The other way around, a combination of low collaborative cost savings and high coordination costs makes it less attractive for companies to collaborate; therefore, under those conditions, the networks have zero participating companies. There also are some conditions where the system is divided in highly occupied network and empty networks. For instance, at coordination costs of €20 and cost savings of 20 %, the number of networks with zero participations and those with six participants is nearly equal. The relative rarity of those conditions implies that the system is attracted to the extreme situations, with a relatively steep transition between them.

Regarding the type of companies that collaborate (identified by their fixed and variable costs), Figure 7.4 presents the distribution of the costs of companies that collaborate and of those that operate individually. This shows that, for almost all conditions, the costs of collaborating companies is slightly below the costs of individual companies. Both the median costs are lower and the majority of collaborating companies have lower costs than the majority of individual companies. When there is virtually no collaboration (i.e., the bottom right plots) the difference in costs of individual and collaborating companies is generally bigger. So, as for the number of collaborating companies, the costs distribution appears to have two patterns towards which the system is attracted. However, for all conditions, the costs of collaborating companies are lower than those of the individual companies. When the conditions are bad for a collaboration, only the best performing companies can make a collaboration work; and when the conditions are good, only the best companies are selected by the networks.

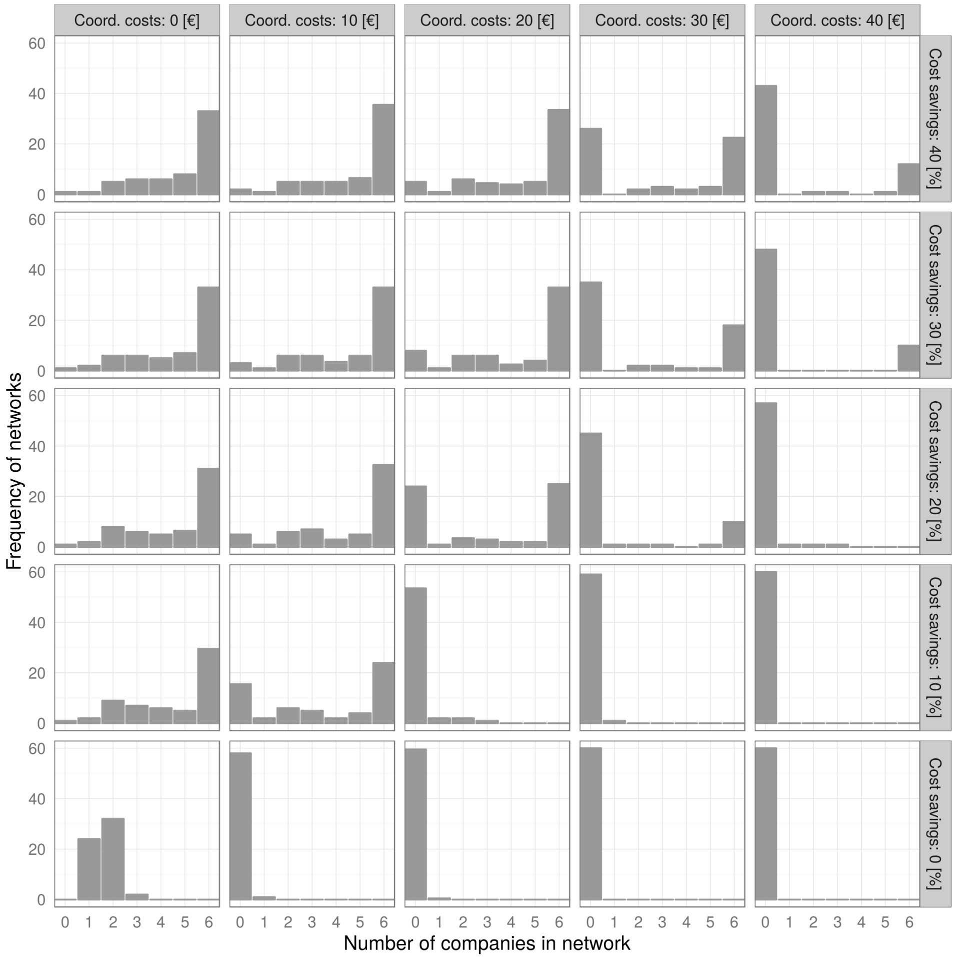

Figure 7.3: Number of companies in a network, under different coordination costs (horizontal facets) and collaborative cost savings (vertical facets)

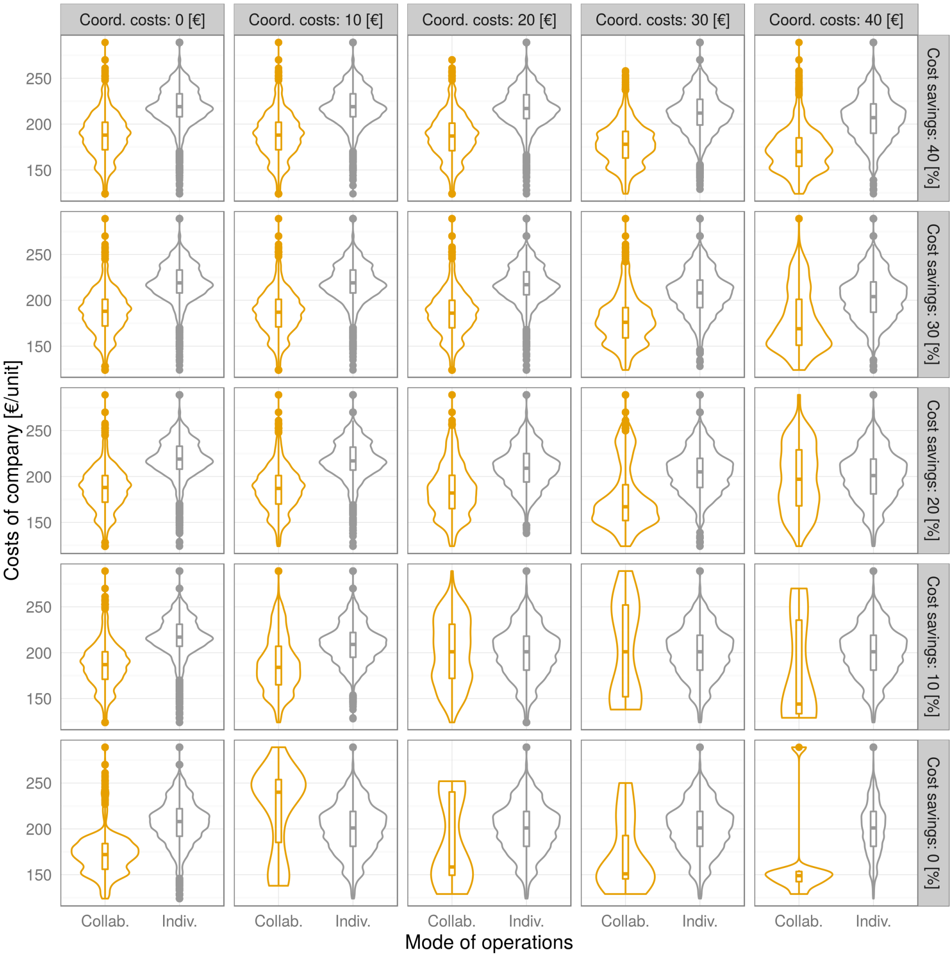

Figure 7.4: Distribution of the costs of collaborating and individual companies, under different coordination costs (horizontal facets) and collaborative cost savings (vertical facets)

Company profitability To get a better understanding of how collaborating affects the profitability of a company, we study the profitability of collaborating and individually operating companies. In our analysis of the network composition, we identified that the conditions could be grouped into three categories: conditions favouring collaboration (collaborative conditions), conditions favouring individual operations (individual conditions), and conditions favouring neither collaboration or individual operations (neutral conditions); where the latter was a steep transition separating the former two groups of conditions. To include those groups of conditions in the assessment, while limiting the number of scenarios that need to be analysed, we assess the companies' profitability for five different combinations of coordination costs and collaborative cost savings: €0 and 40 %, €10 and 30 %, €20 and 20 %, €30 and 10 %, and €40 and 0 %[2]. The first two represent collaborative conditions, the third represent neutral conditions, and the last two represent individual conditions

Figure 7.5 shows, for those different conditions, the profitability of collaborating and individual companies. The plots are ordered so that conditions are collaborative at the left, neutral in the middle, and individual at the right. Under all conditions, the companies are divided into two distinct groups: profitable companies and unprofitable companies. The first group consists of companies that are competitive and can sell their product, while the second group consists of companies that are not competitive and have no (or not enough) sales to recover their (fixed) costs. Generally, the competitive group of companies consists of companies with lower costs (more to the left in a plot), and the non-competitive group of companies consists of companies with higher costs (more to the right in a plot).

When the conditions change from collaborative to individual, we see a number of trends. First of all, the collaboration among companies decreases. As the conditions are less favourable for collaborating companies, the companies' individual (fixed and variable) costs and the coordination costs no longer outweigh the collaborative cost savings. This implies that companies with higher costs are removed from the CN the first; simply because they are too expensive to add any value to the CN. This is observed in the three most left plots of Figure 7.5, where the companies with the higher costs stop collaborating (i.e., become grey instead of orange). In the two most right plots, we see that the collaborating companies all have decided to operate individually. A second trend is that the profit distribution changes. As the conditions become more individual, the lower collaborative cost savings and higher coordination costs reduce the profitability of competitive, collaborating companies. At the same time, we see that the profitability of the non-competitive companies – albeit only slightly – increases. This thus appears to indicate that the profitability not only decreases when the conditions favour individual operations, but it is also redistributed. The other way around, the collaboration among companies thus not only increases their own profitability, but also decreases the profitability of their less fortunate competitors.

Given the distinction in performance between companies with low and high costs, it thus appears that the individual costs of companies are a main determinant of the profitability. The companies with higher costs cannot compete with the companies that have lower costs. This effect is further reinforced by the ability of the com-

[2]This is the main diagonal (top left to bottom right) of the conditions in Figures 7.3 and 7.4.

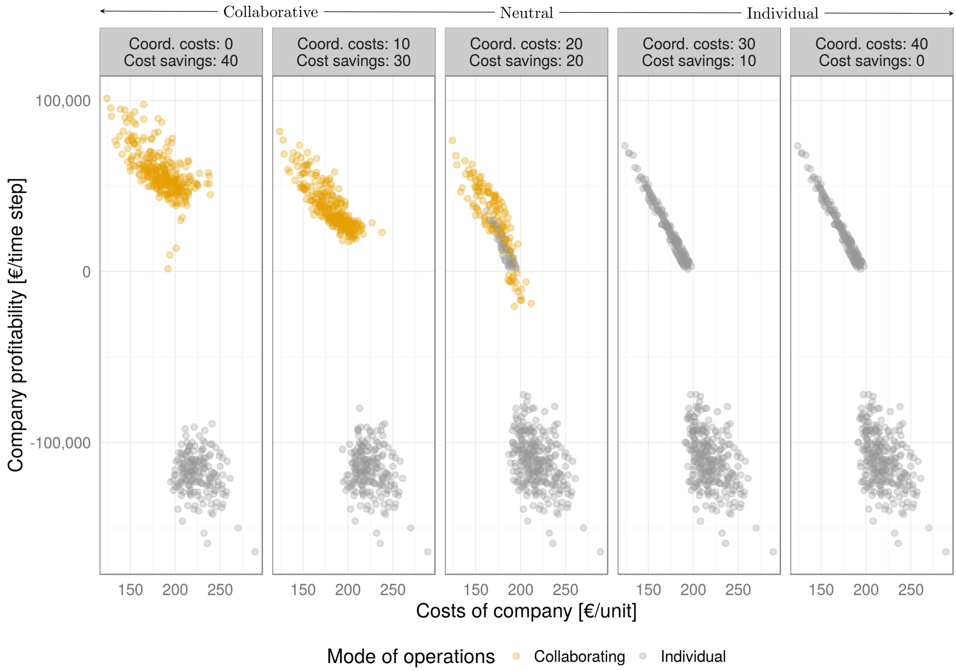

Figure 7.5: Profitability of collaborating (orange) and individual (grey) companies, under different conditions, ranging from collaborative (left) to individual (right)

panies with low costs to collaborate with each other, thereby lowering their costs even further. Hence, the collaboration appears to favour those that are already performing well, while it harms those that are less equipped. Figure 7.6 indicates that this is caused by the collaborating companies that lower the price of the final good (i.e., Good-7) and increases the price of the raw material (i.e., Good-1). The lower costs of collaborating companies allow them to pay a higher price for the raw materials and ask a lower price for the final good. This reduces the margins of the individual companies and thus actually harms their profitability. Nevertheless, it should be noted that, under collaborative conditions, more companies operate at a profit (296) than under individual conditions (198). So, the 'middle class' of companies actually benefits from the collaboration – along with the best companies – at the expense of the worst performing companies.

7.4.2 How to collaborate

Next to the decision on when to collaborate, companies also have to decide how to collaborate. How companies collaborate is to a large extent determined by the management of the CN. This management has many different aspects, of which we focus on three: the allocation strategy, the (participation) duration of a collaborative agreement, and the fine for leaving the CN prematurely. As we can only observe the consequences of the management aspects when companies actually collaborate, we study the effects of the management aspects under collaborative conditions: coordi-

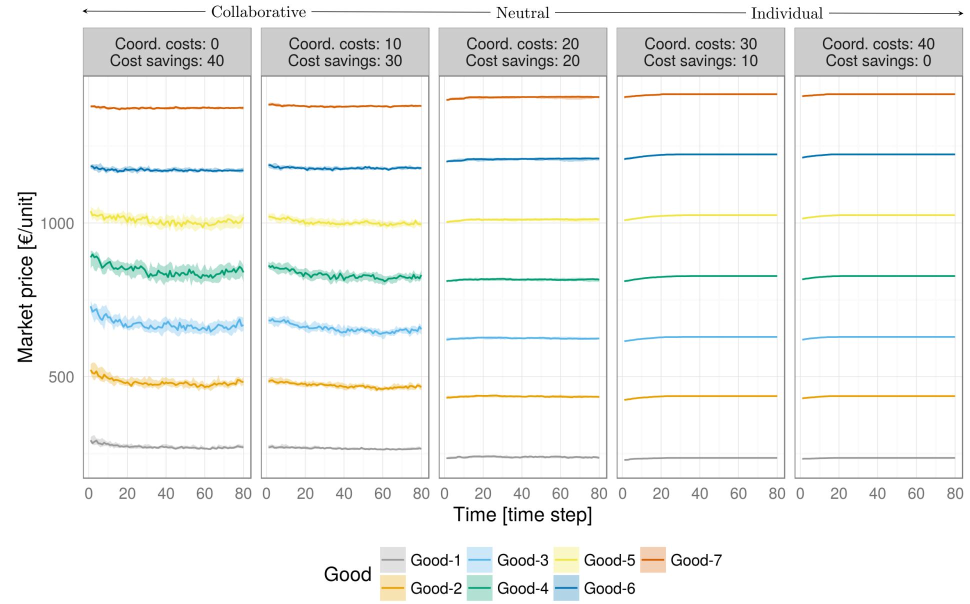

Figure 7.6: Market prices of goods, under different conditions ranging from favouring collaboration (left) to favouring individual operations (right)

nation costs of €0 and collaborative cost savings of 40 %. For each of those three management aspects, we then assess how they affect the network profitability; starting with the allocation strategies, followed by the preferred participation duration, and the preferred fine for breach of contract.

Figure 7.7 indicates how the network profitability (per company) of networks that use the different allocation strategies is distributed. This indicates that the networks with Gately strategy have the highest profits, followed by the Evenly strategy, and the Shapley strategy. However, as the spread of the profits is large, those differences may also be the result of stochasticity. The Welch F-test and a Games Howel test[3] indicate a statistically significant difference between all groups with $p < 2.2 \times 10^{-16}$ Hence, the observed differences between the allocation strategies are unlikely to be attributable to stochasticity, and the differences in profit are likely due to the used allocation strategy. So, it appears that networks that use the Gately strategy can attract companies with lower costs and thereby obtain the highest network profitability.

The profitability of networks with different preferred participation durations is plotted in Figure 7.8 with the median profitability per participation duration as orange line. This graph indicates that the network profitability varies substantially and that this variance is relatively homogeneous over the participation durations. Nonetheless, by looking at the median outcomes, we can observe a trend in the data. At low participations durations, the network profitability is also low; however, as the participation duration increases, the network profitability increases as well.

[3] As the Bartlett's test indicates that the variance of the different allocation strategies is not homogeneous.

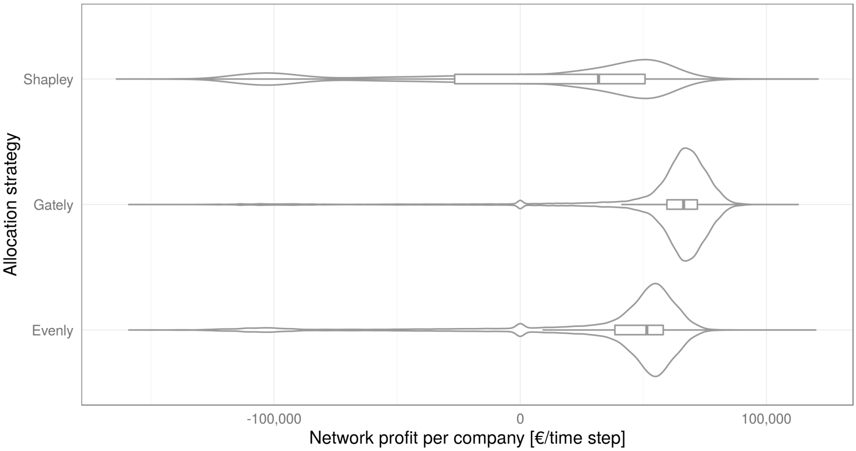

Figure 7.7: Distribution of network profitability obtained by network using the three different allocation strategies

This continues up to a duration of around 20 time steps, after which the network profitability stabilises. So, a participation duration above 20 time steps, does not improve the network profitability any further. A possible explanation for the lower profitability of networks with a low participation duration, is that they have a high turnover of companies. Due to the low participation duration, companies can leave the network easily, which forces the network to look for possible replacements. Due to this, the network is continuously trying to attract new companies and may have to settle for lesser companies. This also prevents it from scouting for companies that improve its profitability. When the participation duration is above 20 time steps, the network gets time to scout for companies that improve the profitability. This improves the network profitability, which subsequently enables the network to attract companies that improve the profitability even further. Hence, the ability to look for improvements to the network – facilitated by a longer participation duration – appears to influence the network profitability substantially.

If either a network or a company decides to end a collaborative agreement before the end date, the party that ends the agreement has to pay a fine to the other party. The height of this fine differs per network and may influence the network's stability and profitability, by preventing companies from leaving the network. Figure 7.9 plots the profitability of networks with different fines for leaving the network prematurely. Again, the variance of the network profitability is substantial and homogeneous over the range of considered fines. However, we cannot discover a trend in the profits. The bold line represents the linear regression fitted to the data points. This regression indicates that per €1,000 added to the fine, the profitability decreases with €5 (with a p-value of 0.02). On a profitability of around €225,000 per time step, this is negligible. Hence, we conclude that the fine has no significant effect on the network's stability and profitability.

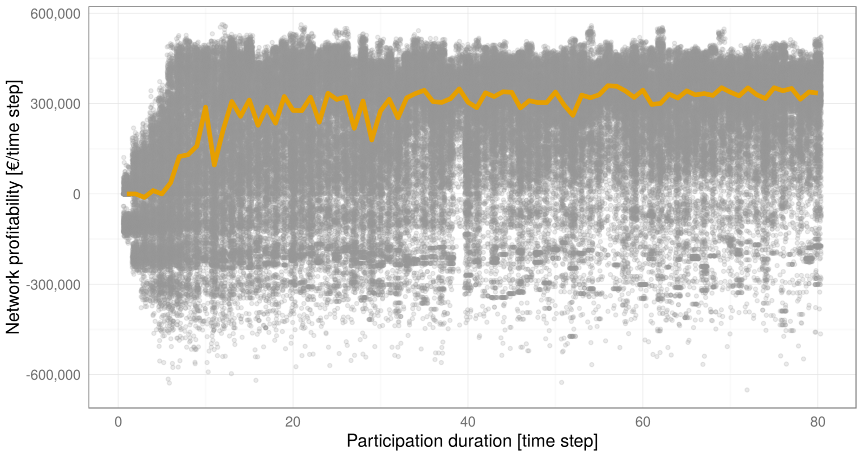

Figure 7.8: The profitability of networks with different (preferred) participation durations with the median for different participation durations (orange)

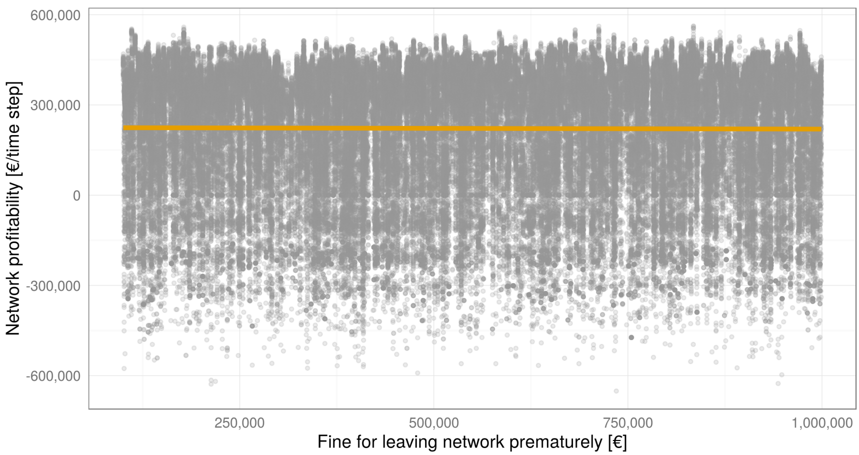

Figure 7.9: The profitability of networks with different (preferred) fines

7.5 Discussion

Based on the experimental outcomes, we discuss the implications for a company that has to decide whether and how to collaborate. The experimental outcomes also provide insights into the model that we used to study the possibilities for collaboration. Therefore, we also discuss how the model enabled this study, with a focus on the effects of the two-levelled market interactions on the outcomes of the experiments.

Possibilities for collaboration For a company that needs to decide about collaborating, the experimental outcomes found conditions in the industry (i.e., the coordination costs and collaborative cost savings) under which collaborating was attractive. It is evident that when those conditions apply and the company has the possibility to collaborate, it is financially the most sensible to collaborate. However, the experiments also showed that the decision to collaborate is not only a financial decision. We saw that the collaboration of companies influenced the market prices of goods that were bought and sold by companies that did not collaborate. This decreased the margin for those individual companies, which thus were disadvantaged by the collaboration of the other companies. This implies that the decision to collaborate thus can also be a strategic decision aimed at reducing the influence of market developments and preventing that one suffers the consequences of collaborating competitors.

With regard to the management of CNs, we found that there were significant differences between the network profit that could be realised applying different profit allocation strategies. Those differences were caused by the attractiveness of a network that is partially determined by its profit allocation strategy. Networks with an allocation strategy that was more attractive could attract better companies and thus realised higher network profits. As a company's profit depends on both the allocated percentage and the total network profit, it should select a CN on both elements. In some situations, it may be more attractive to accept a smaller percentage if that results in a higher network profit. The experiments also indicated that a minimum participation duration (in our experiment around 20 time steps) has a positive effect on the network profit. The stability that was created through this minimum duration enabled the CN management to look for improvements to the network, rather than look for (equal or less performing) companies to replace the companies that left.

Effects of two-levelled market interactions The purpose of developing this model was to enable the assessment of possibilities for collaborations to capture the market interactions at the company-level and network-level. So, rather than only considering the market interactions for the participation of companies in CNs (network-level), the model also included the market interactions for the supply of goods (company-level) and the influences between those levels. We argued that this should enable the model to capture *1*) the influence of the company-level interactions on the network-level interactions, and *2*) the influence of the network-level interactions on the company-level interactions.

All companies that decide to participate in a CN (i.e., a network-level interaction) compare the expected payoff of collaborating to the expected payoff of operating individually. The expected payoff of operating individually is to a large extent determined by the market prices, which emerge from the company-level interactions. In the three previous chapters, we saw that market behaviour influences the market interactions and the resulting market outcomes. Given that the consideration of a company to collaborate is its market behaviour, this all combined implies that the network-level interactions are influenced by the company-level interactions.

The other way around, the experiments demonstrated that the collaboration of many companies had a substantial effect on the market prices of the exchanged goods. When all possible companies collaborated, the margin between the price of raw materials (Good-1) and the end-product (Good-7) decreased by around 7 % compared to when no companies collaborated. The collaboration of companies is an outcome of the network-level interactions, and the market prices of exchanged goods are outcomes of the company-level interactions. The experiments thus indicate that the network-level interactions influence the company-level interactions, which results in changed market prices of the exchanged goods.

This implies that the model can capture the mutual influence between the company-level interactions and the network-level interactions. We saw that this mutual influence decreases the margin between the price of raw materials and the end-product by around 7 % and may influence the composition of materialised CNs. The decreased margin affects both the financial performance of individual companies and that of collaborating companies. Assuming that the margin between the prices of all sequential goods decreases evenly, the mutual influence decreases the margin between the price of an individual company's feedstock and its product also by 7 %. Consequently, the financial performance of the individual company also decreases – possibly with more than 7 %. For collaborating companies, the decreased margin directly influences the network profit of the CN in which it participates. Via the allocated profit, this subsequently also causes the company's profit to decrease. The extent of this decrease depends on the used allocation strategy. Given the system's complexity, it is not straightforward to determine how the mutual influence affects the composition of the CNs and the subsequent effect on the performance of the companies. Nonetheless, using a tool that captures the industrial system's complexity, it is possible to assess how the company-level interactions and network-level interactions can influence the possibilities to collaborate.

7.6 Synthesis

Collaboration has been identified as a means to improve the agility and resilience of companies. The goal of this chapter was to assess a company's possibilities for collaboration. For that purpose, we extended the previous models to capture the market interactions at the network-level as well as at the company-level. Compared to the previous models, this required an extension of the model's scope to include market interactions that cause structural changes in the modelled system. In the experiments, we found that – depending on the coordination costs and the collaborative cost savings – the materialisation of CNs attracted to one of two extremes: no collaboration or much collaboration. The transition between those two extremes was relatively steep. Generally, the companies with lower costs were more likely to be selected to collaborate than companies with higher costs. Hence, the individually operating companies were leftovers that did not contribute (enough) value to the CNs. The collaboration decreased the margin for the individual companies, thereby aggravating their situation[4]. Regarding the management of collaborating companies, we found that the allocation strategy and the participation duration of the CN affected the network profitability considerably. The allocation strategy influenced what quality of companies the network could attract, while a longer participation duration provided stability that enabled the network to scout for better companies.

Based on the experimental outcomes, we discussed the implications for a company that assesses the possibilities for collaboration. We argued that financially a company should decide to collaborate, if the industrial conditions favour collabora-

[4]Note that we did not consider any regulations that would prevent any market-disturbing collaborations.

tions. However, the effect of the CNs on the market prices makes that companies also may decide to collaborate in order to defend themselves against those changing prices. In that sense, the decision to collaborate may also be driven by strategic considerations. Regarding the management of the CN, we discussed that an allocation strategy maximises a company's profitability if it balances the CN's ability to attract high-performing companies and the percentage allocated to the company. Furthermore, the CN benefited from stability, as this allowed the management to scout for companies that improve the CN rather than having to find a replacement for a company that has left.

The experimental outcomes also showed that the model captures the mutual influence between the market interactions at the company-level and at the network-level. The effect of the collaborations on the prices of the exchanged goods was made clear in the experiments. The other way around, the decision to collaborate is influenced by the market prices that follow from the company-level interactions. In the previous chapters, we already determined that changed market behaviour influences the market interactions. In this chapter, we showed that the effect of this mutual influence on the possibilities to collaborate can be captured with a tool that captures the system's complexity by accounting for the market interactions, both at the company-level and at the network-level.

Chapter 8

Strategic investment in a changing world

This chapter is based on Bas et al. (In press 2017a)[1].

8.1 Introduction

So far, we considered changes in the industrial system that initialised from within the system. However, the system does not operate in a vacuum and thus may also be influenced from the outside. Therefore, in this chapter, we assess the decision of port authorities regarding the investment into the infrastructure to supply LNG, while considering the developments in the maritime fuel system due to regulatory changes.

The maritime fuel system consists of the organisations and technical artefacts involved with the supply, distribution, and consumption of maritime fuels (i.e., fuels used to propel vessels). In recent years, there has been increased attention for the environmental effects of those fuels. This has resulted in the implementation of regulations that aim to reduce the emissions of maritime fuels (International Maritime Organization (IMO), 2015). As a consequence, shipping companies have to make adjustments to their vessels. A variety of possible adjustments to vessels have been identified, of which the use of liquefied natural gas (LNG) as maritime fuel is one that is considered both environmentally and economically attractive (Danish Maritime Authority, 2012a). However, LNG is currently available in only some ports, because it requires substantial investments into infrastructure that can store and distribute the LNG at $-162\,^{\circ}\mathrm{C}$ (Wang and Notteboom, 2015). Without sufficient availability of LNG, the shipping companies are unlikely to adjust their vessels to sail on LNG. This implies that port authorities (in association with fuel suppliers) need to decide about investing into the infrastructure to supply LNG, while they have no insights into how the demand for this fuel may develop. An improved understanding

[1] Bas, G., De Boo, K., Vaes van de Hulsbeek, A., and Nikolic, I. (In press, 2017a). MarPEM: An Agent Based Model to Explore the Effects of Policy Instruments on the Transition of the Maritime Fuel System away from HFO. *Transportation Research Part D: Transport and Environment.*

of possible LNG demand developments can help them make decisions regarding the fuel supply that enhance their resilience to these structural fuel demand changes.

To support the port authorities' investment decision, we developed a model through which we could study the development of the maritime fuel system under a variety of scenarios. The used model combines elements of all previous models and thus internalises most of the environment's complexity. The model's dimensions of complexity are as follows:

- *Diameter of the industrial system*: four tiers.
- *Possible market interactions*: all potential partners in all potential markets.
- *Types of changes caused by the focal company*: operational and topological changes.
- *Types of changes caused by the environment*: operational and topological changes.
- *Types of changes caused by the market interactions*: operational changes.
- *Detail of the environment's representation*: geographic and functional aggregation.
- *Decision rules*: double-sided auctions and q-learning.
- *Considered features*: supply, demand, location, and market power.

Section 8.2 introduces the different components of the maritime fuel system and discusses the (regulatory) changes in further detail. Based on this overview, section 8.3 describes the model that we use to assess the investment decision. In section 8.4, we subsequently present the outcomes of the experiments that enable us to study how the adoption of different maritime fuels may develop. Using the experimental outcomes, section 8.5 assesses the investment decision of port authorities by interpreting the outcomes in the context of the decisions.

8.2 The maritime fuel system

8.2.1 System overview

The maritime fuel system consists of the technical artefacts that produce, distribute, and consume maritime fuels, and the organisations that arrange the production, distribution, and consumption of those fuels. Figure 8.1 presents an overview of the maritime fuel system as a socio-technical system. In this section, we discuss the artefacts that form the technical network, the organisations that form the social network, and the 'socio-technical' connection between those networks.

Technical network

The technical network consists of the technical artefacts that extract maritime fuels from the well, process it to meet the right specifications, ship it to the ports, and supply it to the vessels that consume it. The *vessels* consume maritime fuels by sailing between ports to transport cargo. In total, there are around 55,000 sea-going vessels that have a carrying capacity ranging from 10 mt up to 402,000 mt (IMO, 2012). Each vessel has a particular propulsion technology, which determines the type of fuel it uses, its fuel efficiency, and its emissions (Danish Maritime Authority, 2012a).

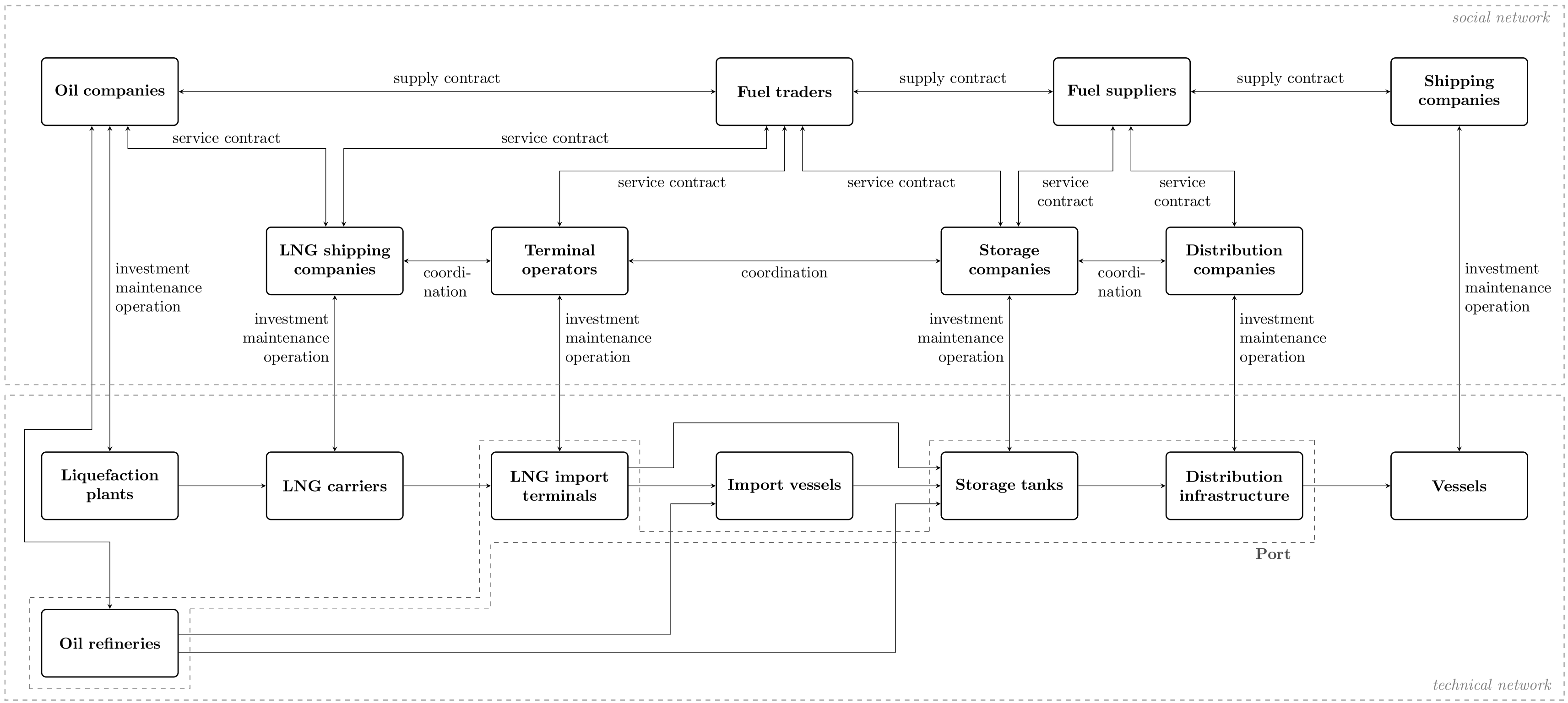

Figure 8.1: Socio-technical structure of the maritime fuel system

Maritime fuel is bunkered (i.e., the supply of fuel for use by vessels) in a port via the *bunker distribution infrastructure*, which can take the form of bunker barges, trucks, or pipelines (De Buck et al., 2011). To ensure sufficient availability, maritime fuels are temporarily stored in *bunker storage tanks* that are situated in the port. Unlike the traditional maritime fuels (heavy fuel oil (HFO) and marine gas oil (MGO)) that are stored and distributed at ambient temperature, LNG needs to be kept at a temperature of −162 °C. This requires that LNG is stored and distributed by means of specialised storage tanks and distribution infrastructure that can keep the LNG at the required temperature (Danish Maritime Authority, 2012a).

Both HFO and MGO are petroleum-based fuels, which implies that they are produced in an *oil refinery*. Those refineries are often situated in large ports, in which case the fuel can be stored directly in the storage tanks. However, in smaller ports, the fuel first needs to be imported from a refinery in another port with an *import vessel* (De Buck et al., 2011). LNG, on the other hand, is not produced in an oil refinery, but by liquefying natural gas in a *liquefaction plant*. Liquefaction plants are located all over the world in areas where natural gas is found, but most liquefaction capacity is installed in Qatar, Indonesia, Australia, and Algeria (International Gas Union, 2015). Once the LNG is liquefied, it is shipped in an *LNG carrier* to an *LNG import terminal* where it can be regasified to natural gas and injected in the natural gas network (International Gas Union, 2015). Another option is to use the LNG as maritime fuel, which implies that it is stored in a storage tank before it is distributed to a vessel. Like the petroleum-based fuels, when a port is not equipped with an LNG import terminal, it needs to import the LNG from another port with an import vessel.

Social network

The social network consists of the autonomously operating organisations that are involved with arranging the production, distribution, and consumption of maritime fuels. *Shipping companies* operate vessels in order to execute the shipping assignments of their customers. There are many different shipping companies, but the available vessel capacity is concentrated, with the five largest container shipping companies operating around 45 % of the global capacity (United Nations Conference on Trade and Development (UNCTAD)), 2015). Shipping companies have to schedule the operation of their vessels, which involves the sequence of ports the vessel is going to visit, and where it is going to bunker fuel (Agarwal and Ergun, 2008). This scheduling decision is influenced by a variety of factors, such as the availability of vessels, the (expected) demand for transport, port dues, fuel availability, and fuel prices (Notteboom, 2009). On a longer timescale, shipping companies invest in new vessels or retrofit existing vessels, which involves decisions about a variety of vessel properties, such as size, depth, vessel type, and propulsion technology (Bendall and Stent, 2005; Evans, 1984). Those decisions are influenced by factors, such as the initial investment costs, the fuel expenses, the emission regulations, and the fuel availability (Acciaro, 2014).

Shipping companies purchase the maritime fuel for their vessels from *fuel suppliers*. Those suppliers operate in one or more ports, where they offer certain maritime fuels. The price they ask for their fuels is the result of their pricing decision that is aimed at maximising the (long-term) profits. On a longer timescale, the fuel suppliers reconsider the range of fuels they offer. The decision to offer a particular fuel not only depends on the expected profit, but also on the availability of storage and distribution infrastructure for this fuel. This infrastructure is not necessarily owned and operated by the fuel suppliers, but is quite often outsourced to *storage companies* and *distribution companies* that store and distribute the fuel for them.

The fuel suppliers purchase their fuel from *fuel traders* that participate in the global fuel markets to purchase fuel and transport it to a port (De Buck et al., 2011). If the fuel trader does not own its own refinery it needs to negotiate with the *oil companies* that own refineries and thus can supply the fuels. Oil companies are also heavily involved in the production of LNG and often (partially) own the liquefaction plants (International Gas Union, 2015). So, when a fuel trader buys LNG, it also negotiates with oil companies on the terms at which the LNG is supplied. To supply the LNG to the port where it is needed, the fuel trader or oil company contracts an *LNG shipping company* to transport the LNG and a *terminal operator* to import the LNG into the port. Like the fuel suppliers, both the fuel traders and the oil companies set the prices for which they sell their fuels and select the types of fuel they offer.

Socio-technical connection

The technical and the social network are connected to each other through the organisations in the social network that own and operate technical artefacts in the technical network. This causes the technical network to influence the social network, and vice versa. The influence of the technical network on the social network manifests itself in the market interactions (i.e., the purchasing and price setting behaviour) between organisations that are influenced by the quantity of fuel that is available. For example, on a short notice, a fuel trader cannot sell more fuel than is available in the port, and thus its market interactions are limited by the physical constraints of the technical network. The same applies for negotiations about service contracts; a storage company cannot store more fuel for a fuel trader than its storage tanks allow. Further down the line, this influences the quantity of fuel that the fuel trader can purchase from the oil companies.

The other way around, the social network also influences the technical network, as the supply contracts and service contracts specify to a large extent the physical flow of fuel through the technical network. For instance, the supply contract between a shipping company and a fuel supplier specifies the purchase of a certain quantity of fuel. Together with the service contract between the fuel supplier and a distribution company, this determines what quantity of fuel is going to flow through the distribution infrastructure to a vessel. Likewise, the supply contract between an oil company and a fuel trader, combined with the service contracts with an LNG shipping company and a terminal operator, determine what quantity of LNG is shipped from a liquefaction plant to an LNG import terminal.

8.2.2 Changes in the maritime fuel system

Deep sea shipping is not only the enabler of our global economy (UNCTAD, 2015), but is also associated with 3 % of global CO_2 emissions, 15 % of global NO_x emissions, and 13 % of global SO_x emissions (IMO, 2014). Those emissions cause a variety of environmental issues, such as climate change, water contamination, and deforestation. In order to reduce the SO_x emissions, current regulation prohibits the use of fuels with a sulphur content above 0.10 %, within the coastal waters of the United States and North West Europe. Outside those sulphur emission control areas (SECAs), the sulphur content of maritime fuels is currently limited to 3.50 %, but this is scheduled to be lowered to 0.5 % in 2020 (IMO, 2015). For years, heavy fuel oil (HFO) has been the main maritime fuel for deep sea shipping (Corbett and Koehler, 2003). However, HFO has a sulphur content of 2.7 % (IMO, 2014) and shipping companies thus need to start looking for alternatives. One of those alternatives is the use of liquefied natural gas (LNG) as a maritime fuel. With a sulphur content of 0.0005 % and relatively low NO_x and CO_2 emissions, LNG is environmentally the most attractive alternative, while different studies have also found it be an economically viable alternative for HFO (Danish Maritime Authority, 2012a).

Despite its excellent economic and environmental performance, LNG is hardly used as maritime fuel. As of July 2015, there are 65 LNG-fuelled vessels in operation and 79 are scheduled to become operational in the coming years (DNV-GL, 2015): only 0.3 % of the total. There are multiple factors underlying the limited use of LNG (Wang and Notteboom, 2014). One important factor is that the infrastructure to store and distribute LNG is virtually non-existent (Wang and Notteboom, 2015), while the existing bunker infrastructure is incapable of storing and distributing LNG at the required −162 °C (Danish Maritime Authority, 2012a). This implies that, for LNG to replace HFO, not only shipping companies need to make adjustments to their vessels, but the entire maritime fuel system needs to change.

In the long run, port authorities aim to maximise the profits they obtain from the lease of land and the throughput of cargo. This requires that the facilities in the port are aligned with the needs of the shipping companies and can efficiently handle the incoming shipments. Hence, port authorities decide what facilities are developed in their ports to improve their attractiveness for shipping companies (Talley, 2009). A port authority that is confronted with the possible transition from HFO to LNG thus needs to decide whether to invest in distribution infrastructure that can supply LNG. To make an informed decision, the port authorities need insights into how the demand for different types of maritime fuel may develop under a variety of conditions, and how the port authority can influence this development.

The last couple of years, a variety of studies have been performed that concern the changes of the maritime fuel system. A large part of those studies are published in the form of technical reports and whitepapers (e.g., Lowell et al., 2013; Verbeek et al., 2011), but there have also been a considerable number of publications in peer-reviewed journals (e.g., Bengtsson et al., 2011; Wang et al., 2007). The majority of this research studied the economic and environmental performance of different maritime fuels from the perspective of the shipping companies. For example, Brynolf et al. (2014) assessed the environmental impact of different maritime fuels; Jiang et al. (2014) examined the costs and benefits of different emission reduction measures; and Acciaro (2014) performed a real-option analysis of investment in LNG retrofit. Another substantial part of the studies investigated the economic performance of different distribution infrastructure configurations. For instance, Danish Maritime Authority (2012a) analysed the costs and benefits of three types of LNG bunkering solutions; Semolinos et al. (2011) compared different bunker terminal lay-outs; and Harperscheidt (2011) provided an overview of the maritime LNG supply chain's technical properties. To date, there have been only a few studies that assessed the development of demand for maritime LNG in the entire system. Herdzik (2013) showed prognoses of how maritime LNG demand might develop in the future and DNV-GL (2012) described four possible paths for the entire maritime fuel industry. However, those studies assume that the distribution infrastructure will develop as the demand for LNG increases, and thereby exclude it as factor from the study. So far, this development has not happened and both the potential buyers and suppliers of LNG are waiting for the other to make a move. Due to their assumptions, the existing studies cannot explore how we can breach those interdependencies. Therefore, there is need for a new model that does account for the influences between demand and supply of maritime LNG.

8.3 Model description

The model used to represent the maritime fuel system and asses the investment decisions of port authorities combines elements of the previous models. As in the previous models, the system is conceptualised as a set of coupled markets, which enables us to capture the influences between the supply and demand of maritime fuels.

8.3.1 Purpose of the model

The goal of this model is to provide insight into how the maritime fuel system – as consequence of the adoption of different types of maritime fuel – may develop in response to investment decisions of port authorities. Those insights are interpreted to advice port authorities on their investment decision. As the port authorities highly depend on the global developments in the maritime fuel system, this approach is expected to provide a better understanding of the investment decision than if we were to limit our attention to a single focal port authority.

8.3.2 Entities, state variables, and scales

The entities in the model represent the organisations and technical artefacts that were introduced in section 8.2. Some organisations and assets have been combined in a single entity, while other organisations have been excluded from the model. Figure 8.2 gives an overview of the agents and objects in the maritime fuel model, along with the connections and interactions between them. Those interactions mainly concern the exchange of fuel.

Vessels A vessel (combining a shipping company and its vessels) sails from an *origin port* to a *destination port* in order to execute its *shipping assignment*. Each vessel belongs to a particular *class*, with an associated *carrying capacity*, *bunker capacity*, and *speed*. The *propulsion technology* used by a vessel specifies the type of *fuel* it uses, its *emissions*, and its *fuel-consumption*. Each vessel has a certain *technical lifetime* after which it will be replaced by a new vessel. However, when a

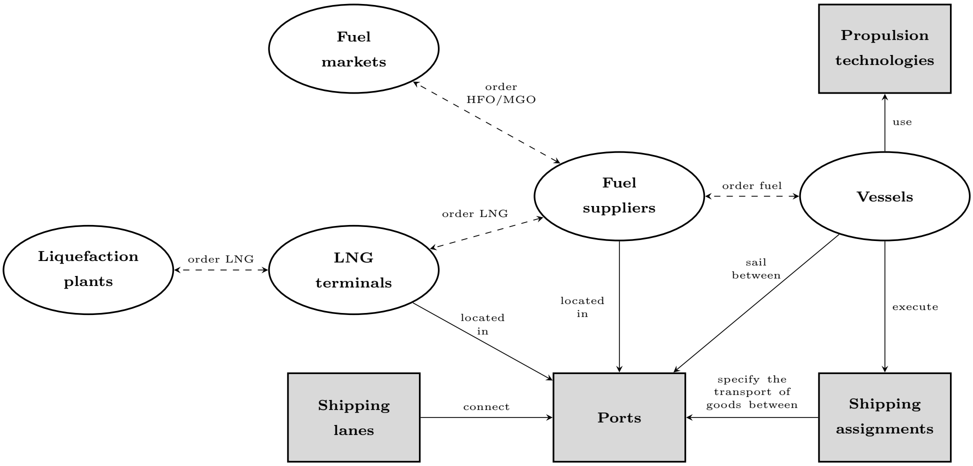

Figure 8.2: Agents (ellipses) and objects (rectangles) in the maritime fuel model, along with their connections (solid lines) and interactions (dashed lines)

vessel's *age* surpasses its *economic lifetime*, its owner may decide to retrofit the vessel by replacing its propulsion technology. This decision is influenced by the *discount rate* and by the *risk aversion* that defines to what extent the vessel considers the availability of fuels in the ports.

Ports Ports are the origin or destination of a shipping assignment and thus are used to trans-ship cargo. The daily amount of cargo that can be trans-shipped in a port is defined by its *capacity*, which imposes a limit on the number of vessels that can moor in the port. To manage its limited capacity, a port has a *reservation-book* in which the vessels can reserve a space in the port. The realised amount of trans-shipped goods in a port are recorded in its *throughput*. Ports are connected to each other by shipping lanes that specify the *distance* and the *allowed emissions* between an *origin* port and a *destination* port.

Fuel suppliers Fuel suppliers are the agents that offer a particular type of *fuel* in a *port*. This agent combines the fuel traders, fuel suppliers, storage companies, distribution companies, storage tanks, and distribution infrastructure in a port. Each fuel supplier sells its fuel for a *retail price*, which is determined on the basis of its *pricing strategy*. If this price is higher than the costs of purchasing the fuel plus the *handling costs*, the fuel supplier operates at a profit. The fuel supplier has a *fuel demand* that is the result of selling fuel to vessels. Depending on its type of fuel, the fuel supplier satisfies this demand by ordering fuel from an LNG terminal or from a fuel market.

Fuel markets Fuel markets represent the established global markets for the prevailing maritime fuels (i.e., heavy fuel oil (HFO) and marine gas oil (MGO)). Each fuel market concerns the exchange of one *fuel type*. The supply-side of the market is specified exogenously as a *supply curve* (i.e., the relationship between the price of a good or service and the quantity supplied), while the demand-side of the market is composed of the fuel that is ordered by the fuel suppliers.

LNG terminals The LNG terminals supply LNG to the bunker suppliers. The LNG arrives at the terminal with an LNG carrier, after which it is shipped to a fuel supplier with an import vessel. To receive, store, and supply the LNG, the terminal incurs certain *handling costs* that it attempts to recover by supplying the LNG to the fuel suppliers. An LNG terminal has a *processing capacity* and thus can supply only a limited amount of LNG. The terminal sells its LNG to fuel suppliers for its *retail price* that it sets on the basis of its *pricing strategy*. Next to the supply of LNG to bunker suppliers, the LNG terminal also regasifies LNG and injects that natural gas in the network. The demand for regasified natural gas is implemented as an exogenously specified *demand curve*.

Liquefaction plants The LNG that the LNG terminal receives is supplied by a liquefaction plant. Each liquefaction plant has a *supply capacity* that it can supply at a *retail price* that is higher than its *willingness to accept*. This willingness to accept is determined by the natural gas price at the *location* where the liquefaction plant is situated. Like LNG terminals and fuel suppliers, the liquefaction plants determine their retail price on the basis of their *pricing strategy*.

Global variables The costs of shipping LNG and the enforcement of regulations are equal for all agents and thus are specified as global variables. The costs of shipping LNG over one nautic mile (nm), with a LNG carrier, from a liquefaction plant to an LNG terminal is specified by the *LNG carrier costs*. Likewise, the costs of shipping LNG over one nm, with an import vessel, from an LNG terminal to a fuel supplier is specified by the *import vessel costs*. To enforce the emission regulations, the vessels have a certain probability of being inspected: the *inspection probability*. If, upon inspection, its emissions are higher than the allowed emissions, the vessel has to pay a *fine*.

Scales The maritime fuel industry is a global industry, so the maritime fuel system also encompasses the whole world. Consequently, the model also represents the agents and entities that are relevant on a global scale. However, through the initialisation, the model focuses at developments in North-West Europe, with the other supranational regions being represented in an aggregated form. A single time step in the model represents a single day, as the operational processes in the model are executed on a daily basis. By including behaviour with a strategic horizon (i.e., an entity's behaviour that concerns a large part of its business and has an effect for at least two years), the model can be used to assess the long-term development of the maritime fuel system.

8.3.3 Process overview and scheduling

The processes in the model are divided into three categories: *1*) the operational behaviour, which covers the sailing of the vessels and the supply of fuels; *2*) the pricing decisions of the agents that supply fuels; and *3*) the vessel adjustment decisions. In this section, those processes are discussed in general terms, with more details available in appendix E.

Operational behaviour A large part of the operational behaviour concerns the sailing of the vessels. This behaviour starts with the arrival of vessels that *moor* in their destination port, where they unload their cargo and determine the quantity of fuel used on their journey. Subsequently, each vessel that is moored in a port *selects a new shipping assignment* on basis of the expected fuel costs, the expected fines, the capacity utilisation, and the availability of the vessel's fuel at the destination of the assignment. The vessel selects the most attractive assignment and reserves a mooring place at its destination. The vessels that have selected a new shipping assignment then assess whether they should *bunker fuel*. For this decision, the vessel compares the costs of bunkering in the current port or (if possible) at its destination. If the vessel decides to bunker in the current port, it pays the fuel supplier for the fuel it needs to refill its fuel stock completely. This contributes to the fuel supplier's fuel demand. Hereafter, the vessel leaves the port and sails the seas until it reaches its destination.

The other part of the operational behaviour concerns the weekly supply of maritime fuel to the fuel suppliers. This starts with the LNG terminals that *inject natural gas in the network*, thereby withholding this quantity from the fuel suppliers. Thereafter, the fuel suppliers *order fuel* either from fuel markets or from LNG terminals. The HFO and MGO fuel suppliers order their fuel by indicating the demanded quantity and willingness to pay to the fuel market. The LNG fuel suppliers order their fuel from the LNG terminal(s) that can supply it at the lowest gross price (i.e., net price + costs of the LNG import vessel). Once all fuel suppliers have ordered their fuel, the fuel markets *clear the market* to determine the market price and the quantity supplied to each fuel supplier. This is followed by the LNG terminals that *ship LNG* to the fuel suppliers. The fuel suppliers *receive fuel*, which reduces their demand and requires them to pay the LNG terminals and fuel markets for the fuel. After the supply of fuel to the fuel suppliers, the LNG terminals *order LNG* from the liquefaction plant(s) that can supply it at the lowest gross price. The ordered LNG is shipped to the LNG terminals, which – upon arrival – reduces their demand.

Pricing decisions Fuel suppliers, LNG terminals, and liquefaction plants make pricing decisions with average intervals of a month. As was introduced in chapter 5, a pricing decision entails that an agent simulates the effect of a range of prices to determine its pricing strategy. The first step in the pricing decision is that a (simulating) agent *creates a copy of the relevant system.* The relevant system consists of the agents that are suppliers, competitors, or customers to the simulating agent. After the copy is created, the simulating agent *simulates the operational behaviour* of the copied system, as was discussed in the previous paragraph. During this simulation, the simulating agent changes its retail price frequently and records the profits that it obtains from each price. It uses this information to develop a pricing strategy, which consists of the perceived attractiveness of a variety of prices. Once the simulation is finished, the simulating agents *completes the simulation* by deleting the copy of the relevant system.

Vessel adjustment decisions The decisions on whether to make adjustments to the vessels are performed on average once per year. As the model is concerned with the fuel use of vessels, the adjustment decision is limited to the vessel's propulsion technology. The adjustment decision is made either because the vessel is retrofitted or because it is replaced. When a vessel's age has surpassed its economic lifetime, it *considers retrofitting*. This consideration starts with the vessel that *computes the present expenses* of each of the available propulsion technologies. For the evaluation of a particular technology, the vessel determines the initial investment of replacing the current propulsion technology with the evaluated technology, as well as the annually recurring expenses, such as fuel costs, expected fines, and the opportunity costs of lost cargo space. The present expenses then are computed by discounting the annual expenses and adding those to the initial investment. To account for the risk of not being able to moor in every port, due to the limited availability of a fuel, the present expenses are divided by the percentage of ports that offer the technology's fuel (weighted by the vessel's risk aversion). Once the risk-corrected present expenses of all technologies are computed, the vessel *selects the technology with the lowest expenses*. On the other hand, the *decision to replace a vessel* is made when a vessel's age surpasses its technical lifetime. In this case, an identical vessel is created, with an age of 0 and possibly a different propulsion technology. The propulsion technology is selected similarly as when the vessel is retrofitted, only the computation of the present expenses uses different cost figures for the initial investment.

8.3.4 Design concepts

Basic principles: The core of this model is that the availability of maritime fuels and the demand for those fuels mutually influence each other. Accounting for those influences may lead to an altered development of the adoption of different maritime fuels. *Emergence:* The market interactions between agents that supply maritime fuels and those that use the fuels result in the emergence of prices for the different fuels. Moreover, those prices influence the vessel adjustment decisions and thus contribute to the emergence of changed demand. *Adaptation:* During the operational processes, the buyers of fuels adapt their market behaviour to the availability of the fuels, and the sellers adapt their prices to the received orders. *Objectives:* All agents in the model aim to maximise their profits, for which they each have different means. Some agents can set a price, while others can select a shipping assignment or a propulsion technology. *Learning:* The sellers of LNG use a Q-learning algorithm to learn which pricing strategy enables them to maximise their profits under the current market conditions. *Prediction:* For their pricing decision, the sellers of LNG simulate the effect of a variety of retail prices with the purpose of predicting how the buyers and other sellers may adapt to the changed retail price. *Sensing:* The buyers of fuels only know the quotations they obtain from the sellers, and the sellers are only aware of the orders they have received to set their prices. The vessels have more extensive senses, as they can also consider the state of different shipping assignments, ports, and shipping lanes. *Interaction:* The buyers and sellers for a particular fuel interact directly with each other, by ordering fuel and shipping that fuel. Amongst themselves, the buyers and sellers do not interact directly. *Stochasticity:* The main source of stochasticity in the model follows from the order in which the agents are asked to perform a process. Next to that, stochasticity also follows from the scheduling of the pricing decisions and the vessel adjustment decisions. *Observation:* The model observes the adoption of the different fuel types as an indication of changes in the maritime fuel system. The adoption of fuel is observed through two indicators: *1*) the technology adoption, being the share of vessels that uses a certain propulsion technology; and *2*) the fuel demand, being the share of total fuel demand attributable to a certain fuel.

8.3.5 Model initialisation

The model is developed in partnership with the Port of Rotterdam, and therefore is initialised with a focus on North-West Europe. However, as the developments in North-West Europe are influenced by the global developments, the agents and objects in the model need to cover the global maritime fuel system. To limit the computational expenses, the agents and objective outside North-West Europe are aggregated into regional agents and objects.

Table 8.1 gives an overview of how the agents and variables in the maritime fuel model are initialised. The vessels are aggregated into 73 different agents, which are grouped in eight capacity classes. Those capacity classes determine the vessel's fuel consumption, carrying capacity, and the investments to replace or retrofit the vessel. The ports are initialised to represent the ports in the Hamburg - Le Havre (HLH) range in detail, and the ports outside North-West Europe as aggregated regional agents. The capacity of each ports is 10 % higher than their maximum throughput in 2012 to 2014. Each port has a fuel supplier that offers HFO and one that offers MGO. The presence of a fuel supplier that offers LNG differs per experiment. The distances of the shipping lanes that connect the ports are based on data of Sea-Distances.org (2015), and the allowed emissions follow the regulations that apply in 2016 (IMO, 2014). Under those regulations, the vessels are not allowed to use HFO in North-West Europe and North America, while this is allowed in the rest of the world. Hence, vessels that visit North-West Europe or North America either need to replace their (HFO-powered) propulsion system or accept a fine. The decision they are going to make will most likely depend on how often they visit the regions in the world where HFO is not allowed.

The quantities and number of the shipping assignments are computed using the annually shipped quantities between ports, as reported by Seabury Group (2015). The size of a shipping assignment is set proportional to the annually shipped quantities between the assignment's ports, so that the largest shipping assignments connect ports that have the highest annual shipped quantities. Consequently, the vessels of the largest classes mainly sail between ports with the largest shipped quantities. On the other hand, the vessels of the smallest classes sail between ports with the lowest shipped quantities. Generally, the size of shipping assignments (and thus the deployment of vessel classes) can be grouped into four categories, ranked from largest to smallest: *1*) *huge:* Far East and Middle East; *2*) *large:* North America, Europe, and South America; *3*) *medium:* Rotterdam, Antwerp, and Hamburg; and

Table 8.1: Initialisation of the agents and variables in the maritime fuel model (* = agent is an aggregation of multiple agents)

Agent / variable	Initialisation
Vessels	73 vessels, 8 capacity classes
Fuel suppliers	HFO and MGO in all ports, LNG differs per experiment
LNG terminals	France, Netherlands, United Kingdom, Belgium, (South) Europe*, Far East*, Middle East*, North America*, South America*
Liquefaction plants	Africa*, Australasia*, Far East*, Middle East*, North America*, Norway*, South America*
Fuel markets	HFO costs: 800 $/mt, MGO costs: 1,780 $/mt, LNG costs: 728 $/mt
Ports	Amsterdam, Antwerp, Hamburg, Le Havre, Rotterdam, Zeebrugge, (South) Europe*, Far East*, Middle East*, North America*, South America*
Propulsion technologies	HFO, LNG, MGO, HFO with scrubber
LNG transport	Carrier costs: 0.0095 $/nm, import costs: 0.08 $/nm

4) *small:* Amsterdam, Le Havre, and Zeebrugge. The retrofit-expenses and the new-built-expenses of the propulsion technologies are based on data of Danish Maritime Authority (2012b) and the capacity of the different classes of vessels.

The prices of the different fuels in the fuel markets are set on the basis of multiple maritime fuel price studies (Danish Maritime Authority, 2012a; Deloitte Center for Energy Solutions, 2013; Lloyd's Register, 2012; MAN Diesel & Turbo and GL, 2011). The terminals that regasify LNG outside North-West Europe are aggregated per region. The available import capacity is based on figures of International Gas Union (2015); and each terminal has handling costs of €17/mt (Shareholdersunite.com, 2008). Like the LNG terminals, the liquefaction plants are aggregated into regional plants with supply capacities based on figures of International Gas Union (2015). The willingness to accept of each plant is based on data of Satapathy et al. (2014).

8.4 Exploring the maritime fuel system's development

In this section we present three experiments that aim to obtain insights into the development of the maritime fuel system, how this changes the adoption of the maritime fuels, and how this adoption can be influenced. In each experiment, we measure the development of the maritime fuel system by two indicators: *1*) the technology adoption, which is the percentage of vessels that uses a certain propulsion technology; and *2*) the fuel demand, which is the percentage of total fuel demand that is attributable to a particular maritime fuel.

Each experiment simulates the effect of different interventions on the maritime fuel system. The first experiment focuses on the availability of LNG as maritime fuel in the ports. In the second experiment, we assess how the enforcement of emission regulations influences the development of the maritime fuel system. And the third experiments focuses on the behaviour of shipping companies, by assessing the effect of their willingness to retrofit vessels. Each simulation covers a time period of 15 years. The variability tests showed that the patterns of fuel adoption were not influenced substantially due to stochasticity. Combined with the substantial computational expenses (i.e., around an hour per simulation run), this caused us to repeat each simulation 10 times.

8.4.1 Availability of maritime LNG

An important prohibiting factor for the use of maritime LNG is the lack of ports where vessels can bunker LNG (Wang and Notteboom, 2015). This is a prohibiting factor that port authorities can handle themselves, as they can directly influence what kind of maritime fuels are offered in their ports. The availability of maritime LNG in a port is implemented in the model as the presence of fuel suppliers that offer LNG in that port. In this experiment, we consider four scenarios in which different ports have a fuel supplier that offers LNG:

1. *None*: no additional LNG fuel suppliers, and LNG availability limited to Zeebrugge.
2. *3MP*: additional LNG fuel suppliers in the 3 main bunker ports: Far East, North America, and Rotterdam.
3. *SECA*: additional LNG fuel suppliers in the ports in the current SECAs: Amsterdam, Antwerp, Hamburg, North America, and Rotterdam.
4. *All*: LNG fuel suppliers in all ports.

To enable a clear assessment of the LNG availability's effect, the inspection probability was set at 50% (with a fine that depends on the level of the vessel's aggregation, but equals €400,000 for a single vessel) and the economic lifetime of the vessels was set at 3,650 days.

Figure 8.3 shows the development of the maritime fuel system (in terms of fuel demand and technology adoption) in each of the scenarios. Even though the development of the system appears to differ considerably for each of the scenarios, there actually are considerable similarities between the 'None' and the 'SECA' scenarios, and between the '3MP' and the 'All' scenarios. In both cases, the fundamental patterns of the two scenarios are comparable, with only some differences in the exact values of the indicators.

'None' and 'SECA' scenarios Figure 8.3 indicates that, in both the 'None' and the 'SECA' scenario, the HFO adoption (in terms of the technology adoption and the fuel demand) decreases quickly at first. After little more than 2,000 days, the HFO fuel demand stabilises around 50 %, while the technology adoption continues to decrease. There are two main reasons for this discrepancy. First, the vessels that keep using HFO are the vessels of the biggest class (with high fuel consumptions) that sail in the Far East and Middle East. Even though there are only a few of them, their demand for HFO is still substantial. Second, many vessels replace the HFO technology with a scrubber and thus still consume HFO.

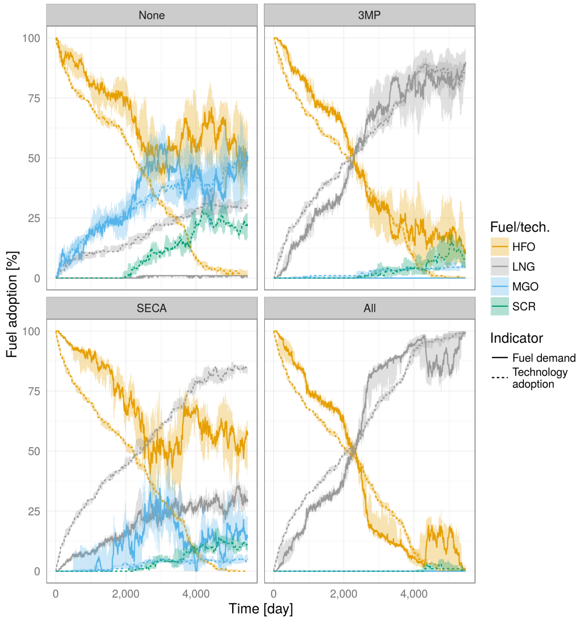

Figure 8.3: Adoption of different fuels (HFO, LNG, MGO, and scrubber (SCR)), measured in terms of fuel demand and technology adoption, in different LNG availability scenarios (None, 3MP, SECA, and All).

The 'None' and the 'SECA' scenario differ from each other regarding the technology that replaces HFO. In the 'None' scenario, MGO is the main replacement of HFO in terms of fuel demand and technology adoption. LNG is only used marginally in this scenario, because the vessels that want to use LNG need to moor in Zeebrugge. The port of Zeebrugge is mainly visited by small vessels with relatively low fuel consumptions. So, even when those vessels decide to use LNG (as indicated by the considerable technology adoption), their fuel demand never becomes substantial. In the 'SECA' scenario, LNG is used more extensively, especially in North-West Europe and North America, which is due to the availability of LNG in more ports. In the Far East and Middle East, the lack of LNG availability causes the vessels there to use MGO and scrubbers. So, this scenario results in a divided world, with LNG-powered vessels in North-West Europe and North America, and MGO- and HFO-powered vessels in the Far East and Middle East.

'3MP' and 'All' scenarios In the '3MP' and 'All' scenarios, the maritime fuel systems develop comparably. In both scenarios, the HFO adoption becomes marginal and is largely replaced by LNG. LNG can replace HFO because, in both scenarios, it is offered in the major ports. Most vessels visit one or more of those major ports on a regular basis and thus can use LNG without running the risk of not being able to execute a shipping assignment or running out of fuel. Consequently, the vessels evaluate the LNG purely on economic performance, which is competitive with HFO (BMI Research, 2013; Danish Maritime Authority, 2012a).

The only difference between the two scenarios is that, in the '3MP' scenario, the

LNG use is capped at around 90 %, while it reaches near 100 % in the 'All' scenario. This is most likely due to the vessels that rarely or never moor in the Far East, North America, Rotterdam, or Zeebrugge. In the '3MP' scenario, this prevents them from bunkering LNG and forces them to use another fuel. In the 'All' scenario, however, this limitation does not exist, as vessels can bunker LNG in all ports.

8.4.2 Enforcement of emission regulations

Global availability of LNG is not the only factor that prohibits the use of LNG as maritime fuel. For instance, the enforcement of emission regulations may support the use of LNG, as it makes the use of HFO less attractive and stimulates shipping companies to look for alternatives. The enforcement of emission regulations is implemented in the model as the probability that a vessel's emissions are inspected. This inspection probability influences the vessels' decision to select a shipping assignment and thus influences what kind of vessels are deployed in what regions. More importantly, the inspection probability influences the vessel adjustment decision by changing the attractiveness of the propulsion technologies. In this experiment, we study the effect of five different inspection probabilities on the development of the maritime fuel system: 0 %, 25 %, 50 %, 75 %, and 100 %. To be able to observe the effects of the inspection probabilities, the economic lifetime of the vessels was set at 3,650 days and all ports offered LNG.

Figure 8.4 shows, for each of the examined inspection probabilities, the development of the adoption of the maritime fuels. The plots indicate that changing the inspection probabilities has little effect on how the adoption of the fuels and technologies develops. For all probabilities, the HFO fuel demand and HFO technology adoption decrease quickly are replaced almost completely by LNG. The lack of differences caused by the inspection probability may be unexpected, but it can be explained by the LNG price that is set at 90 % of the HFO price. This is sufficient to recover the higher initial investment in the LNG propulsion technology, even when there is no penalty for exceeding the emission regulations. Combined with the availability of LNG in all ports, this makes LNG a fundamentally more attractive fuel than HFO. Consequently, the inspection probability does not change the attractiveness of LNG and we observe the same pattern for each of the assessed inspection probabilities.

It thus appears that the limited LNG use in the real world is not due to lacking enforcement of the emission regulations. Other possible causes are a higher LNG price (relative to the HFO price) or the missing availability of LNG in ports over the world. The last seven years, the price of LNG has been considerably lower than the price of HFO (BMI Research, 2013), which is in line with our assumptions. Hence, this is unlikely to have caused the differences between our model outcomes and the observed LNG use in the real world. However, as we showed in the first experiment, the availability of LNG in ports has a substantial influence on the development of the LNG use. As of 2016, there are 14 ports in the world where LNG bunkering is possible, 10 of which are situated in North-West Europe (LNG Fuelled Vessels Working Group, 2016). This is a much smaller percentage than we assumed in our model and therefore is probably the cause of the difference between the model outcomes and the real-world observations.

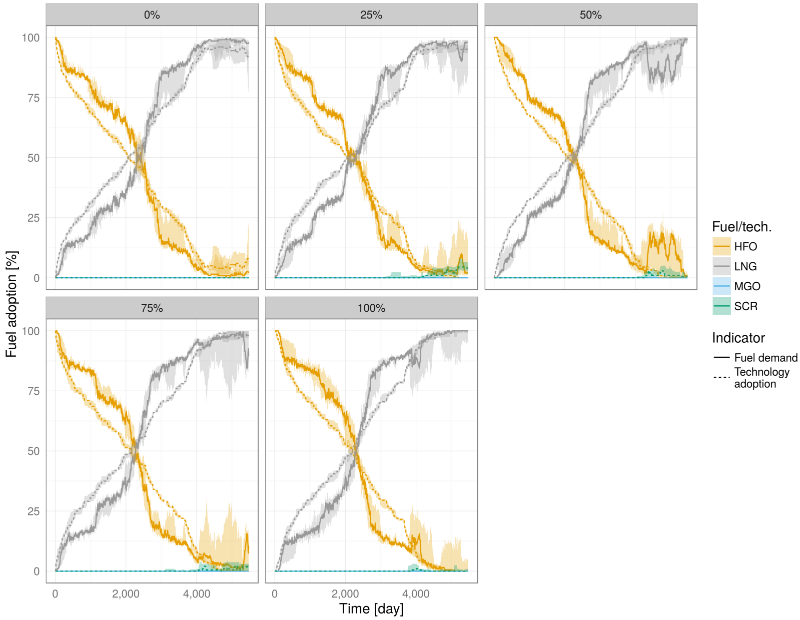

Figure 8.4: Adoption of different fuels (HFO, LNG, MGO, and scrubber (SCR)), measured in terms of fuel demand and technology adoption, for each of the assessed inspection probabilities (0%, 25%, 50%, 75%, and 100%).

8.4.3 Willingness to retrofit vessels

Given that the shipping companies determine what propulsion technology they use for their vessels, the development of the maritime fuel system depends to a large extent on the decisions of the shipping companies. Port authorities can only create conditions that incentivise shipping companies to replace their HFO-powered vessels by LNG-powered vessels. Shipping companies can change the propulsion technology of their vessels either by replacing the vessel completely or by retrofitting it and thus only replace the propulsion systems. Given the large number of relatively new vessels (UNCTAD, 2015), the retrofitting of vessels is likely to contribute substantially to the change of the maritime fuel system. However, not all shipping companies are equally willing to retrofit their vessels, as those represent large sunk costs. In the model, the willingness to retrofit is implemented as the economic lifetime of a vessel. Above this lifetime, a vessel considers retrofitting. Therefore, a lower economic lifetime indicates a higher willingness to retrofit. To determine the effect of the willingness to retrofit, we experiment with different values of the economic lifetime: 1,825 days (5 years), 3,650 days (10 years), and 7,300 days (20 years). In this experiment, LNG is available in all ports and the inspection probability is set at 50 %.

Figure 8.5 shows, for each assessed economic lifetime, the development of the maritime fuel system, indicated by the adoption of the different fuels. Although there appear to be large differences in how the system develops, the fundamental patterns of all three economic lifetimes are similar. In each of the three plots of Figure 8.5, we see that the use of HFO decreases and is almost exclusively replaced by LNG. So, independent of the economic lifetime of the vessels, LNG eventually

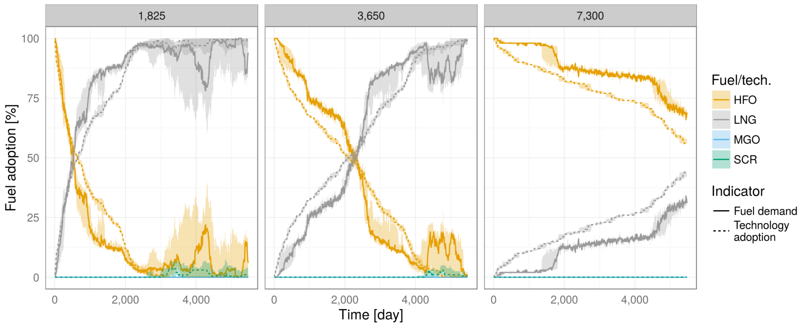

Figure 8.5: Adoption of different fuels (HFO, LNG, MGO, and scrubber (SCR)), measured in terms of fuel demand and technology adoption, for the different economic lifetimes of vessels (1,825 , 3,650 , and 7,300 days).

becomes the main maritime fuel. This implies that the economic lifetime of the vessels had no effect on the end state (i.e., adoption of the fuels) that the system develops to (possibly after the simulated period). Or, to put it in terms of complex adaptive systems, the economic lifetime had no effect on the system's attractor.

However, the economic lifetime does influence the speed at which the system develops, and thus how fast it moves towards the attractor. At an economic lifetime of 1,825 days, HFO is replaced almost completely after around 2,000 days. However, the longer shipping companies delay their retrofitting, the longer it takes the LNG adoption to reach 100 %. At an economic lifetime of 7,300 days, HFO is not replaced completely by LNG within the simulated 15 years. However, that does not mean that this is not going to happen over a longer timeframe. The economic lifetime thus has no effect on which fuel eventually becomes the main maritime fuel – this is determined by other factors – but it does influence how long it takes that fuel to become the main fuel.

8.5 Discussion

In this section, we discuss the implications of the experimental outcomes for the investment decision of port authorities. Next to that, we also discuss how accounting for the influences between the supply and demand of fuels affected the outcomes of the simulation model. This provides additional insights into the use of the simulation model.

Investment decision in a changing world The experimental outcomes showed that, under most conditions, LNG became a viable alternative for HFO or even replaced HFO altogether. Hence, the outcomes indicated that LNG is the most likely fuel to replace HFO as a consequence of the stricter emission regulations. This is in line with many studies, which concluded that LNG is an economically viable alternative for HFO (e.g., BMI Research, 2013; Danish Maritime Authority, 2012a; Egloff et al., 2015). The experiments also demonstrated that the global availability of LNG in ports was important to stimulate the use of LNG.

Even though the prospects for LNG appear positive, this does not automatically mean that a port authority should start investing in infrastructure to supply LNG. The experimental outcomes confirm that the unavailability of LNG in ports prevents LNG from becoming the main maritime fuel. We also observed that a single port's decision to supply LNG had little effect on the adoption of LNG. Consequently, the only viable way to start offering LNG seems to be if multiple port authorities collaborate. Together, they can develop a global network of ports that supply LNG and make LNG available to many of the vessels. This network does not have to consists of all ports. In the experiments, we saw that it suffices if some of the major bunker ports supply LNG. When the availability of LNG was limited to the Far East, North America, and Rotterdam, 90 % of the vessels switched to LNG. In reality, it probably requires more than just three ports, as the ports in the Far East and North America were aggregated in the model. However, the experiments do indicate that the availability of LNG in some well-chosen ports can stimulate the LNG adoption substantially.

The experimental outcomes showed that the enforcement of emission regulations had very little effect on the adoption of LNG. When LNG was globally available, LNG replaced HFO as main maritime fuel, even when the emission regulations were not enforced. We concluded that this was due to positive economics of LNG in comparison to the other types of fuels. This implies that it suffices that emission regulations are enforced to the extent that is needed to make LNG economically more attractive than HFO[2]. Port authorities do not directly determine the enforcement of emission regulations, but they do have contact with the authorities that do. They can use those contacts to ensure that the limited resources are not spent on 'unnecessary enforcement', while those could have more impact when used differently.

In our perception, port authorities are best off with a swift transition from HFO to LNG, as opposed to a lengthy process. When the transition to LNG is slow, the port authorities have invested considerable sums of money in the infrastructure to supply LNG, while this infrastructure is only used partially. When the infrastructure is used partially, it is unlikely to be profitable. A fast transition from HFO to LNG would limit this period of partial utilisation, and thus would improve the port authority's profitability. The experimental outcomes demonstrated that the transition to LNG can be accelerated substantially by enhancing the willingness of shipping companies to retrofit their vessels. The port authorities themselves have limited possibilities to stimulate the retrofitting of vessels – next to reducing the port dues for LNG-powered vessels (Port of Rotterdam, 2016) – and thus will have to collaborate with other stakeholders, such as national governments or non-governmental organisations.

All three measures thus influenced the use of LNG as a maritime fuel in different ways: *1*) the LNG availability makes that the shipping companies consider LNG as a potential alternative for HFO; *2*) the enforcement of emission regulations influences the economic attractiveness of LNG compared to HFO; and *3*) the stimulation of vessel retrofitting influences the pace at which shipping companies consider alternative fuels and thus how fast LNG is adopted. Hence, we recommend an approach

[2]Note that we do not propose to stop enforcing regulations. All we argue is that the enforcement of emission regulations does not necessarily support the use of LNG while the economics of LNG are more attractive than the economics of HFO.

that integrates all three measures. This approach is the most likely to lead to a swift adoption of LNG. Since one port authority cannot achieve this transition by itself, the approach should also integrate the efforts of multiple port authorities and even the other organisations that enforce the regulations or can influence the shipping companies.

Accounting for influences between the supply and demand of fuels In the simulation model, the supply and demand of fuels influence each other through the market interactions over the exchange of those fuels. The demand for fuels develops through shipping companies that retrofit their vessels, possibly changing the type of fuel that those vessels use. This changed demand subsequently influences the market interactions for the different types of fuels, which may affect the fuel prices that emerge from those interactions. Those prices determine the attractiveness of the different types of fuels, which influences the economic assessment that the shipping companies perform to compare different propulsion technologies. This thus closes the loop. However, the market interactions are not only influenced by the demand for fuel, but also by the availability of that fuel in the ports. That way, the supply of fuels also influences the development of the system and thereby the demand for fuels.

To show the effect of accounting for those influences, we compare the LNG price for two scenarios. In the 'All' scenario, LNG replaced HFO completely; in the 'None' scenario, LNG was hardly used as a maritime fuel. We compare the LNG prices for those two scenarios as this price indicates to what extent the changed availability of LNG influences the development of the modelled maritime fuel system. Figure 8.6 shows the development of LNG price in the 'None' and the 'All' fuel availability scenarios. The plot indicates that, when LNG becomes better available, the LNG price increases. The difference with the 'None' scenario, in which the availability and demand for LNG is lower, is substantial. This shows that a changed availability of LNG caused adaptations in the modelled system that went beyond the direct effects of the changed availability. It affected the market interactions and the LNG price that materialised from those interactions. As the decision to retrofit a vessel is influenced by the fuel prices, the higher LNG price may limit the LNG adoption. However, given that the LNG adoption in the 'All' scenario was near 100 %, the experimental outcomes indicated that this did not occur. This leads us to conclude that the developed model can capture the influences between the supply and demand of fuels, but that this had little effect on the assessment outcomes of this particular case.

8.6 Synthesis

In this chapter, we set out to explore the development of the maritime fuel system as a consequence of new emission regulations, with a focus on the LNG adoption. For that purpose, the study of the maritime fuel system accounted for the influences between the demand and supply of maritime fuels, in order to get a comprehensive understanding of the system's development. In the experiments, we studied how the adoption of different maritime fuels was influenced by three different interventions.

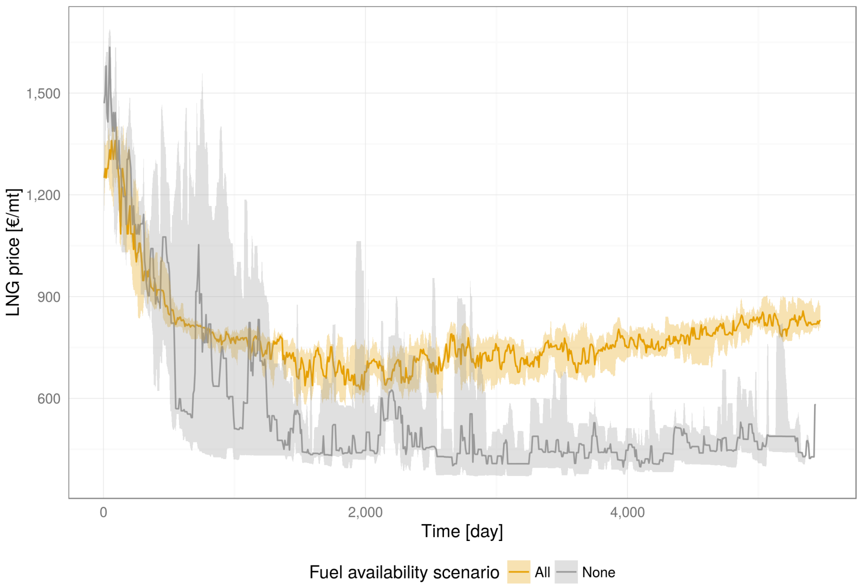

Figure 8.6: Maritime LNG price development for different fuel availability scenarios

We found that the global availability of LNG was essential for the maritime fuel system to transition from HFO to LNG. When the economics of LNG are better than those of HFO, all that is holding back shipping companies to adjust their vessels to run on LNG is the risk of not being able to bunker LNG in a port. If the economics of LNG are not better than those of HFO, the enforcement of emission regulations can make LNG more attractive than HFO and thereby stimulate shipping companies to invest in LNG propulsion systems for their vessels. The willingness of companies to retrofit their vessels only influenced the speed at which the system transitioned – and thus not how the system transitioned.

We used the experimental outcomes to determine how port authorities should act in the maritime fuel system that is changing due to the new emission regulations. To date, there have been no studies that use an understanding of the entire maritime fuel system to assess how port authorities should respond to the regulatory changes. As the experiments demonstrated that LNG is likely to replace HFO as main maritime fuel, port authorities are advised to invest in the infrastructure to supply LNG. However, to ensure that those efforts cause a transition to LNG, the port authorities should collaborate to develop a global network of ports that supply LNG. The enforcement of emission regulations is needed to stimulate the use of LNG when the economics of LNG are worse than those of HFO. As port authorities do not enforce the emission regulations themselves, they should discuss this with the responsible authorities. To enable a swift transition from HFO to LNG, shipping companies should be stimulated to retrofit their vessels to use LNG. Given the limited influence of port authorities on shipping companies, this requires a collaboration with other organisations that do have the means to influence shipping companies. The three measures discussed in this study stimulate the use of LNG in different ways and thus could reinforce each other. Therefore, we advocate an integrated approach to stimulate the LNG adoption. This approach should not only consists of different measures, but should also integrate the efforts of different organisations: multiple port authorities, governments, and other stakeholders.

Accounting for the influences between the demand and supply of maritime fuels had a substantial effect on the development of the modelled system. The experiments showed that the increased availability of LNG resulted in a much larger demand for maritime LNG. By comparing the LNG prices for different levels of LNG demand, we found that the changed demand for LNG resulted in a substantially higher LNG price. As the LNG price is fundamental to the decisions in the maritime fuel system, the changed LNG price influences the development of the modelled system. In this specific case, the influences between demand and supply had little influence on the LNG adoption, as the adoption became nearly 100 %, despite the higher LNG price. Nonetheless, the experiments did indicate that the model can capture the influences between the supply and demand of fuels and thus provides a comprehensive view on the maritime fuel system.

Those outcomes show that our developed model can internalise the complexity in the environment of a port authority. By capturing the mutual influences between the supply and demand of fuels the prices in the system developed differently, which has a direct influence on the retrofitting decision of shipping companies. Consequently, the internalised complexity enabled a comprehensive assessment of a decision to supply LNG as a maritime fuel.

Part III

Synthesis

Chapter 9

A system perspective to support business decisions

9.1 Introduction

In the case studies, we developed and used computer simulations to assess a variety of actions that could enhance a company's resilience. We proposed that – to assess the direct and indirect effects of those actions – we needed to internalise the complexity of the company's environment into the assessment. Therefore, all the developed simulation models applied our system perspective to capture the entire system's complexity. The models were developed with a co-evolutionary development method and therefore internalised increasing levels of complexity. This level of complexity consisted of eight dimensions, of which 1-6 concern the scope of the model and 7-8 concern the behavioural richness:

1. Diameter of the industrial system.
2. Possible market interactions.
3. Types of changes caused by the focal company.
4. Types of changes caused by the environment.
5. Types of changes caused by market interactions.
6. Detail of the environment's representation.
7. Decision rules used to represent (inter)actions.
8. Features considered by companies in their decision-making.

Figure 9.1 shows for each developed simulation model the level of internalised complexity, as indicated by the eight dimensions.

Not all actions require an assessment that captures all complexity in the focal company's environment. It may suffice for some actions to use a model that only internalises some aspects of the environment's complexity or internalises those aspects only to a limited extent. By developing the simulation models with different levels of internalised complexity, we obtained more insight into our system perspective and how it can be used to assess future actions. In this chapter, we use those insights to discuss our system perspective in more detail and how the needed level of internalised complexity can be established. In section 9.2 we discuss the six dimensions of the model's scope: their relevance for our system perspective, their use in the

1. Supply network reconfiguration	**2. Transportable plants**	**3. Process flexibility**	**4. Collaboration in networks**	**5. Strategic investment in a changing world**
1) *Five tiers*	*Three* tiers	Three tiers	*Eight* tiers	*Four* tiers
2) *Current partners in current market*	*Potential partners* in current market	Potential partners in *potential markets*	Potential partners in current markets	Potential partners in potential markets
3) *Operational*	Operational and *topological*	Operational and topological	Operational and topological	Operational and topological
4) *Operational*	Operational	Operational and *topological*	Operational and topological	Operational and topological
5) *Operational*	Operational	Operational	Operational and *topological*	Operational
6) *Aggregated raw material suppliers*	Aggregated raw material suppliers	Aggregated raw material suppliers and *customers*	*No aggregation*	*Geographical aggregation, functional aggregation*
7) *Coupled single-sided auctions*	*Q-learning*	Q-learning	*Double-sided auctions*	Q-learning, double-sided auctions
8) *Supply, demand, location*	Supply, demand, location, *market power*	Supply, demand, location, market power	Supply, demand	Supply, demand, location, market power

Figure 9.1: Dimensions of complexity in the models developed for the case studies

case studies, and how to use them to assess future actions. We discuss the same aspects in section 9.3 for the two dimensions of behavioural richness. In section 9.4 we combine those discussions into an overview of our system perspective.

9.2 Scope of the model

The essence of our system perspective is that it includes the industrial system that forms the focal company's environment. The focal company's assessed action influences this environment, which then changes and subsequently influences the focal company. Consequently, by capturing the focal company's environment, the model can assess the indirect effects of the assessed action on the company's financial performance. The scope of the model thus concerns to what extent the focal company's environment is included in a model. This entails which companies are included, how interconnected the network of companies is, and how the system can change in response to internal and external stimuli. For each of the six dimensions of the model's scope, we discuss their role in our system perspective and how they can be used to assess future actions.

9.2.1 Diameter of the industrial system

Given that our system perspective extends beyond the boundaries of the focal company, the developed models all included (a part of) the industrial system that formed the focal company's environment. This environment consisted of all the companies whose (inter)actions could influence the effects of the assessed action. Not only the companies with whom the focal company directly interacted or those that were a part of its supply chain, but also the companies that indirectly influenced the focal company, such as its competitors. Those companies did not form a 'classic' linear supply chain, but were interconnected into a network.

What part of that network is included in a model influences how the environment may behave (Moyaux et al., 2010) and thus may influence the assessment of an action's indirect effects. In our case studies, we indicated the included part of the network by the diameter of the modelled industrial system. This diameter specifies the number of tiers between the most upstream and the most downstream companies.

Table 9.1: The diameter of the industrial systems in the case studies

Case study	No. of tiers	Rationale
1. Supply network reconfiguration	5	The further downstream companies (i.e., customers of customers) influence to what extent the prices can increase in response to the changed costs of operating smaller plants.
2. Transportable plants	3	The transportable plants are not considered to have a different cost structure, so we expect no substantial price increase. Hence, there is no need to include further downstream companies to determine to what extent the price can increase.
3. Process flexibility	3	Further downstream companies are not expected to influence the assessment outcomes, as the compared types of plants obtain the same price for their product. The costs of feedstock are determined by the scenario, so there is no need to include further upstream companies.
4. Collaboration in networks	8	The collaborative networks (CNs) span six tiers. To include the customers and suppliers of the CNs, we thus need to consider 8 tiers.
5. Strategic investment in a changing world	4	The chosen number of tiers span the entire relevant supply chain. The objective of the model – and the subsequent geographic and functional scope – do not require the additional complexity that comes from the intermediate tiers.

Given the network structure of the industrial system, the diameter of a model is not limited to sequential tiers but also concerns parallelly related tiers.

Table 9.1 gives an overview of the diameters used in the case studies, together with argumentation on why that diameter was used. In this overview, we see two main lines of argumentation. The first line of argumentation was used for the 'collaboration in networks' case study and regarded the *number of tiers spanned by the focal company*. Our system perspective requires that the model includes the focal company's suppliers, competitors, and customers. Therefore, the diameter of the industrial system should at least contain the tiers spanned by the focal company and the two tiers of its suppliers and customers. The second line of argumentation was used for the other case studies and regarded the *effect of the further upstream or downstream companies on the assessment outcomes*. For instance, in the 'supply network reconfiguration' case study, we considered the further downstream companies, because we expected them to influence the price change that followed from the higher costs of the smaller decentralised plants. Given that those prices were driving the assessment outcomes, the consideration of the further downstream companies was essential to accurately assess the indirect effects of the supply network reconfiguration.

We conclude that the diameter of the modelled industrial system in our system perspective thus should minimally span the focal company plus the tier of its suppliers and the tier of its customers. So, to assess an action of a focal company that spans one tier, a model should at least have three tiers of the industrial system. However, when the market price is expected to change in response to the assessed action (and the subsequently changed costs of the focal company), we considered further upstream and/or downstream companies. The system perspective thus is not limited to the focal company's direct environment, but includes all components of the system that can potentially influence the effects of the assessed action.

9.2.2 Possible market interactions

The complex adaptive system perspective in chapter 3 showed us that the possibility of companies to interact connects them in a social network. Together with the system's diameter, this interconnectedness determines what level of the environment's complexity is internalised in the model. When a system consists of many different companies that are heavily interconnected, the system's behaviour is more complex than when it is sparsely connected (Newman, 2003). As market interactions also enable companies to influence each other and thereby spread change through the system, those interactions are a fundamental element of our system perspective.

The possible market interactions in an industrial system specify with what (group of) other companies a certain company can interact. In our case studies, we distinguished three different levels of possible market interactions: *1*) interactions with the current partners (i.e., suppliers and customers); *2*) interactions with all potential partners in the company's current market; and *3*) interactions with all potential partners in all potential markets. Given that market interactions are driving the industrial system's behaviour, the selected level of possible market interactions can have substantial consequences for the assessment of an action's indirect effects.

Table 9.2 presents an overview of the possible market interactions selected in the case studies. For all case studies, we selected the level of possible market interactions based on *how the simulated period relates to the interval at which companies have market interactions.* In the 'transportable plants' case study, the simulated period was longer than the interval at which the focal company switched between partners. Therefore, this case study captured market interactions with all potential partners in the company's current market. The same applied for the 'process flexibility' case study, where the interval at which the flexible plant could switch between markets was shorter than the simulated period and we enabled the focal company to interact with all potential partners in the potential markets for feedstock.

Given this discussion, we conclude that the selection of the possible market interactions requires insight into the simulation period and into the intervals at which the companies have market interactions. The simulated period is generally relatively fixed as it should span the time horizon of the assessed action. The intervals at which the companies interact differ per type of market interactions. Therefore, all relevant market interactions need to be identified as well as the intervals at which they occur. Of those market interactions, those with an interval shorter than the simulated period need to be included in the model. The other market interactions are unlikely to influence the assessment outcomes and thus do not contribute to a more comprehensive assessment.

Table 9.2: The possible market interactions in the case studies

Case study	Possible market interactions	Rationale
1. Supply network reconfiguration	Current partners in current market	The simulation concerns a short period in which the focal company is unlikely to change its partners and thus can limit its interactions to its current partners.
2. Transportable plants	Potential partners in current market	The simulation concerns a longer period in which the focal company can switch between partners, which requires it to interact with all those (potential) partners.
3. Process flexibility	Potential partners in potential markets	The assessed flexible plant can switch quickly between markets within the simulated period. Therefore, the focal company needs to be able to interact with all potential partners in those (potential) markets.
4. Collaboration in networks	Potential partners in current market	The simulation concerns a period during which the focal company can switch between partners, which requires it to interact with all those partners.
5. Strategic investment in a changing world	Potential partners in potential markets	The vessels can switch between markets when they change their fuel, which means that they need to be able to interact with all potential partners in those different markets.

9.2.3 Types of changes caused by the focal company

As shown by the competitive strategy perspective in chapter 3, the assessment of an action's indirect effects require that the industrial system can change in response to the action. This implies that our system perspective should not only capture the focal company's environment and the market interactions among companies, but also needs to capture how the system changes due to the assessed action. In our system perspective, we distinguish two types of changes: operational and topological changes. The operational changes concern the changes to the prices and volumes of exchanged goods, whereas the topological changes concerns the changes to the structure of the industrial system. The changed prices and volumes of exchanged goods have a direct influence on the focal company's performance and thus the assessment outcomes. Therefore, the operational changes are essential to assess the indirect effects of an action and are a fundamental part of our system perspective. The topolical changes alter the conditions for the market interactions over the exchange of goods, thereby causing operational changes. This implies that the topological changes can influence the assessment outcomes, but are not necessarily crucial to assess the indirect effects.

Changes of the industrial system can have three different sources: *1*) the behaviour of the focal company, *2*) the behaviour of companies in the environment, and *3*) the market interactions among companies. Even when different sources cause

Table 9.3: The types of changes caused by the focal company in the case studies

Case study	Types of changes	Rationale
1. Supply network reconfiguration	Operational	The reconfiguration does not enable the focal company to make decisions that structurally change the industrial system.
2. Transportable plants	Operational and topological	By operating a transportable plant, the focal company can relocate its plant during the simulated period, through which it changes the industrial system structurally.
3. Process flexibility	Operational and topological	By operating a flexible plant, the focal company can switch between markets, through which it changes the structure of the two involved markets.
4. Collaboration in networks	Operational and topological	The simulated period is so long that the interval at which the focal company takes decisions that can change the system's structure is shorter than the simulated period.
5. Strategic investment in a changing world	Operational and topological	By supplying LNG, the vessels get more fuel options, which may cause them to switch between fuel markets. Those switches change the structure of the industrial system and thus require that we consider the topological changes.

the same type of changes, their effect on the behaviour of the system differs substantially. Therefore, we discuss the considerations each of those sources separately. In this section, we limit our discussion to the types of changes caused by the focal company.

Table 9.3 presents the types of changes caused by the focal company's behaviour that were captured in the developed models. In all case studies, we captured the operational changes caused by the behaviour of the focal company. Those changes have a direct effect on the focal company's performance and thus are a fundamental aspect of our system perspective. In four case studies, the decision to capture the topological changes was based on the (focal company's) *behaviour that was enabled by the assessed action*. For instance, in the 'transportable plant' case study, the investment into a transportable plant enabled the focal company to quickly relocate its plant and thereby change the system's structure. For the remaining 'collaboration in networks' case study, we decided to capture the system's topological changes because the *simulated period was longer than the interval of the focal company's behaviour that could cause structural changes*. Had we not included the topological changes, we would have missed changes that could influence the assessment outcomes.

Our system perspective thus requires that the model captures the operational changes caused by the focal company's behaviour. With regard to the topological changes, the model should capture all aspects of the focal company's behaviour that can cause changes to the system's structure with an interval shorter than the simulated period. Special attention should be paid to the (focal company's) decisions

Table 9.4: The types of changes caused by the environment in the case studies

Case study	Types of changes	Rationale
1. Supply network reconfiguration	Operational	Complexity of the model is not sufficient to include topological changes caused by the environment.
2. Transportable plants	Operational	Complexity of the model is not sufficient to include topological changes caused by the environment.
3. Process flexibility	Operational and topological	The horizon of investing into a flexible plant is longer than the time it takes the environment to cause topological changes.
4. Collaboration in networks	Operational and topological	The simulated period is longer than the time it takes the environment to cause topological changes.
5. Strategic investment in a changing world	Operational and topological	The horizon of investing into the LNG-supplying infrastructure is longer than the time it takes the environment to cause topological changes.

that are enabled by the assessed action. All those decisions need to be included in the model. When those decisions cause changes to the system's structure, the model thus automatically includes topological changes caused by the focal company.

9.2.4 Types of changes caused by the environment

Not only the focal company causes the system to change; the companies in the environment can also make decisions that lead to system changes. Table 9.4 gives an overview of what types of changes caused by the environment's behaviour are included in the case studies. We captured the topological changes caused by the environment in three of the case studies because *the horizon of the assessed action (and therefore the simulated period) was longer than the time it took the environment to cause structural changes.* This means that within the horizon of the assessed action the industrial system's structure could change in response to the action. As this could influence the assessment outcomes, we needed to capture the topological changes caused by the environment. The other two case studies also met this requirement, but the models at that point did not have the complexity needed to capture the topological changes. In the 'supply network reconfiguration', we saw that this led to assessment outcomes that were overly optimistic.

Considering our experiences in the case studies, we conclude that the assessment of actions with a horizon that spans multiple years requires a model that includes both operational and topological changes caused by the environment. Given that our system perspective is developed to capture the (indirect) effects of the changed industrial system, it is likely to be used to assess actions with long time horizons. Therefore, we conclude that most models that use our system perspective need to include the environment's behaviour that causes topological changes.

Table 9.5: The types of changes caused by the market interactions in the case studies

Case study	Types of changes	Rationale
1. Supply network reconfiguration	Operational	The effects of the supply network reconfiguration are only influenced by market interactions that change the prices and volumes of exchanged goods.
2. Transportable plants	Operational	The effects of investing in a transportable plant are only influenced by market interactions that change the prices and volumes of exchanged goods.
3. Process flexibility	Operational	The effects of investing in a flexible plant are only influenced by market interactions that change the prices and volumes of exchanged goods.
4. Collaboration in networks	Operational and topological	The effects of collaborating is influenced by market interactions over the exchange of goods, as well as market interactions over the participation in collaborative networks.
5. Strategic investment in a changing world	Operational	The effects of investing in LNG-supplying infrastructure are only influenced by market interactions that change the prices and volumes of exchanged goods.

9.2.5 Types of changes caused by market interactions

The market interactions between companies are the third source of change in the industrial system. Table 9.5 shows per case study what types of changes were induced by the market interactions and why we chose to capture those changes. In four out of five case studies, it sufficed to only include the market interactions that caused operational changes. The reason for that was that in those case studies *the assessment outcomes were only influenced by market interactions that changed prices and volumes of exchanged goods.* Even when topological changes to the system influenced the effects of the assessed action, those changes typically influenced the assessment outcomes via changed prices and volumes of exchanged goods. Hence, there was no need in those case studies to include market interactions that caused topological changes. In the 'collaboration in networks' case study, we captured the system's topological changes caused by market interactions, because the market interactions over the participation in collaborative networks (CNs) influenced in what CN the company participated and thereby what its payoff was. Consequently, those market interactions influenced the assessment outcomes and needed to be included in the model.

Whereas the topological changes caused by the focal company and by the environment were captured in almost all case studies), the market interactions that caused topological changes were only included in one case study. This is caused by the fact that our system perspective focuses on market interactions over the exchange of goods as a mechanism for companies to influence each other. Therefore, the market interactions that cause operational changes are an integral part of our system perspective. Market interactions that cause topological changes should only be included if they influence the assessment outcomes.

9.2.6 Detail of the environment's representation

The companies, market interactions, and changes in the industrial system that are central to our system perspective do not always have to be included in full detail. Sometimes it may be preferred or even required to aggregate multiple companies (in the environment) into a single company. This automatically aggregates the market interactions that the aggregated companies would have, which can influence the changes of the industrial system. Consequently, the level of detail can substantially influence the assessment outcomes and is relevant to our system perspective.

Table 9.6 gives an overview of the level of detail used to represent the environment in the case studies. The main reason to aggregate companies was that the aggregation had no effect on the outcomes of the assessment, while it did reduce computation time and simplified the initialisation of the model. This tells us that a model needs to balance the *need for heterogeneity* with the *detail of the available initialisation data* and the *available computation time.* The level of needed heterogeneity is determined by the extent to which (inter)actions of individual companies influence the assessment outcomes. This can be established through research into the characteristics of the industrial system and discussions with experts on the functioning of the system. The detail of the available initialisation data and the available computation time are generally fixed for an assessment.

The need for heterogeneity determines the minimum level of detail that is needed, while the other two elements – i.e., initialisation data and computation time – determine the maximum level of detail. While the need for heterogeneity is lower than the maximum level of detail, it is possible to capture the required level of detail in the model. However, when the need for heterogeneity is higher than the maximum level of detail, aspects of the industrial system cannot be simulated even though they may influence the assessment outcomes. In that case, the model is aggregated to such an extent that the added value of our system perspective decreases and the complexity is possibly better reduced by adjusting one of the other dimensions. This entails that the level of detail needs to be determined in combination with the other dimensions of the model's complexity. That way, the model's complexity can be selected that allows sufficient level of detail.

9.3 Behavioural richness

So far, we established that – to assess the indirect effects of an action – our system perspective includes the companies that form the focal company's environment. Through market interactions among all those companies, the focal company and its environment influence each other and the environment can change in response to decisions of the companies. The (inter)actions of companies thus are central to our system perspective. However, those (inter)actions can be represented in models in different ways, which influences the internalised complexity. This behavioural richness has two dimensions: *1)* the features of other agents considered for the

Table 9.6: The detail of the environment's representation in the case studies

Case study	Aggregation	Rationale
1. Supply network reconfiguration	Aggregated raw material suppliers	The real-world industrial system consists of a large number of raw material suppliers for whom only the regional differentiation is expected to influence the assessment outcomes.
2. Transportable plants	Aggregated raw material suppliers	The real-world industrial system consists of a large number of raw material suppliers for whom only the regional differentiation is expected to influences the assessment outcomes.
3. Process flexibility	Aggregated raw material suppliers and customers	The industrial system consists of a large number of raw material suppliers and customers for whom only the regional differentiation, market power, and use of caprolactam is expected to influence the assessment outcomes.
4. Collaboration in networks	None	No clear insight into what level of heterogeneity is needed, while initialisation data is abundantly available.
5. Strategic investment in a changing world	Geographical and functional aggregation	Focus on North-West Europe does not require heterogeneity in other regions, while the global long-term perspective does not require heterogeneity of all vessels. The need for heterogeneity is balanced with the available computation time.

(inter)actions, and *2*) the decision rules used to implement the (inter)actions. For both those dimensions, we discuss their role in our system perspective and how they can be used to assess future actions.

9.3.1 Considered features

To (inter)act, each company considers features of other companies to base its decisions on (i.e., output of other companies that serves as input for the company). This implies that through the considered features the companies influence each others' behaviour and subsequently the emergent behaviour of the industrial system as a whole. Whereas the possible market interactions determine *which* companies are connected and can influence each other, the considered features determine *how* those companies influence each other and thereby the behaviour of the system as a whole. Consequently, the considered features are a relevant element of our system perspective.

Table 9.7 presents an overview of the features that are considered by companies in the case studies. The supply and demand of other companies are considered in all case studies, because those features are *essential to include market interactions in a model.* The decision to consider the location or market power of other companies was based primarily on the *characteristics of the modelled industrial system.* The

Table 9.7: The features considered by companies in the case studies

Case study	Considered features	Rationale
1. Supply network reconfiguration	Supply, demand, and location	The location of companies is considered to enable geographic heterogeneity that is relevant in a global industrial system.
2. Transportable plants	Supply, demand, location, and market power	The market power is considered to enable a better representation of the markets that consist of relatively few companies.
3. Process flexibility	Supply, demand, location, and market power	The market power is considered to enable a better representation of the markets that consist of relatively few companies.
4. Collaboration in networks	Supply and demand	The abstract nature of this case does not require geographic heterogeneity, while market power is unimportant due to the large number of companies in a market.
5. Strategic investment in a changing world	Supply, demand, location, and market power	Companies in the well-established markets only consider supply and demand, because location and market power have little effect in those markets; companies in the emerging markets do consider the local and market power, because those markets have considerable geographic differences and consist of relatively few companies.

location of other companies was considered if the industrial system contains markets with geographical differences that influence the development of those markets. The market power was considered in markets with few participants, because those companies were expected to have substantial market power that could influence the development of those markets.

A model with our system perspective thus should always enable the companies to consider the supply and demand of the other companies in the system. Without those features, the market interactions that are driving the system's behaviour cannot be included in the model. The decision to enable the consideration of location and market power (and possibly other features) needs to be based on the extent to which geographical heterogeneity and market power influence market developments in the modelled system. This can be determined by consulting experts of the industrial system. While such a consultation is normal in the model development process, our system perspective focuses this discussion substantially.

9.3.2 Decision rules

The (inter)actions of the companies in the industrial system are implemented in the model as decision rules of the companies. The decision rules specify how a

Table 9.8: The decision rules used in the case studies to represent (inter)actions

Case study	Decision rules	Rationale
1. Supply network reconfiguration	Coupled single-sided auctions	Need for direct interactions between companies in order to enable companies to consider each others' location.
2. Trans-portable plants	Q-learning	Decision rules needed that enable a company to use its market power.
3. Process flexibility	Q-learning	Decision rules needed that enable a company to use its market power.
4. Collabora-tion in networks	Double-sided auctions	Generic case of the case does not require companies to interact directly.
5. Strategic investment in a changing world	Double-sided auctions and Q-learning	The representation of the well-developed market does not require direct interactions and thus can be represented through double-sided actions; the emerging markets requires the consideration of location and market power and the companies in those markets thus need Q-learning decision rules.

company translates input and its internal state to a changed internal state and output (Holland, 1995). Thereby, they define *how* the companies behave and interact with each other, and subsequently how the system as a whole behaves. This may influence the indirect effects of an assessed action, which makes that we should select the decision rules carefully.

Table 9.8 shows per case study what decision rules were used to implement the (inter)actions of the companies. This overview shows that the main reason to select certain decision rules was because they were needed to *enable the companies to consider the relevant features of other companies*. For instance, in the 'transportable plants' case study, more sophisticated decision rules were used to enable the consideration of market power. In the 'collaboration in networks' case study, on the other hand, we could use simpler decision rules because only the supply and demand needed to be considered by the companies. The considered features and the decision rules thus are tightly linked. The selection of certain considered features has consequences for the decision rules, and together they specify specify how the (inter)actions are represented in the model. Therefore, the decision rules should only be selected after the considered features have been determined. The considered features, on the other hand, should be selected while keeping in mind their consequences for the decision rules.

9.4 Synthesis

In a nutshell, our system perspective entails that the assessment of a focal company's action is not limited to that company, but also includes the industrial system that forms its environment. The focal company purchases its feedstock from companies in its environment and sells its products to companies in the environment. This supply of goods is the consequence of market interactions that cause companies to influence each other. Through its actions, the focal company influences its environment, which subsequently changes in response and reciprocally influences the focal company. This way, the environment can affect the consequences of the assessed action. By capturing those indirect effects of an action, the assessment can provide more comprehensive insights into the consequences of the action. Moreover, with the complexity of the focal company's environment captured, our system perspective is suited to assess resilience-enhancing actions.

A main factor of our system perspective thus is the inclusion of companies other than the focal company. Which other companies to include in the model depends primarily on the problem (i.e., the assessment of an action for a company in an industrial system) for which the model is developed. A model with our system perspective should at least cover the focal company's direct suppliers, competitors, and customers. Otherwise, the model does not meet the requirements to assess an action's indirect effects. Depending on the nature of the problem, it may be needed to include companies in the model that are not directly connected to the focal company – e.g., suppliers of suppliers, or customers of customers. However, only those companies should be included that can actually influence the consequences of the assessed action.

The behaviour of the industrial system emerges from market interactions among the companies. Through those interactions the companies in the industrial system influence each other, which is driving the development of the system as a whole. Consequently, the possible market interactions (i.e., what groups of companies can interact) is an important consideration in the development of models that use our system perspective. The possible market interactions should be selected on basis of how the simulated period relates to the horizon of the market interactions. Only those market interactions that have a horizon shorter than the simulated period need to be included in the model.

The environment and the market interactions are included in the model to assess the indirect effects of the assessed action. This requires that the focal company can influence the environment, that the environment can change, and that the environment can influence the focal company. So, our system perspective does not just entail that we consider the industrial system in which the focal company operates; that industrial system also has to be able to change in response to internal and external stimuli. In our system perspective, we distinguish two types of changes: *1*) operational changes that concern the changes to the prices and volumes of exchanged goods in the system, and *2*) topological changes that concern changes to the system's structure. The types of changes that are captured in a model condition the influences and adaptation that are possible in the modelled industrial system. Thereby, they control to what extent the indirect effects of an action can be assessed. The case studies showed that capturing the operational changes is fundamental to our system perspective, whereas the decision to capture the topological changes depends on the problem for which the model is developed. Therefore, the use of our system perspective requires the explicit consideration of whether to include the topological changes in the model.

The changes in the industrial system can have three different sources: *1*) the behaviour of the focal company, *2*) the behaviour of the companies in the environment, or *3*) the market interactions among companies. As those sources all have different effects on the topological changes, each source of changes requires different considerations.

- The focal company's behaviour can influence the part of the industrial system's structure that is directly associated with that company. Given that the system's structure sets the conditions for the market interactions over the exchange of goods, this behaviour can indirectly cause operational changes throughout the entire industrial system. If the assessed action enables the focal company to make decisions that cause topological changes, those changes should be captured. Topological changes should also be captured if the simulated period is longer than the interval at which the focal company makes decisions that can change the system's structure.

- The behaviour of companies in the environment can change the structure of the focal company's environment. Via market interactions over the exchange of goods this changed structure can influence the focal company and thereby the assessment outcomes. Like the behaviour of the focal company, the environment's behaviour that causes topological changes needs to be included if the simulated period is longer than the interval at which the companies make those decisions.

- Generally, the market interactions that are a part of our system perspective concern the exchange of goods and thus only cause operational changes. However, the consequences of some actions are directly influenced by market interactions that cause topological changes. When this is the case, the topological changes caused by those market interactions need to be included in the model as well.

The (inter)actions of the companies in our system perspective can be implemented in a variety of ways. Different decision rules may be used to represent the behaviour of the companies. Depending on the used decision rules, the market interactions between companies may be more or less direct. Consequently, explicit consideration is needed what decision rules are used to represent the companies' (inter)actions. This depends heavily on what features of others the companies need to consider when making a decision. If those are system-level features – e.g., supply and demand – there is no need for decision rules that enable companies to interact directly. However, if those features are agent-level properties – e.g., location and market power – the decision rules need to enable companies to interact directly. The decision on what features the companies need to consider, on its turn, depends on the characteristics of the industrial system that is modelled, such as the influence of geographical heterogeneity or market power on the market outcomes.

Sometimes, we can or need to aggregate the companies, market interactions, and changes that are central to our system perspective. The level of the model's detail can change the behaviour of the system and subsequently the assessment outcomes. A model has a minimum level of detail that is determined by the heterogeneity that is needed to enable all interactions that influence the system outcomes. A model's maximum level of detail, on the other hand, is determined by the detail of the available initialisation data and the available computation time. If the need for heterogeneity is lower than the maximum level of detail, it is possible to capture the required level of detail in the model. However, if the maximum level of detail is lower than the need for heterogeneity, the complexity of the model needs to be reduced by adjusting other dimensions. The dimensions of the model's complexity thus should not be considered in isolation from each other, but need to be integrated.

Chapter 10

Discussion and conclusions

10.1 Main conclusions

In this thesis, we reported on research that studied *how we can conduct a more comprehensive assessment of a company's actions that can enhance its resilience?* The main conclusions of this research present the answer to this main research question. Section 10.1.1 presents the answers to the sub-questions that were posed for the main research question to be answered. Hereafter, the main research question is addressed in three parts: *1*) the theoretical perspectives used to capture and understand industrial systems (10.1.2); *2*) the models that were developed to assess resilience-enhancing actions (10.1.3); and *3*) our system perspective, which specified how an industrial system should be conceptualised to internalise system-wide complexity in an action's assessment (10.1.4).

10.1.1 Sub-questions

To answer the main research question, we addressed seven sub-questions in different chapters of this thesis. In this section, we present the insights obtained in the different chapters to explicitly address each of the seven questions.

What are the requirements for a simulation model to enable the assessment of an action's indirect effects? To be able to assess the indirect effects of an action (i.e., one of the options that can be selected in a decision), a simulation model has to *1*) measure the focal company's total financial performance; *2*) enable the volumes and prices to emerge endogenously; *3*) include all relevant potential suppliers, competitors, and potential customers; *4*) enable all included actors to adapt their behaviour; and *5*) allow both interacting parties to influence the relations that are formed. The combination of those requirements ensures that a simulation model accounts for the mutual influence between the focal company and its environment. Next to that, it also ensures that the environment can adapt to the assessed action. Those two mechanisms are driving the indirect effects of an action. So, if those are accounted for, the model can assess the indirect effects.

To what extent can current computer simulation models be used to assess an action's indirect effects? Our literature review of the existing simulation models (that were used to support business decisions) indicated that 89 % of the reviewed models focus only on the focal company's internal dynamics. Those models met none of the requirements (listed in our discussion of the previous sub-question) and thus were unable to assess the indirect effects. Around 10 % of the models considered some aspects beyond the focal company. Those thus only met some of the requirements, which still did not suffice to assess the indirect effects of an action. Only one model (out of 209) met all the requirements and thus could assess the indirect effects of an action. However, this model needed to be generalised – in terms of the represented industrial system and the in terms of the represented behaviour and decisions – before it could be used to support a business decision. Hence, we concluded that the existing simulation models cannot directly be used to assess the indirect effects of an action, but some initial steps have been taken in this direction.

What theories are needed to internalise the environment's complexity into a simulation model? To internalise the environment's complexity into a simulation model, we need theories that can describe that complexity, how it is influenced by the focal company, and conversely how it influences the focal company. We used a combination of four different theories for that description. Socio-technical system theory specified the entities that operate in the industrial system. Complex adaptive system theory described the (inter)actions of those entities and how those interactions caused the emergence of complex system behaviour. We used networked markets theory to describe how this complex system behaviour propagated through the system, causing it to adapt to internal and external developments. Competitive strategy theory focused at the mutual influence between the focal company and its environment, to describe how the environment causes the indirect effects of the focal company's action. Together, those four theories described all aspects of industrial systems that are needed to internalise the environment's complexity into a simulation model.

How is the mutual influence between a focal company and its environment driving the indirect effects of a resilience-enhancing action? The focal company influences its environment via improved properties of its products or via an increased production rate. Both those influences are the result of the assessed action that improves the focal company's operations. The companies in the environment change their market behaviour – either directly or via structural changes – in response to those influences, which we refer to as the adaptation of the environment. As a consequence of this adaptation, the market interactions between the focal company and the companies in its environment are changed, as are the supply contracts that materialise from those interactions. Given that the prices and volumes of the supply contracts are driving the focal company's revenues and costs, the changed supply contracts influence the focal company's financial performance. This completes the mutual influence between the focal company and its environment that – together with the environment's adaptation – enables an action to indirectly influence the focal company's financial performance.

How and to what extent do a resilience-enhancing action's indirect effects materialise in the developed simulation models? The indirect effects of the assessed action materialise in the simulation models as changed market developments. In all case studies, we found that capturing the mutual influence between the focal company and its environment, combined with the environment's adaptation, influenced the prices of the exchanged goods substantially. In the first case study (chapter 4), we saw price changes of up to 75 %, while in chapter 5 the influence of the prices materialised as delayed price developments. The first case study also showed that the price changes were caused by the market interactions among the companies that changed in response to the assessed action. Those market interactions enabled the focal company to influence its environment, the environment to adapt to the assessed action, and the environment to influence the focal company. Thereby, the market interactions were fundamental to the materialisation of the indirect effects of the assessed action.

How and to what extent do an action's indirect effects influence the assessment outcomes? As a consequence of the changed market prices, the indirect effects of the assessed action influenced the revenues and costs of the focal company. The outcomes of the assessments (e.g., operational margin, net present value) were directly coupled to the revenues and costs. Hence, via the changed market prices, the indirect effects of the assessed action could influence the assessment outcomes. The extent of this influence differed per case study. In chapter 4, the indirect effects caused the operating margin (of a decision to operate decentralised) to increase from −19 % to 27 %. However, in chapter 5, the indirect effects decreased the net present value (of a transportable plant) by 4 %. In chapter 6, the indirect effects decreased the net present value (of a flexible plant) by a maximum of 50 %. So, although the influence of the indirect effects on the assessment outcomes differs considerably, the case studies demonstrated that this influence can be substantial.

How can our system perspective be employed to assess future actions that may enhance a company's resilience? To assess a specific action, the simulation model can be focused by specifying what complexity is internalised in the model. We identified eight dimensions that specify this complexity: *1*) diameter of the industrial system; *2*) possible market interactions; *3*) types of changes caused by the focal company; *4*) types of changes caused by the environment; *5*) types of changes caused by market interactions; *6*) detail of the environment's representation; *7*) decision rules used to represent (inter)actions; and *8*) features considered by companies in their decision-making. By comparing the case studies, we found what factors needed to be considered to set the dimensions. Table 10.1 presents, for each dimension, what factors need to be considered.

10.1.2 Theories

To enable a more comprehensive assessment of a company's actions, we needed a thorough understanding of industrial systems, their functioning, and their influence on the focal company. This thorough understanding could only be obtained by analysing industrial systems through four different theoretical perspectives: *1*) the

Table 10.1: Considerations to set the dimensions of complexity

Dimension of complexity	Factors to set dimension
Diameter of the industrial system	The tiers spanned by focal company; the tiers of the industrial system that influence the focal company's financial performance
Possible market interactions	Relation between the simulated period and the interval at which companies have market interactions
Types of changes caused by the focal company	Behaviour enabled by the assessed action; relation between the simulated period and the interval at which the focal company makes decisions that cause structural changes
Types of changes caused by the environment	Relation between the simulated period and the interval at which the environment causes structural changes
Types of changes caused by market interactions	The type of market interactions that influenced the assessment outcomes
Detail of the environment's representation	Need for heterogeneity; available initialisation data; available computation time
Considered features	Market characteristics of the modelled industrial system
Decision rules	Need for companies to interact directly and consider each others' features

socio-technical system (STS) perspective, *2*) the complex adaptive system (CAS) perspective, *3*) the networked markets perspective, and *4*) the competitive strategy perspective. The competitive strategy perspective showed that an action's indirect effects consist of three aspects: the influence of the focal company on its environment, the adaptation of the environment, and the influence of the environment on the company. Through the STS perspective, we could identify the entities in the environment, as well as the relations between them and the focal company. The CAS perspective built on that and showed that the agent-level (inter)actions of those entities resulted in the emergence of the system-level behaviour. To capture the system-level adaptation, we required insights into the propagation of developments through the system. The networked markets perspective showed how the interactions of individual companies caused patterns at the system level to propagate, thereby enabling the system to adapt to changes.

All four perspectives thus analysed different aspects of industrial systems at different levels: agent-level, network-level, and system-level. Therefore, it would not have been possible to obtain a thorough understanding of industrial systems had we not used those different perspectives. In this research, we showed that this combination of theories can be used to analyse the complexity of industrial systems. Moreover, we operationalised this combination of theoretical perspectives into simulation models.

10.1.3 Models

Building on the theoretical foundations, we developed five computer simulation models that were used to assess actions of a focal company that may enhance its resilience. Those models internalised the environment's complexity in the form of the (inter)actions of companies in that environment. As we changed the included companies and the allowed (inter)actions, we were able to vary the internalised complexity to the extent needed for the assessment.

By internalising the environment's complexity, the assessment could capture the environment's dynamics and their influence on the focal company. As the value of enhanced resilience depends to a large extent on developments in the company's environment, the internalisation of the environment's complexity is essential to assess resilience-enhancing actions. The conducted experiments showed that the developed model were able to capture the environment's influence on the focal company. Moreover, those models also captured the influence of the focal company's action on the environment. We thereby showed that it was possible to assess (next to its direct effects) an action's indirect effects. The experiments also indicated that capturing those indirect effects of an action resulted in substantially different assessment outcomes. And thus, by internalising the environment's complexity, the models could capture crucial aspects of resilience-enhancing actions and thereby enabled us to conduct more comprehensive assessments of those actions.

10.1.4 System perspective

Using the experience of the developed models, we established our system perspective with which simulation models can be developed for the comprehensive assessment of resilience-enhancing actions. This system perspective is centred around the notion that the assessment of a focal company's action includes the industrial system that forms its environment. This environment is represented as a set of autonomous companies that interact with each other to supply goods. Through those interactions, prices and volumes of exchanged goods emerge that cause the companies influence each other. When we use this perspective to assess an action of the focal company, the assessed action changes the focal company's behaviour. This causes changes to the focal company's interactions with the companies in its environment. Those companies adapt in response to this influence and subsequently influence the focal company via changed interactions. By internalising the complexity of the focal company's environment, the entities in that environment thus can influence the consequences of the action, which enables a more comprehensive assessment and thus answers our main research question.

To apply this developed system perspective to a specific case study, the right level of complexity needs to be internalised into the simulation model. The level of complexity that is internalised through our system perspective has eight dimensions: *1*) diameter of the industrial system; *2*) possible market interactions; *3*) types of changes caused by the focal company; *4*) types of changes caused by the environment; *5*) types of changes caused by market interactions; *6*) detail of the environment's representation; *7*) decision rules used to represent (inter)actions; and *8*) features considered by companies in their decision-making. The development of a simulation model with our system perspective requires that we explicitly select (for each dimension) the level of internalised complexity that is best suited for the assessed action and industrial system.

10.2 Reflections

The main purpose of a simulation model is to obtain insights that help a problem owner address a certain problem. On the one hand, those insights follow from using the model to simulate the system and explore the effects of certain actions. On the other hand, those insights can also follow from the model's development itself. The development of the model requires the modeller to explicitly specify the behaviour of the modelled system. Through this process, the modeller obtains a detailed understanding of the system's behaviour, how this is driving relevant patterns, and how changes to the behaviour may influence those patterns.

During our research, we found that problem owners rarely have a complete and detailed understanding of the system in which they operate. Often, they understand their own operations and general aspects of their environment. However, it also occurs that even within an organisation there is uncertainty and different opinions on the system behaviour. If a problem owner has a limited understanding of the system, it can benefit substantially from being involved in the model development process. By being involved in this process, the problem owner can obtain better insights into the functioning of the system. Discussing the details of the system behaviour with the modeller helps a problem owner structure what it knows (and what is does not know) about the system. Moreover, to fill the missing insights into the system behaviour, further (theoretical) research is needed which the problem owner can assimilate as 'side-effect' of the model development. And third, the systematic structuring of the insights, which is needed to develop the model, provides a detailed overview of the system and its behaviour.

Given the model's objective to provide insight into a problem, the utility of a model can be enhanced if the problem owner is involved in the model development process. Not only will that allow the problem owner to obtain more insights from the model, it also helps the modeller to develop a better model. Discussions between modeller and problem owner requires the modeller to explain its understanding of the system and enables the problem owner (as an expert of the system) to provide input, both of which improved the model considerably. We experienced those benefits also in our model development processes. Ideally, a simulation study thus is a social process in which the problem owner and the modeller collaborate with each other and learn from each other. The modeller learns from the expertise of the problem owner, while the problem owner learns from the research and the analytical qualities of the modeller. Only when this mutual learning is enabled in the development process, the insights derived from the model can be maximised.

This applies especially for very complex models, like we presented in this thesis. We experienced that it is more difficult to capture more complexity in a simulation model and that we, as modellers, needed more insight into the functioning of the system. The expertise of problem owners helped us obtain those insights, which often concerned tacit knowledge. For the problem owners, it is also more important to be involved in the development of more complex models. We noted that, as the complexity of a model increases, its precision decreases. As a model's precision decreases, the insights that can be derived from the simulation of the system decrease as well. This implies that the insights derived from the model development process become more important. So, for highly complex models, the involvement of problem owners in the development process is more important to maximise the model's utility.

10.3 Recommendations for the research community

Now that we showed how resilience-enhancing actions can be assessed comprehensively through simulations that internalise the environment's complexity, there is need for research to develop this concept further. We identified three main directions in which our system perspective can be further developed: *1*) explore and advance the perspective's application, *2*) extend the perspective to capture more complexity, and *3*) the incorporation of our thinking in theories.

Explore and advance the perspective's application The case studies showed that our system perspective can be used to assess a variety of resilience-enhancing actions. However, we have reasons to believe that this perspective can also be applied to assess other actions. We currently have no overview of the type of actions and industrial systems to which our system perspective can best be applied. Therefore, we propose further research to study the common features of actions and industrial systems that can best be studied with our system perspective. This research can consist of desk research and more case studies to develop an overview of the problems to which our system perspective can be applied. With such an overview it becomes easier to decide about applying our system perspective, and it also allows the identification of future research questions that can be addressed with it.

Moreover, the application of our system perspective can be advanced by insights into the contribution of our system perspective to an assessment. In this research, we focused on the development of the system perspective and to what extent it influenced the assessment of an action. We thus did not assess to what extent the assessment *improved* by using our system perspective. Further research is needed to obtain those insights. This research should consist of extensive case studies in which the outcomes of an assessment with our system perspective are compared to the outcomes of a traditional form of assessment. With enough case studies, it becomes possible to determine in advance how much better an assessment with our system perspective is going to be and thus whether it is worthwhile to use this perspective.

A third way to support the application of our system perspective is by lowering the costs of assessing an action with our system perspective. In the case studies, we found that it takes a substantial amount of time to develop and use a model with our system perspective. We focused on how we could internalise the environment's complexity. Therefore, the ease of development and the efficiency of the used algorithms had no priority. Through further research, those aspects of the system perspective can be improved without decreasing the quality of the assessment. This thus is not simply a matter of improving the software in which the system perspective is implemented; it requires new insights into the efficiency and effectiveness of decision rules to represent the market interactions in the industrial system. To obtain those insights, we propose a thorough study with regard to possible decision rules. As part of the current research, we came across many different decision rules to simulate market interactions, but there was no overview of the pros and cons of decision rules and guidelines on when to use them. With such an overview, it would become easier to apply our system perspective, which can advance its use.

Extend the captured complexity The second direction of further research concerns the extension of our system perspective to capture more complexity. This research showed that complexity can substantially influence the outcomes of an assessment. With further increasing levels of complexity in industrial systems, there thus is need to continue internalising additional complexity into the assessment of actions. As a consequence of our focus on the market interactions between companies, the decisions made by companies were mainly driven by economic considerations. However, companies also have other non-economic considerations in their decision-making, such as political or personal considerations. By including non-economic considerations, we can improve the representation of the industrial system in the model and thereby the assessment conducted with that model. Through further research, in the form of additional case studies, we can explore how to include those considerations.

Another way to extend the captured complexity is to combine the internal with the external complexity. The current research focused on internalising the environment's complexity (external to the focal company). Therefore, we decided to limit the internal complexity. Traditionally, (operations) research has focused on this internal complexity, so it is well known how this complexity can be represented in a model. However, so far there has been no research on how to combine the internal complexity with the external complexity. With more research, this combination can be studied and implemented. Moreover, as we did in the current study, that research should also assess what level of (internal and external) complexity is needed for a specific action and what factors influence that decision. Those insights can be used to select the right level of complexity to assess a specific action. Hence, this research would not only extend the captured complexity, but could also advance our system perspective's application.

Incorporation in theories In this research, we found that the complexity in a company's environment can have a substantial influence on that company. To date, theories concerning the decisions of companies (e.g., operations research and supply chain management) hardly consider this complexity. They focus on the focal company and its existing supply chain, thereby disregarding substantial aspects of the company's environment. Depending on the business decision, it may be justified to use this focused perspective. However, for other business decisions, a wider theoretical view may be needed to comprehensively understand a business decision. There thus appears to be a reason to incorporate our system perspective in the existing theories. We therefore recommend that future research studies in what theories our system perspective can be useful and how it then should be incorporated.

10.4 Recommendations for companies

The case studies in this research showed that our system perspective can be used to assess resilience-enhancing actions in a complex environment. By internalising the complexity, more comprehensive assessments are possible, which can better support a company's decisions. Especially, with increasing complexity in industrial systems, it becomes more important for companies to internalise that complexity in the assessment of their actions. If they continue to limit their assessment to their own operations, they risk missing crucial dynamics in their environment that (as we saw in this research) can substantially influence the assessment outcomes. That could cause them to make the wrong decisions, which may harm their business.

Given the ability of our system perspective to enable a more comprehensive assessment and the increasing complexity in industrial system, we recommend companies to use our system perspective and internalise the complexity in their assessment. However, the complexity of our system perspective makes that the successful application in an assessment has some conditions. Therefore, we also provide recommendations on what companies should do to successfully apply our system perspective.

Preliminary study While reflecting on this research, we concluded that the development of a model with our system perspective requires technical expertise and is relatively time consuming. This implies that companies that want to develop and use this type of models need to invest substantial resources. Not all business decisions need to be assessed with models that use our system perspective. For some business decisions, the influence of the indirect effects is so small that it is not worth the invested resources to develop a model with our system perspective for the assessment of those decisions.

We therefore recommend that companies first perform a preliminary study to determine to what extent the indirect effects influence the assessment of a business decision. In this research, we found that the influence of the indirect effects was the most substantial when the focal company had the (market) power to influence the company's in its environment. In practice, that would mean that the company has a high market share or that companies in the industry can quickly adopt each others' developments. Through a more detailed initial study, the company may be able to determine whether the benefits of the more comprehensive assessments outweigh the costs of developing the models. Only if that is the case, the company should proceed to developing the models.

Model development If the company decides to develop models with our system perspective, it will have to invest to acquire the required expertise. As this expertise is highly specialised and the models can be used for business decisions throughout the organisation, it is best to post this knowledge in a separate (or at least central) division. The divisions that want to have a decision assessed then can request the 'modelling division' to develop a model for that assessment. Given that the development and use of the models require the use of a variety of sophisticated tools and machinery, the computing infrastructure of the company should accommodate that. The modelling division needs sufficient computing power at their disposal to finish the experiments within a reasonable time. Moreover, it also needs the freedom to select and apply the software tools that best match the requirements of the simulation model. This may seem trivial, but too often still is a problem.

Given the impossibility to develop complex systems from scratch, we developed the models in this research via a co-evolutionary method. The same applies for companies that set out to develop their own simulation models. The development of a sufficiently detailed and precise model will proceed incrementally and will take time. It is important that the management is aware of this and provides the developers sufficient time to develop the complex models. Even if the initial iteration(s) do not meet the required standards, the management needs to have the vision to continue the development. This experience is a fundamental aspect of the co-evolutionary modelling method that eventually enables the development of complex models. In this regard, expectation management is of the utmost importance.

Model initialisation One of the main challenges during the case studies was that the models needed to be initialised with detailed data describing the entire industrial system. Companies generally have detailed data concerning their own operations, but do not have data at this level for the other companies in their industry. Without this data, the company may have to reconsider the development of the model and therefore we recommend companies to consider the availability of data before the development of the model. If the available data is insufficient to initialise the model, the company may decide to not develop the model at all. Another option is to make (well substantiated) assumptions, so that the model still can be developed and new insights can be obtained.

Model use A model may be used for a number of (related) business decisions and thus needs to be developed with that in mind. To enable the reuse of a model (with minimal effort) for other business decisions, it is important that the users (i.e., the people that work at the division for which the model is developed) are aware of what the model can and cannot do. This requires that the users are involved in the model development process. An additional effect of this is that this makes the more familiar with the model, so that they are more likely to actually use it. Given the complexity of the model, this requires efforts of all involved parties, but it does enable to create more value for the company.

10.5 Final remarks

During this research, we have obtained substantial experience with developing simulation models; especially, models with different levels of complexity. We set out to develop a conceptualisation of industrial systems that could capture the complexity in a focal company's environment. As the research progressed, we developed our system perspective that could internalise that complexity. Through the experiments we performed, we found that this internalised complexity enabled more comprehensive assessments. Those comprehensive assessments are needed to assess resilience-enhancing actions. As the effects of those actions depend considerably on developments in the company's environment, a comprehensive system perspective is needed to capture all relevant dynamics.

Even though more complex models with our system perspective enable more comprehensive assessments, models should not be complex for the sake of being complex. All models are developed to obtain insights. Therefore, the level of complexity should match the objective of the model. We found during our research that a substantial part of the insights were obtained during the model development. We argued before that problem owners therefore should be included in this process. This may be more difficult to realise with complex models, as they generally require more time and experience to understand. In that regard, it sometimes can be recommended to develop less complex models that are easier to understand for a problem owner. The decision to select the complexity captured in a model should not be based on what the modeller *can* do, but on what is required to obtain the desired insights: on what it *should* do. Only then, successful models can be developed that enable comprehensive assessments of resilience-enhancing actions and thereby the development of more resilient industrial systems.

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Appendices

Appendix A

Supply network reconfiguration model

A.1 Determine demand

In the 'determine demand' sub-process, the buyer of a particular good determines the demand it has for that good and what maximum price it is willing to pay for it. This sub-process consists of two parts: *1*) determining the demand; and *2*) determining the willingness to pay. The pseudo-code for this sub-process is as follows:

```
Ask all companies that use the negotiated good:
  If not end-consumer:
    Sold-quantity = sum (quantity of orders for sold product)
    Ratio-feedstock-to-product = process-output-quantity * efficiency / process-input
     ↪ -quantity
    Demand = ceiling (sold-quantity / ratio-feedstock-to-product)

    Sales = mean (net-price of orders for sold product)
    Left-of-sales = sales * process-output-quantity
    Left-of-sales = left-of-sales - (fixed-costs + variable-costs)
    Left-of-sales = left-of-sales * efficiency / process-input-quantity
    Willingness-to-pay = floor (left-of-sales)
```

A.2 Determine supply

In the 'determine supply' sub-process, the seller of a particular good determines the quantity of that good it can supply and what minimum price it is willing to accept for it. This sub-process consists of two parts: *1*) determining the supply; and *2*) determining the willingness to accept. The pseudo-code for this sub-process is as follows:

```
Ask all companies that produce the negotiated good:
  If not raw-material-supplier:
    Supply = floor (capacity * process-output-quantity)

    Costs = mean (gross-price of shipments with feedstock)
    Costs = costs * process-input-quantity / efficiency
    Costs = costs + fixed-costs + variable-costs
```

```
Costs = costs / process-output-quantity
Willingness-to-accept = ceiling (costs)
```

A.3 Negotiations

The negotiations consist of rounds in which buyers and sellers send bids and offers to each other. While there are *any buyers willing to negotiate*, a new round of negotiations starts. The round starts with the *initialisation of the round*, which entails that the buyers and sellers determine their market strategies. Subsequently, the buyers that are still negotiating *create bids*, in which they communicate to each seller what gross price they want to pay for the good. The sellers *process the received bids* and determine what quantity of goods they can supply at the net price they obtain at the communicated gross price. This quantity is made up of the seller's available supply and the quantity of its less profitable orders, which the seller can discard if a more profitable opportunity arises. This quantity is communicated to each buyer in the form of offers. The buyers *process the offers* they have received, by comparing the quantity that the seller want to supply to its demand. On basis of how supply and demand relate to each other, the buyer may decide to increase or decrease its price, send final bids, or stop negotiating. If the buyer sends final bids, it believes it is not going to sign a better deal than the currently available deal. So, if a seller receives a final bid, it either has to accept or reject it. To *process the final bids*, a seller first accepts that part of the final bids that can be supplied from the available supply. If some final bids are left after this, the seller discards the previously signed orders with the lowest net prices. The buyers of the discarded orders are notified of this, so that they can rejoin the negotiations. Figure A.1 provides an overview of the sub-processes and the underlying logic of the negotiations. In sub-sections A.3.1 through A.3.4, those sub-processes are discussed in further detail.

A.3.1 Create bids

In the 'create bids' sub-process, the buyers that are still negotiating communicate the price they bid for the good to the sellers of the good. The pseudo-code for this sub-process is as follows:

```
Ask all companies that use the negotiated good and that are negotiating:
  For each company that produces the negotiated good:
    Create supply-contract:
      Origin = seller
      Destination = buyer
      Good = negotiated good
      Gross-price = price of buyer
      Net-price = gross-price - transport-costs
      State = "bid"
```

A.3.2 Process bids

In the 'process bids' sub-process, the sellers that have received bids determine the quantity they can supply at the bid price and communicate this to the buyers in an offer. The pseudo-code for this sub-process is as follows:

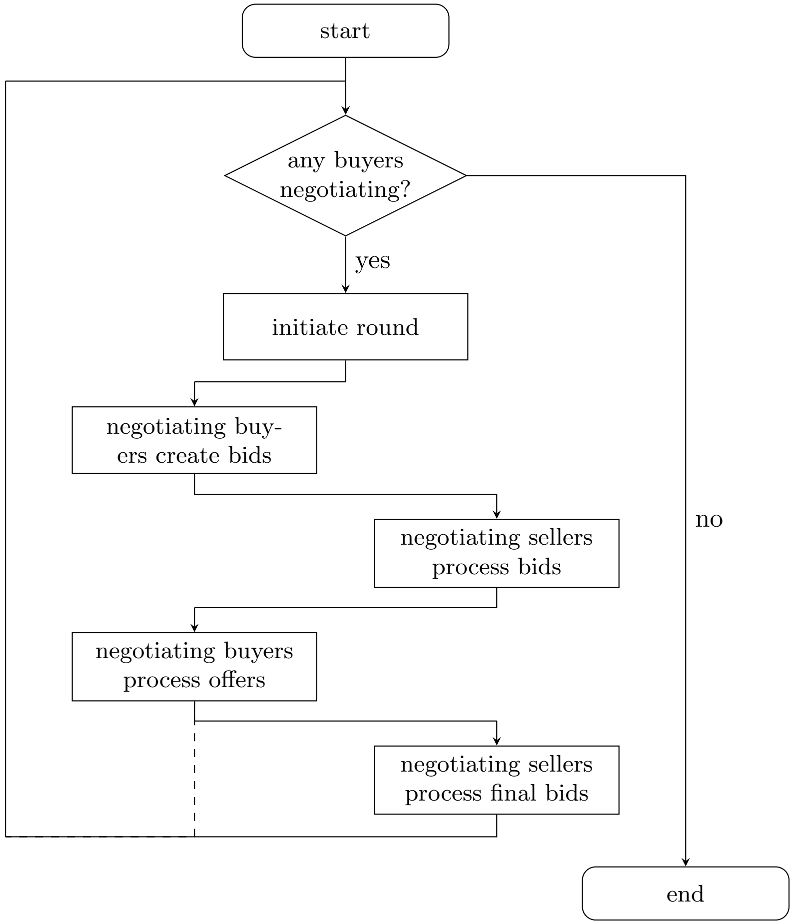


Figure A.1: Negotiation processes overview

```
Ask all companies that produce the negotiated good and have received a bid:
  For each supply-contract with origin == seller and state == "bid":
    Reserved-quantity = sum(quantity of orders with origin == seller and state == "
     ↪ signed" and gross-price >= gross-price of bid)
    If net-price of bid > willingness-to-accept of seller:
      Quantity of bid = supply of seller - reserved-quantity
    Else:
      Quantity of bid = 0
    State of bid = "offer"
```

A.3.3 Process offers

In the 'process offers' sub-process, the buyers that have received offers determine, on basis of the received offers and their demand, how to continue their negotiations. This sub-process consists of three parts: *1*) assessing the possible supply of the sellers; *2*) assessing the demand of the buyer; and *3*) comparing the supply and demand to determine how to continue the negotiations. The pseudo-code for this sub-process is as follows:

```
Ask all companies that use the negotiated good and have received an offer:
  My-supply = sum (quantity of orders with destination == buyer and state == "offer")

  If price >= willingness-to-pay:
    My-demand = demand - sum (quantity of orders with destination == buyer and state
     ↪ == "signed")
  Else:
    My-demand = 0

  If my-supply > my-demand:
    Decrease price
    Delete orders with destination == buyer and state == "offer"
  Else:
    If my-supply < my-demand:
      Increase price
      Delete orders with destination == buyer and state == "offer"
    Else:
      If my-supply == my-demand > 0:
        For each supply-contract with destination == buyer and state == "offer":
          State of offer = "final bid"
      Else:
        Stop negotiating
        Delete orders with destination == buyer and state == "offer"
```

A.3.4 Process final bids

In the ‘process final bids’ sub-process, the seller that have received final bids decide to accept or reject those final bids. This sub-process consists of three parts: *1*) assessing the available supply; *2*) assessing which previously signed orders can be discarded; and *3*) accepting the final bids. The pseudo-code for this sub-process is as follows:

```
Ask all companies that produce the negotiated good and have received a final bid:
  Available-supply = supply - sum (quantity of orders with origin == seller and state
     ↪  == "signed")
  For each orders with origin == seller and state == "final bid":
    Accepted-quantity = min (quantity of final bid, available-supply)

    Less-attractive-orders = orders with orgin == seller and state == "signed" and
     ↪ net-price < net-price of final bid; sorted ascending on net-price
    While accepted-quantity < quantity of final-bid and any? less-attractive-orders:
      Least-attractive-supply-contract = first less-attractive-orders
      Discarded-quantity = min ((quantity of final bid - accepted-quantity), quantity
     ↪  of least-attractive-supply-contract)
      Accepted-quantity = accepted-quantity + discarded-quantity
      Quantity of least-attractive-supply-contract = quantity - discarded-quantity
      If quantity of least-attractive-supply-contract == 0:
        Remove least-attractive-supply-contract from less-attractive-orders
        Tell destination of least-attractive-supply-contract to start negotiating
        Delete least-attractive-supply-contract

    Quantity of final bid = accepted-quantity
    State of final bid = "signed"
```

A.4 Receive feedstock

In the 'receive feedstock' sub-process, the shipper of a good receives the feedstock it needs to produce that good. The pseudo-code of this sub-process is as follows:

```
Ask all companies that produce the shipped good:
  If not raw-material-supplier:
    Received-feedstock = sum (quantity of shipments with destination == shipper and
     ↪ good == feedstock of shipper)
```

A.5 Produce products

In the 'produce products' sub-process, the shipper of a good determines what quantity of that good it can produce using the shipments of feedstock it has received. The pseudo-code of this sub-process is as follows:

```
Ask all companies that produce the shipped good:
  If not raw-material supplier:
    Ratio-product-to-feedstock = process-input-quantity * efficiency * process-output
     ↪ -quantity
    Produced-quantity = received-feedstock * ratio-product-to-feedstock
  Else:
    Produced-quantity = capacity * process-output-quantity
```

A.6 Ship products

In the 'ship producs' sub-process, the shipper of a good ships the produced goods to the buyers that ordered those goods. The pseudo-code of this sub-process is as follows:

```
Ask all companies that produce the shipped good:
  For each orders with origin == shipper and good == shipped good; sorting on
     ↪ descending net-price:
    Create shipment:
      Origin = origin of supply-contract
      Destination = destination of supply-contract
      Good = good of supply-contract
      Net-price = net-price of supply-contract
      Gross-price = gross-price of supply-contract
      Quantity = min (quantity of supply-contract, produced-quantity)
    Produced-quantity = produced-quantity - quantity of shipment
```

Appendix B

Transportable plants model

B.1 Market interactions

The market interactions are largely identical to the processes used in the supply network reconfiguration model (appendix A). The main change concerns the negotiation which is replaced by the 'order feedstock' process, the 'update pricing strategy' process, and the 'set new retail price' process. Hence, we limit our discussion to those three processes.

B.1.1 Order feedstock

In the 'order feedstock' sub-process the buyer of a good determines from which seller(s) it can buy its feedstock at the lowest gross price. The sub-process consists of two parts: *1*) exploration of the prices charged by each seller; and *2*) ordering of the feedstock from the seller(s) with the lowest price. The pseudo-code of this sub-process is as follows:

```
Ask all companies that use the negotiated good:
  Possible-sellers = all companies that can supply the negotiated good, sorted
    ↪ ascendingly on their retail price + the expenses of transporting the good

  Remaining-demand = demand
  While remaining-demand > 0 and any possible-sellers:
    Create supply-contract to first of possible-sellers:
      Origin = selected seller
      Destination = buyer
      Quantity = min (remaining-demand, available-supply of selected seller)
      Net-price = retail price of selected seller
      Gross-price = retail price of selected seller + expenses of transporting the
    ↪ good
      Good = negotiated good
    Remaining-demand = remaining-demand - quantity of supply-contract
    Remove selected seller from possible-sellers
```

B.1.2 Update pricing strategy

In the 'update pricing strategy' sub-process, the seller of a good learns how attractive its current retail price is. The sub-process consists of two parts: *1*) assessment of the obtained reward; and *2*) updating the attractiveness of its current retail price in its pricing strategy. The pseudo-code of this sub-process is as follows:

```
Ask all companies that sell a good:
  Revenues = sum (quantity * net-price of shipments of sold goods)
  Capacity-utilisation = sum (quantity of shipments of sold goods) / (capacity *
    ↪ process-output-quantity)
  Capacity-usage = ((capacity-utilisation / required-capacity-utilisation) ^
    ↪ importance-capacity-utilisation)
  Reward = revenues * capacity-usage

  Q-old = item in pricing-strategy corresponding to the current retail price
  Q-new = q-old + (learning-rate * (reward - q-old))
  Item in pricing-strategy corresponding to the current retail price = q-new
```

B.1.3 Set new retail price

In the 'set new retail price' sub-process, the seller of a good picks a new retail price. The pseudo-code of this sub-process is as follows:

```
Ask all companies that sell a good:
  If random 1.0 < exploration-rate:
    Retail-price is random price from pricing-strategy
  Else:
    Retail-price = one-of the prices in the pricing-strategy with the highest
     ↪ attractiveness (q-value)
```

B.2 Pricing decision

The pricing decision consists of a number of sub-processes that together enable the company to explore its pricing strategy. Figure B.1 presents an overview of the different sub-processes and which logic connects them. In this section, we discuss each sub-process in detail.

B.2.1 Create simulation

In the 'create simulation' sub-process, the simulating company prepares the price simulation that it uses to explore a new pricing strategy. The sub-process consists of two parts: *1*) the company updates the properties of its pricing strategy to comprise the potential profitable prices; and *2*) the company creates a copy of all companies in the industry. The pseudo-code of this sub-process is as follows:

```
Ask all companies that sell a good:
  If random 4 == 0:
    Simulating-company = this company
    Lowest price of pricing strategy = willingness-to-accept
    Highest price of pricing strategy = max net-price any customer is willing to pay
    Other prices in the pricing strategy are chosen to uniformly cover the interval
     ↪ between the lowest and highest price of the pricing strategy

    Ask all companies (including myself):
      Create copy of yourself:
        If representation of simulating-company:
          Simulated-self = this company
        Add this company to the set of simulated-companies
```

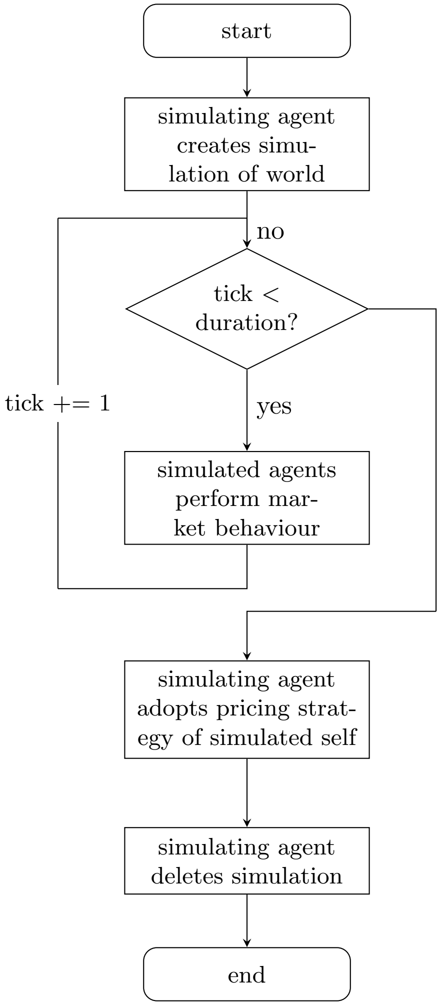


Figure B.1: Process overview of the pricing decision in the transportable plants model

B.2.2 Simulate market behaviour

In the 'simulate market behaviour' sub-process, the simulated agents perform the market behaviour as it was introduced in chapter 5. The main distinction from the market behaviour in the main simulation is that in the price simulation only simulated-self updates its pricing strategy and sets a new retail price. The pseudocode of this sub-process is as follows:

```
While simulation-time < simulation-duration:
  Ask simulated-self:
    Learning-rate = initial-learning-rate / (1 + (((simulation-time) ^ 2) / (learning
     ↪ -rate-decay)))
    Exploration-rate = initial-exploration-rate / (1 + (((simulation-time) ^ 2) / (
     ↪ exploration-rate-decay)))

  For all goods in the industry, sorted downstream to upstream:
```

```
    Ask all simulated-companies that use the good: determine demand and willingness
     ↪ to pay
    Ask all simulated-companies that use the good: order feedstock

  For all goods in the industry, sorted upstream to downstream:
    Ask all simulated-companies that produce the good: receive shipments of feedstock
    Ask all simulated-companies that produce the good: ship produced products to
     ↪ buyers

  Ask simluated-self: update pricing strategy and set new retail price

  Simulation-time = simulation-time + 1
```

B.2.3 Adopt pricing strategy

In the 'adopt pricing strateg' sub-process, the simulating agent adopts the pricing strategy that has been learned in the price simulation. The pseudo-code of this sub-process is as follows:

```
Ask simulating-company:
  Pricing-strategy = pricing-strategy of simulated-self
```

B.2.4 Delete simulation

In the 'delete simulation' sub-process, the simulating agent deletes all simulated companies. The pseudo-code of this sub-process is as follows:

```
Ask simulating-company:
  Delete all simulated-agents
```

B.3 Relocation decision

The relocation decision starts with the initial selection of the site with the highest potential margin. Hereafter, the simulating agent performs a relocation simulation at its current site (the left column), which is followed by a relocation simulation at the site with the highest potential margin (the middle column). The actual decision to relocate is made by comparing the outcomes of the different simulations (the most right column). Figure B.2 presents an overview of the processes and the logic of the relocation decision. In this section, we discuss the four aspects of the relocation decision.

B.3.1 Initial selection

In the 'initial selection' sub-process, the transportable company compares all available sites under the current market conditions. The pseudo-code of this sub-process is as follows:

```
Ask transportable company:
  Ask all sites of companies that use my product:
    revenues = average gross-price paid by the company at this site for my product
    costs = variable-costs + fixed costs of transportable company + minimum gross-
     ↪ price to supply feedstock to this site
    margin = (revenues - costs) / revenues
```

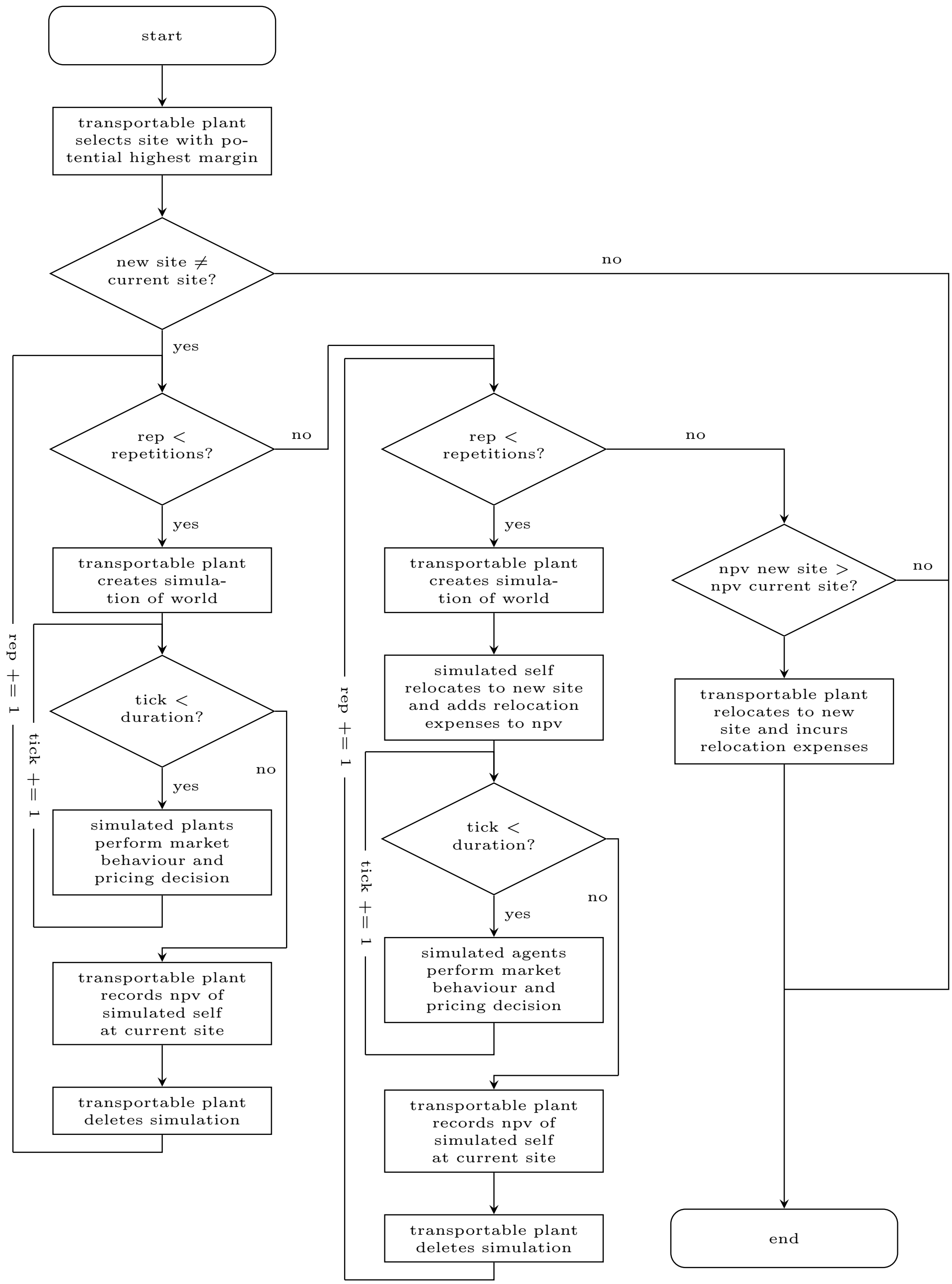


Figure B.2: Process overview of the relocation decision in the transportable plants model

```
  End ask
  new-site = site with highest margin
End ask
```

B.3.2 Relocation simulation at current site

In the 'relocation simulation at current site' sub-process, the transportable companies determines its net present value if it continues to operate at its current site. To limit stochasticity, the simulation can be repeated multiple times after which the mean net present value is computed. The pseudo-code of this sub-process is as follows:

```
Ask transportable company:
  Create copies of self and of and of other companies
  While simulation-time < simulation-duration:
    For all goods in the industry, sorted downstream to upstream:
      Ask all simulated-companies that use the good: determine demand and willingness
     ↪  to pay
      Ask all simulated-companies that use the good: order feedstock
    End for

    For all goods in the industry, sorted upstream to downstream:
      Ask all simulated-companies that produce the good: receive shipments of
     ↪ feedstock
      Ask all simulated-companies that produce the good: ship produced products to
     ↪ buyers
    End for

    Ask simulated-companies that sell any good:
      Update pricing strategy and set new retail price
    End ask

    Ask simulated-self:
      cash-flows = (sum ((quantity * net-price) of shipments to sell products) - ((
     ↪ quantity * gross-price) of shipments to buy feedstock) - (variable-costs *
     ↪ sold-quantity / process-output-quantity) - (fixed-costs * capacity))
    End ask

    Ask simulated-companies that sell any good:
      If random 4 == 0:
        pricing decision
      End if
    End ask

    simulation-time = simulation-time + 1
  End while
  npv-current-site = net present value of simulated self
  Delete simulated-companies
End ask
```

B.3.3 Relocation simulation at new site

In the 'relocation simulation at new site' sub-process, the transportable company determines its net present value if it would operate at the selected site with the highest potential margin. This simulation is identical, except that the simulated-self is not located at the transportable company's current site, but at the site with the highest potential margin (i.e., new-site). Consequently, the cash-flows of the transportable company do not start at 0, but are negative due to the relocation expenses.

B.3.4 Decision to relocate

In the 'decision to relocate' sub-process, the transportable company determines whether the simulation outcomes give enough reason to relocate. The pseudo-code of this sub-process is as follows:

```
Ask transportable company:
  If npv-new-site > (1 + relocation-threshold) * npv-current-site:
    my-site = new-site
    incurred-relocation-expenses = relocation-expenses
  End if
End ask
```

Appendix C

Process flexibility model

C.1 Process selection decision

Like the 'relocation decision' in the transportable plants model, the 'process selection decision' consists of a number of simulations that a flexible company uses to assess the effects of a potential process change. The process selection decision starts with the initial selection of the process with the highest potential margin. Based on the outcomes of this selection, the flexible company simulates its operations with its current process to determine the expected value. Hereafter, it simulates its operations with the new process to determine the expected value of the new process. Finally, for the actual decision to change its process, the flexible company compares the values that materialised from the simulations.

C.1.1 Initial selection

In the 'initial selection' sub-process, the flexible company compares all available processes under the current market conditions. The pseudo-code of this sub-process is as follows:

```
Ask flexible company:
  Ask all processes that produce the good my current process produces:
    Revenues = retail-price of flexible company * capacity of flexible company *
     ↪ process-output-quantity / efficiency of company
    Costs = process-variable-costs * variable-costs-efficiency of flexible company +
     ↪ process-fixed-costs * fixed-costs-efficiency of flexible company + min(net-
     ↪ price + transport-costs of any supplier of process's feedstock)
    Margin = (revenues - costs) / revenues
  New-process = process with highest margin
```

C.1.2 Process selection simulation with current process

In the 'process selection simulation with current process' sub-process, the flexible companies determines its net present value if it continues to operate its current process. To limit stochasticity, the simulation can be repeated multiple times after which the mean net present value is computed. The pseudo-code of this sub-process is as follows:

```
Ask flexible company:
  Create copies of self and of and of other companies
  While simulation-time < simulation-duration:
    For all goods in the industry, sorted downstream to upstream:
      Ask all simulated-companies that use the good: determine demand and willingness
     ↪  to pay
      Ask all simulated-companies that use the good: order feedstock

    For all goods in the industry, sorted upstream to downstream:
      Ask all simulated-companies that produce the good: receive shipments of
     ↪ feedstock
      Ask all simulated-companies that produce the good: ship produced products to
     ↪ buyers

    Ask simulated-companies that sell any good:
      Update pricing strategy and set new retail price

    Ask simulated-self:
      Cash-flows = (sum ((quantity * net-price) of shipments to sell products) - ((
     ↪ quantity * gross-price) of shipments to buy feedstock) - (variable-costs *
     ↪ sold-quantity / process-output-quantity) - (fixed-costs * capacity))

    Ask simulated-companies that sell any good:
      If random 4 == 0:
        Pricing decision

    Simulation-time = simulation-time + 1
  Npv-current-process = net present value of simulated self
  Delete simulated-companies
```

C.1.3 Process selection simulation with new process

In the 'process selection simulation with new process' sub-process, the transportable company determines its net present value if it would operate the selected process with the highest potential margin. This simulation is identical, except that the simulated-self is not performing the flexible company's current process, but the process with the highest potential margin (i.e., new-process). Consequently, the cash-flows of the transportable company do not start at 0, but are negative due to the process change expenses.

C.1.4 Decision to change process

In the 'decision to change process' sub-process, the flexible company determines whether the simulation outcomes give enough reason to change its process. The pseudo-code of this sub-process is as follows:

```
Ask flexible company:
  If npv-new-process > (1 + process-change-threshold) * npv-current-
    ↪ process:
    My-process = new-process
    Incurred-process-change-expenses = process-change-expenses
```

C.2 Model initialisation

The model initialisation concerns the entities and state variables that are initially set-up in the model. For the process flexibility model, this concerns the properties of the processes, the properties of the companies that perform those processes, and the global variables. The companies are categorised in feedstock suppliers, caprolactam producers, and nylon-6 producers. For each of the companies, we present the relevant properties.

Table C.1: Properties of processes used in the process flexibility model

	Feedstock		Product		Fixed costs	Variable costs
Process	Type	Quantity	Type	Quantity	[€/mt]	[€/mt]
Benzene supply			Benzene	1.00		
Phenol supply			Phenol	1.00		
Bz-based CPL production	Benzene	1.00	Caprolactam	1.00	200	200
Ph-based CPL production	Phenol	1.00	Caprolactam	1.00	200	200
Nylon-6 production	Caprolactam	1.00				

Table C.2: Properties of the suppliers in the process flexibility model

#	Region	Process	Supply [mt]	WTA [€/mt]
1	1	Phenol supply	1,092	552
2	1	Phenol supply	729	652
3	1	Benzene supply	636	831
4	1	Benzene supply	843	884
5	2	Phenol supply	907	897
6	2	Phenol supply	638	729
7	2	Benzene supply	878	631
8	2	Benzene supply	948	585
9	3	Phenol supply	713	750
10	3	Phenol supply	921	620
11	3	Benzene supply	757	547
12	3	Benzene supply	938	722

Table C.3: Properties of the caprolactam producers in the process flexibility model

#	Region	Process	Capacity [mt]	WTP [€/mt]	WTA [€/mt]	Variable costs efficiency
1	1	Ph-based CPL production	415	987	1,487	0.83
2	1	Bz-based CPL production	478	932	1,432	1.09
3	3	Ph-based CPL production	468	903	1,403	0.79
4	2	Bz-based CPL production	330	1,116	1,616	0.86
5	1	Ph-based CPL production	310	582	1,082	1.00
6	3	Bz-based CPL production	529	917	1,417	1.12
7	1	Ph-based CPL production	342	1,057	1,557	0.96
8	3	Bz-based CPL production	311	1,057	1,557	1.01
9	1	Ph-based CPL production	310	935	1,435	0.83
10	3	Bz-based CPL production	75	602	1,102	1.11
11	3	Ph-based CPL production	347	930	1,430	1.19
12	2	Bz-based CPL production	233	973	1,473	1.09
13	2	Ph-based CPL production	327	1,261	1,761	0.99
14	1	Bz-based CPL production	456	1,000	1,500	0.98
15	1	Ph-based CPL production	298	935	1,435	1.00
16	3	Bz-based CPL production	278	737	1,237	1.12
17	2	Ph-based CPL production	180	865	1,365	1.12
18	2	Bz-based CPL production	421	792	1,292	0.96
19	2	Ph-based CPL production	312	1,010	1,510	0.88
20	3	Bz-based CPL production	146	932	1,435	0.97

Table C.4: Properties of the nylon-6 producers in the process flexibility model

#	Region	Process	Demand [mt]	WTP [€/mt]
1	1	Nylon-6 production	695	2,481
2	1	Nylon-6 production	536	2,700
3	1	Nylon-6 production	721	2,308
4	2	Nylon-6 production	894	2,362
5	2	Nylon-6 production	829	2,401
6	2	Nylon-6 production	604	2,009
7	3	Nylon-6 production	774	2,488
8	3	Nylon-6 production	544	2,571
9	3	Nylon-6 production	492	2,780

Table C.5: Initialised global variables in the process flexibility model

Global variable	Value
Required-capacity-utilisation	0.90
Importance-capacity-utlisation	0.50
Price-simulation-hoirzon	400
Initial-learning-rate	0.40
Initial-exploration-rate	0.40
Learning-rate-decay	12,000
Exploration-rate-decay	12,000
Process-simulation-repetitions	2
Process-simulation-horizon	26

Appendix D

Collaboration model appendix

D.1 Exchange interactions

The exchange interactions consist of rounds of market interactions over the exchange of different goods. This behaviour can be divided into three phases: negotiating, shipping, and accounting. The first two phases consist of rounds in which consecutive goods are negotiated or shipped. The negotiations start with the most downstream good and continue with increasingly more upstream goods; and the shipping starts with the most upstream good and continues with increasingly more downstream goods.

D.1.1 Negotiating

Determine demand

In the 'determine demand' sub-process, the buyer of a good determines what quantity of the negotiated good it wants to buy and what price it is willing to pay for that good. The pseudo-code of this sub-process is as follows:

```
Ask all companies that use the negotiated good:
  If not end-consumer:
    If any supply-contracts for the sale of my product:
    Synergy = (1 - collaborative-cost-savings) ^ number of direct collaborating
     ↪ supply chain partners
      Sales = mean (net-price of supply-contracts for sold product)
      Left-of-sales = sales * process-output-quantity
      Left-of-sales = left-of-sales - (fixed-costs + (variable-costs * synergy))
      Left-of-sales = left-of-sales / process-input-quantity
      Willingness-to-pay = floor (left-of-sales)

      Sold-quantity = sum (quantity of supply-contracts for sold product)
      Ratio-feedstock-to-product = process-output-quantity / process-input-quantity
      Demand = ceiling (sold-quantity / ratio-feedstock-to-product)
    Else:
      Demand = 0
```

Determine supply

In the 'determine supply' sub-process, the seller determines what quantity of the negotiated good it can sell. The pseudo-code of this sub-process is as follows:

```
Ask all companies that produce the negotiated good:
  If not raw-material-supplier:
    Supply = capacity * process-output-quantity
```

Order good from the network

In the 'order good from the network' sub-process, the buyers of the negotiated good order, when possible, the good from the company in their network that can supply this good. The pseudo-code of this sub-process is as follows:

```
Ask all companies that use the negotiated good:
  Possible-suppliers = companies in my network that produce the negotiated good,
     ↪ descendingly sorted on willingness to accept
  While any possible-suppliers and demand > 0:
    Create supply-contract:
      Origin = first possible-suppliers
      Destination = buyer
      Quantity = min(demand of destination, supply of origin)
      Net-price = willingness-to-pay of destination
      Gross-price = willingness-to-accept of origin
    Demand of buyer = demand - quantity of supply-contract
    Remove first company from possible-suppliers
```

Bid in the market

In the 'bid in the market' sub-process, the buyers of the negotiated good order their remaining demand from the market where the good is traded. The pseudo-code of this sub-process is as follows:

```
Ask all companies that use the negotiated good:
  Create supply-contract:
    Origin = market where the negotiated good is traded
    Destination = buyer
    Quantity = demand of buyer
    Gross-price = willingness-to-pay of buyer
```

Offer in the market

In the 'offer in the market' sub-process, the sellers of the negotiated good offer their remaining demand to the market where the good is traded. The pseudo-code of this sub-process is as follows:

```
Ask all companies that produce the negotiated good:
  Create supply-contract:
    Origin = seller
    Destination = market where the negotiated good is traded
    Quantity = supply of seller - sum (quantity of received supply-contracts to
     ↪ supply good)
    Net-price = willingness-to-accept of seller
```

Clear the market

In the 'clear the market' sub-process, the market of the negotiated good determines which companies get to supply and get to receive the good, and the price of the good. The pseudo-code of this sub-process is as follows:

```
Ask markets where the negotiated good is traded:
  Offers = received supply-contracts to sell good, sorted ascendingly on net-price
  Bids = received supply-contracts to buy good, sorted ascendingly on gross-price
  Market-price = price where cumulative quantity of offers equals cumulative quantity
     ↪  of bids
  Delete offers with net-price > market-price and bids with gross-price < market-
     ↪ price
  Ask remaining offers and bids:
    Net-price = market-price
    Gross-price = market-price
```

D.1.2 Shipping

Ship goods to collaborating buyers

In the 'ship goods to collaborating buyers' sub-process, the shipper of a good ships the good it has produced to the buyers that participate in the same network. The pseudo-code of this sub-process is as follows:

```
Ask all companies that produce the shipped good:
  For all supply-contracts received from companies that use the shipped good and
     ↪ participate in the same network:
    Create shipment:
      Origin = origin of supply-contract
      Destination = destination of supply-contract
      Quantity = min(quantity of supply-contract, supply of shipper)
      Net-price = net-price of supply-contract
      Gross-price = gross-price of supply-contract
    Supply of shipper = supply - quantity of shipment
    Delete the supply-contract
```

Ship goods to the market

In the 'ship goods to the market' sub-process, the shipper of a good ships the good it has produced to the market to which it has sold the good. The pseudo-code of this sub-process is as follows:

```
Ask all companies that produce the shipped good:
  For all supply-contracts to the market where the shipped good is traded:
    Create shipment:
      Origin = origin of supply-contract
      Destination = destination of supply-contract
      Quantity = min(quantity of supply-contract, supply of shipper)
      Net-price = net-price of supply-contract
      Gross-price = gross-price of supply-contract
    Supply of shipper = supply - quantity of shippment
    Delete the supply-contract
```

Transfer goods

In the 'transfer goods' sub-process, the market where a good is traded ships the goods it has received to the buyers of those goods. The pseudo-code of this sub-process is as follows:

```
Ask markets where the shipped good is traded:
  Received-shipments = shipments destined to market
  Received-quantity = sum (quantity of received-shipments)
  Expenses = expenses + sum (quantity * gross-price of received-shipments)
  Ask origin of received-shipments:
    Revenues = revenues + quantity * net-price of shipments sent by origin
  For all supply-contracts to supply goods to companies:
    Create shipment:
      Origin = origin of supply-contract
      Destination = destination of supply-contract
      Quantity = min(quantity of supply-contract, received-quantity)
      Net-price = net-price of supply-contract
      Gross-price = gross-price of supply-contract
    Received-quantity = received-quantity - quantity of shipment
    Delete the supply-contract
```

Receive shipments

In the ‘receive shipments’ sub-process, the buyers of the shipped good receive the shipments. The pseudo-code of this sub-process is as follows:

```
Ask all companies that use the shipped good:
  Received-shipments = shipments destined to buyer
  Received-quantity = sum (quantity of received-shipments)
  Expenses = expenses + sum (quantity * gross-price of received-shipments)
  Ask origin of received-shipments:
    Revenues = revenues + quantity * net-price of shipments sent by origin

  If not end-consumer:
    Synergy = (1 - collaborative-cost-savings) ^ number of direct collaborating
     ↪ supply chain partners
    Costs = mean (gross-price of shipments with feedstock)
    Costs = costs * process-input-quantity
    Costs = costs + fixed-costs + (variable-costs * synergy)
    Costs = costs / process-output-quantity
    Willingness-to-accept = ceiling (costs)

    Ratio-product-to-feedstock = process-input-quantity * process-output-quantity
    Supply = received-quantity * ratio-product-to-feedstock
```

D.1.3 Accounting

Update network accounts

In the ‘update network account’ sub-process, the networks determine the network profit and allocate this profit over the participating companies. The pseudo-code of this sub-process is as follows:

```
Ask all networks:
  Network-expenses = sum (expenses of participating companies)
  Network-revenues = sum (revenues of participating companies)
  Network-fixed-costs = sum (fixed-costs * capacity of participating companies)
  Ask participating companies:
    Synergy = (1 - collaborative-cost-savings) ^ number of direct collaborating
     ↪ supply chain partners
    company-variable-costs = variable-costs * synergy * sum (quantity of shipments
     ↪ sent by company / process-output-quantity)
  Network-variable-costs = sum (company-variable-costs of participating companies)
```

```
Network-profit = network-revenues - network-expenses - network-fixed-costs -
  ↪ network-variable-costs

Ask participating companies:
  Revenues = network-profit * allocated-percentage of my collaborative agreement
   ↪ with network
  Expenses = 0
```

Update company accounts

In the 'update company accounts' sub-process, the companies that operate individually determine their revenues and expenses. The pseudo-code of this sub-process is as follows:

```
Ask all companies that do no participate in a network:
  Expenses = expenses + (fixed-costs * capacity) + (variable-costs * sum (quantity of
    ↪  shipments sent by company / process-output-quantity))
```

D.2 Collaboration interactions

D.2.1 Reconsider operations

In the 'reconsider operations' sub-process, the companies determine how they want to operate. This involves determining the net present value of operating individually, in the current network, or in another network. The pseudo-code of this sub-process is as follows:

```
Ask all companies that are not raw-material-supplier or end-consumer:
  If random reconsider-interval == 0 or collaborative agreement ends:
    Own-revenues = capacity * market-price of produced good * process-output-quantity
    Own-expenses = capacity * (market-price of used good * process-input-quantity + (
     ↪ fixed-costs + variable-costs))
    If part of network and collaborative agreement does not end:
      Own-npv = - fine of collaborative agreement
    Own-npv = own-npv + net present value of (own-revenues - own-expenses) with
     ↪ discount-rate and reconsidering-horizon

    For number of randomly selected network with the company's process available:
      If part of network and collaborative agreement does not end:
        This-network-npv = - fine of collaborative agreement
      Expected-allocated-percentage = allocation-strategy computation of network with
    ↪  the reconsidering company
      Expected-network-profit = revenues - costs of network with participation of the
    ↪  reconsidering company
      This-network-payoff = expected-allocated-percentage * expected-network-profit
      This-network-npv = this-network-npv + net present value of (this-network-payoff
    ↪ ) with discount-rate and reconsidering-horizon
    New-network-npv = max (this-network-npv of selected new networks)

    Current-network-payoff = allocated-percentage of my collaboration agreement *
     ↪ expected revenues - costs of current network
    Current-network-npv = net present value of (current-network-payoff) with discount
     ↪ -rate and reconsidering-horizon

    If own-npv is highest:
      My-network = nobody
      Delete collaborative agreement
```

```
Else:
  If new-network-npv is highest:
    My-network = nobody
    Delete collaborative agreement
    Create agreement with network with highest this-network-npv:
      State = "offer"
      Added-value = value of network with company - value of network without
 ↪ company
      Expected-payoff = this-network-payoff of selected network
  Else:
    If agreement ends:
      My-network = nobody
      Delete collaborative agreement
      Create agreement with current network:
        State = "offer"
        Added-value = value of network with company - value of network without
 ↪ company
        Expected-payoff = current-network-payoff
```

D.2.2 Reconsider participants

In the 'reconsider participants' sub-process, the network determine which companies they want as participants in the network. This involves determining the net present value of the current companies, the worst performing company removed, or the worst performing company replaced. The pseudo-code of this sub-process is as follows:

```
Ask all networks:
  If random reconsider-interval == 0 or not all positions taken:
    If not all positions taken:
      Reconsidered-position = one of available positions
    Else:
      Reconsidered-company = company with lowest added value
      Reconsidered-postion = position of reconsidered-company

    Current-network-revenues = expected revenues of operating the current network
    Current-network-expenses = expected expenses of operating the current network
    Current-network-npv = net present value of (current-network-revenues - current-
     ↪ network-expenses) with discount-rate and reconsidering-horizon

    Remaining-network-revenues = expected revenues of operating the current network
     ↪ without the reconsidered-company
    Remaining-network-expenses = expected expenses of operating the current network
     ↪ without the reconsidered-company
    If reconsidered-company != nobody:
      Remaining-network-npv = - fine of collaborative agreement
    Remaining-network-npv = remaining-network-npv + net present value of (remaining-
     ↪ network-revenues - remaining-network-expenses) with discount-rate and
     ↪ reconsidering-horizon

    For number of randomly chosen individually operating companies with reconsidered-
     ↪ position:
      This-company-network-revenues = expected revenues of operating the remaining
     ↪ network plus the assessed company
      This-company-network-expenses = expected expenses of oeprating the remaining
     ↪ network plus the assessed company
      If reconsidered-company != nobody:
        This-company-network-npv = - fine of collaborative agreement
      This-company-network-npv = this-company-network-npv + net present value of (
     ↪ this-company-network-revenues - this-company-network-expenses) with discount-
```

```
 ↪ rate and reconsidering-horizon
New-company-network-npv = max (this-company-network-npv of assessed companies)

If remaining-network-npv is highest:
  Remove reconsidered-company from participating companies
  Delete collaborative agreement
Else:
  If new-company-network-npv is highest:
    Remove reconsidered-company from participating companies
    Delete collaborative agreement
    Create agreement with company with highest this-company-network-npv:
      State = "offer"
      Added-value = value of network with company - value of network without
 ↪ company
      Expected-payoff = expected allocated percentage with company * expected
 ↪ network profit with company
```

D.2.3 Sign collaborative agreements

In the 'sign collaborative agreements' sub-process, the companies and networks determine whether they want form a collaborative agreement with each other. The pseudo-code of this sub-process is as follows:

```
While any collaborative agreements with state == "offer":
  Best-agreement = collaborative agreement with state == "offer" and highest added-
    ↪ value
  Ask new-company of best-agreement:
    If expected-payoff of best-agreement > expected-payoff of other collaborative
     ↪ agreements with state == "offer" for new company:
      Ask new-network of best-agreement:
        If expected-payoff for all companies in the network with new company >=
     ↪ expect-payoff for all companies in the network without new company:
          Ask new-company:
            My-network = new-network
          Add new-company to participating companies
          Ask best-agreement:
            State = "signed"
            End-date = current-date + preferred-participation-duration of new-network
          For all collaborative agreements of network:
            Allocated-percentage = percentage of total network profit that is
     ↪ allocated to the agreement's company under the network's allocation strategy
          Delete other offers for new-company
          Delete other offers for new-network
        Else:
          Delete best-agreement
    Else:
      Delete best-agreement
```

Appendix E

Maritime fuel model appendix

E.1 Operational behaviour

The operational behaviour consists of vessels that sail around the world and moor in ports, and of the agents in those ports that trade the fuel that are used by the vessels. The first three sub-processes concern the behaviour of the vessels and are executed every time step, while the other sub-process concern the behaviour of the agents in the ports and those are executed once in every seven time steps.

E.1.1 Vessel operations

Moor vessel

In the 'moor vessel' sub-process, the vessels arrive at their destination, where they unload their cargo and complete their shipping assignment. The pseudo-code of this sub-process is as follows:

```
Ask all vessels that arrive at their destination:
  Moored-port = destination
  Ask moored-port:
    Throughput = throughput + quantity of vessel's my-shipping-assignment
  Fuel-stock = fuel-stock - (distance of shipping lane to execute my-shipping-
    ↪ assignment) * fuel consumption of vessel
  Remove my-shipping-assignment
```

Select new shipping assignment

In the 'select new shipping assignment' sub-process, the vessels that are moored in a port select a new shipping assignment that they can execute. The pseudo-code of this sub-process is as follows:

```
Ask all vessels are moored in a port and have selected no shipping assignment:
  Possible-assignments = all available shipping assignments of the vessel's class and
    ↪  that concern a quantity that is lower than the vessel's carrying capacity
  If any possible-assignments:
```

```
  If fuel-stock < fuel-considering-percentage * fuel-capacity AND current port does
   ↪  not offer vessel's fuel:
    Possible-assignments = all possible-assignments to a port that offer the vessel
   ↪ 's fuel
  My-shipping-assignment = one of possible-assignments with lowest sum of (distance
   ↪  * vessel's fuel-consumption) and (fine * inspection-probability (if vessel's
   ↪  emission exceed the allowed-emission at the shipping line))
  Ask destination port of my-shipping-assignment:
    Add quantity of my-shipping-assignment to port's reservation-book at the
   ↪ nearest time after the vessel's arrival where there is enough available
   ↪ capacity in the port
  My-arrival-time = current-time + distance to execute my-shipping-assignment /
   ↪ vessel's speed
```

Bunker fuel

In the 'bunker fuel' sub-process, the vessels that are about to leave a port determine whether they should bunker fuel before they leave. The pseudo-code of this sub-process is as follows:

```
Ask all vessels are moored in a port and have selected a shipping assignment:
  If fuel-supplier in current port that offers vessel's fuel:
    If fuel-supplier in destination of my-shipping-assignment that offers vessel's
     ↪ fuel:
      If distance of my-shipping-assignment * vessel's fuel-consumption <= fuel-stock
     ↪ :
        If price of fuel in current port <= price of fuel in destination port:
          Fill fuel-stock to fuel-capacity, Add bunkered quantity to the fuel-
     ↪ supplier's fuel-demand, and Add bunkered quantity * supplier's price to fuel-
     ↪ supplier's revenues
      Else:
        Fill fuel-stock to fuel-capacity, Add bunkered quantity to the fuel-supplier'
     ↪ s fuel-demand, and Add bunkered quantity * supplier's price to fuel-supplier'
     ↪ s revenues
    Else:
      Fill fuel-stock to fuel-capacity, Add bunkered quantity to the fuel-supplier's
     ↪ fuel-demand, and Add bunkered quantity * supplier's price to fuel-supplier's
     ↪ revenues
```

E.1.2 Maritime fuel trade

Inject natural gas

In the 'inject natural gas' sub-process, the LNG terminals regasify the requested quantity of LNG and inject it into the network. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all lng-terminals:
    Requested-natural-gas = quantity of demand-curve at the lng-terminal's retail-
     ↪ price
    Fuel-demand = requested-natural-gas
    Available-capacity = capacity - requested-natural-gas
    Revenues = retail-price * requested-natural-gas
```

Order fuel

In the 'order fuel' sub-process, the fuel suppliers order fuel from their suppliers to meet the quantity that was supplied to the vessels. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all fuel-suppliers:
    Willingness-to-pay = retail-price - handling-costs
    Demand = fuel-demand
    If fuel == "LNG":
      Possible-suppliers = lng-terminals with retail-price + (import-vessel-costs *
     ↪ distance to lng-terminal) <= willingness-to-pay; sorted ascendingly by retail
     ↪ -price + (import-vessel-costs * distance to lng-terminal)
      While fuel-supplier's demand > 0 and any possible-suppliers:
        Selected-supplier = first of possible-suppliers
        Create supply-contract:
          Origin = selected-supplier
          Destination = fuel-supplier
          Quantity = min(demand, available-capacity of selected-supplier)
          Net-price = retail-price of selected-supplier
          Gross-price = retail-price + (import-vessel-costs * distance between origin
     ↪  and destination)
          Fuel = fuel of fuel-supplier
        Demand = demand - quantity of supply-contract
        Remove selected-supplier from possible-suppliers
    Else:
      Create supply-contract:
        Origin = fuel-market with fuel == fuel-supplier's fuel
        Destination = fuel-supplier
        Quantity = demand of fuel-supplier
        Gross-price = willingness-to-pay of fuel-supplier
        Fuel = fuel of fuel-supplier
```

Clear market

In the 'clear market' sub-process, the fuel-markets determines the price at which supply meets demand and what quantity is supplied to each fuel-supplier. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all fuel-markets:
    Supply = supply-curve
    Bids = received supply-contracts to buy fuel, sorted ascendingly on gross-price
    Market-price = price where cumulative quantity of bids equals the quantity of the
     ↪  supply curve
    Delete bids with gross-price < market-price
    Ask remaining bids:
      Create shipment:
        Origin = origin of bid
        Destination = destination of bid
        Quantity = quantity of bid
        Net-price = market-price
        Gross-price = market-price
        Fuel = fuel of bid
```

Ship LNG

In the 'ship LNG' sub-process, the LNG terminals supply the ordered quantity of LNG to the fuel suppliers. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all lng-terminals:
    Fuel-demand = fuel-demand +  sum quantity of received supply-contracts for LNG
    Revenues = revenues + sum (quantity * net-price of received supply-contracts for
     ↪ LNG)
    Create shipment for each received supply-contract:
      Origin = origin of supply-contract
      Destination = destination of supply-contract
      Quantity = quantity of supply-contract
      Net-price = net-price of supply-contract
      Gross-price = gross-price of supply-contract
      Fuel = fuel of supply-contract
```

Receive fuel

In the 'receive fuel' sub-process, the fuel suppliers receive the fuel they ordered. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all fuel-suppliers:
    Fuel-demand = fuel-demand - sum (quantity of received shipments)
    Expenses = expenses + sum (quantity * gross-price of received shipments)
    Remove all received shipments
```

E.1.3 Bulk LNG trade

Order bulk LNG

In the 'order bulk LNG' sub-process, the LNG terminals order LNG from the liquefaction plants. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all lng-terminals:
    Willingness-to-pay = retail-price - handling-costs
    Demand = fuel-demand
    Possible-suppliers = liquefaction-plants with retail-price + (lng-carrier-costs *
     ↪  distance to liquefaction-plant) <= willingness-to-pay; sorted ascendingly by
     ↪  retail-price + (lng-carrier-costs * distance to liquefaction-plant)
    While lng-terminals's demand > 0 and any possible-suppliers:
      Selected-supplier = first of possible-suppliers
      Create supply-contract:
        Origin = selected-supplier
        Destination = lng-terminal
        Quantity = min(demand, available-capacity of selected-supplier)
        Net-price = retail-price of selected-supplier
        Gross-price = retail-price + (lng-carrier-costs * distance between origin and
    ↪  destination)
        Fuel = "LNG"
      Demand = demand - quantity of supply-contract
      Remove selected-supplier from possible-suppliers
```

Ship bulk LNG

In the ‘ship bulk LNG’ sub-process, the liquefaction plant ship the ordered LNG to the LNG terminals. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all liquefaction-plants:
    Revenues = revenues + sum (quantity * net-price of received supply-contracts for
     ↪ LNG)
    Create shipment for each received supply-contract:
      Origin = origin of supply-contract
      Destination = destination of supply-contract
      Quantity = quantity of supply-contract
      Net-price = net-price of supply-contract
      Gross-price = gross-price of supply-contract
      Fuel = fuel of supply-contract
```

Receive bulk LNG

In the ‘receive bulk LNG’ sub-process, the LNG terminals receive the shipments of LNG. The pseudo-code of this sub-process is as follows:

```
Once every 7 time steps:
  Ask all lng-terminals:
    Fuel-demand = fuel-demand - sum (quantity of received shipments)
    Expenses = expenses + sum (quantity * gross-price of received shipments)
    Remove all received shipments
```

E.2 Pricing decisions

In the ‘pricing decision’ sub-processes, the sellers of fuel (i.e., liquefaction plants, LNG terminals, and fuel suppliers) update their pricing strategy by simulating the effect of a variety of prices. Those sub-processes are equal to the sub-processes discussed in appendix B and thus are not discussed in further detail.

E.3 Vessel adjustment decisions

E.3.1 Refurbish vessel

In the ‘refurbish vessel’ sub-process, the vessels determine whether they need to replace their propulsion technology. The pseudo-code of this sub-process is as follows:

```
Ask all vessels:
  If random 365 == 0 and age > economic-lifetime :
    Available-technologies = all propulsion-technologies with vessel-class == class
     ↪ of vessel
    For all available-technologies:
      If technology != my-propulsion-technology of vessel:
        Initial-investment = refurbishment-expenses of technology

      Fuel-expenses = annual distance of vessel * fuel-consumption of technology *
     ↪ mean price of fuel of technology
      Expected-fines = percentage of shipping assignments where technology would
     ↪ exceed allowed emissions * mean number of executed shipping assignments per
     ↪ year * inspection-probability * fine
```

```
      Lost-cargo-expenses = capacity of vessel * lost-cargo-percentage of technology
     ↪ * costs-of-lost-cargo
      Annual-expenses = fuel-expenses + expected-fines + lost-cargo-expenses

      Present-expenses = sum of annual-expenses / (1 + discount-rate) ^ years from
     ↪ now, for years until vessel reaches technical-lifetime
      Present-expenses = present-expenses + initial-investment
      Risk-corrected-present-expenses = present-expenses / (percentage of ports (
     ↪ where the vessel can sail to) that offer technology's fuel) ^ risk-aversion
     ↪ of vessel
    My-propulsion-technology = one of available-technologies with highest risk-
     ↪ corrected-present-expenses
```

E.3.2 Replace vessel

In the 'replace vessel' sub-process, the vessels determine what technology they need to use in the new replacement vessel. The pseudo-code of this sub-process is as follows:

```
Ask all vessels:
  If random 365 == 0 and age > technical-lifetime :
    Age = 0
    Available-technologies = all propulsion-technologies with vessel-class == class
     ↪ of vessel
    For all available-technologies:
      Initial-investment = new-built-expenses of technology

      Fuel-expenses = annual distance of vessel * fuel-consumption of technology *
     ↪ mean price of fuel of technology
      Expected-fines = percentage of shipping assignments where technology would
     ↪ exceed allowed emissions * mean number of executed shipping assignments per
     ↪ year * inspection-probability * fine
      Lost-cargo-expenses = capacity of vessel * lost-cargo-percentage of technology
     ↪ * costs-of-lost-cargo
      Annual-expenses = fuel-expenses + expected-fines + lost-cargo-expenses

      Present-expenses = sum of annual-expenses / (1 + discount-rate) ^ years from
     ↪ now, for years until vessel reaches technical-lifetime
      Present-expenses = present-expenses + initial-investment
      Risk-corrected-present-expenses = present-expenses / (percentage of ports (
     ↪ where the vessel can sail to) that offer technology's fuel) ^ risk-aversion
     ↪ of vessel
    My-propulsion-technology = one of available-technologies with highest risk-
     ↪ corrected-present-expenses
```

Summary

Introduction Industrial systems supply a substantial part of the goods that we use in our daily lives: our groceries are supplied by the agri-food industry, the fuel for our cars by the petrochemical industry, and our cell phones by the electronics industry. Those industrial systems consists of autonomous companies that collectively produce the end-product that is used by us, consumers. All those companies perform a part of the total production process and thus have to supply (intermediate) goods to each other. As a consequence, the companies are connected and together make the industrial system an interconnected web of organisations and physical assets.

Each manufacturing company operates within and interacts with this web of organisations. Given the relative stability of this environment in the last decades, manufacturing companies have mainly focused on improving their efficiency with little attention for their environment's influence on their business decisions. However, in recent years, the industrial systems have become increasingly volatile. As a result, manufacturing companies need to enhance their resilience, to enable them to thrive in that volatile environment. Moreover, the increasing volatility strengthens the environment's influence on a company's decisions. Consequently, it becomes increasingly important that manufacturing companies account for those (indirect) effects of the environment when they assess their business decisions.

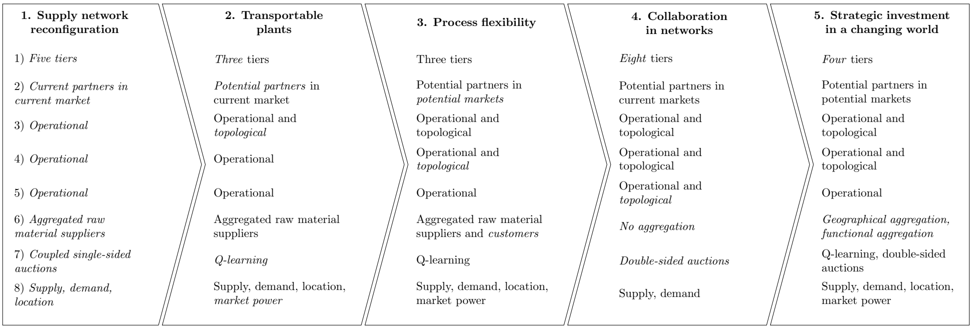
To assess the indirect effects of a business decision, the assessment needs to capture the mutual influence between the focal company and its environment, as well as the adaptation of that environment. This requires that the assessment uses a system perspective that includes the companies in the focal company's environment as well as their mutual interactions. Through such a perspective, the environment's complexity can be internalised into the assessment. The current assessment tools do not internalise this complexity, since they focus on the internal dynamics of the focal company. Therefore, we need to develop and structure a system perspective that can be used to assess the indirect effects of a business decision. The development of such a system perspective requires a conceptualisation of industrial systems that includes both the focal company, its environment, and their mutual interactions.

In this research, we sought to develop a new conceptualisation of an industrial system that can be used to assess both the direct and indirect effects of a business decision. With that new conceptualisation, we aimed to enable more comprehensive assessment of actions that can enhance a manufacturing company's resilience in an increasingly volatile world. The main research question addressed in this research was: *How can we conduct a more comprehensive assessment of a company's actions that can enhance its resilience?*

Foundations The first step of this research consisted of a literature review of the existing computer simulations that are used to support business decisions. Through this review, we aimed to identify the ability of those simulations to assess the indirect effects of business decisions. For a simulation to be able to assess those effects, it had to meet four requirements: *1*) measure the financial performance of the focal company; *2*) allow the volumes and prices of goods to adapt to developments in the system; *3*) include all potential suppliers, competitors, and potential customers of the focal company; *4*) enable all actors to adapt their behaviour autonomously; and *5*) allow the terms of a relation to be influenced by all parties directly connected through it. We found that 89% of the reviewed simulations primarily considered the focal company and therefore did not meet any of the requirements. Consequently, they could not assess the indirect effects of a business decision. Little over 10% of the simulations met a subset of the requirements. Even though they include some aspects of the focal company's environment, they could not assess a decision's indirect effects. There was only 1 out of 209 simulations that met all requirements and thus was able to assess the indirect effects. However, this simulation could not directly be used to assess a business decision for a specific company. We concluded that this would require generalisation of the used conceptualisation – in terms of the represented industrial system and behaviour – and the assessed business decision.

To get a thorough understanding of the focal company and its environment, which was needed to develop the new conceptualisation, we analysed industrial systems from a variety of perspectives: *1*) the socio-technical system (STS) perspective; *2*) the complex adaptive system (CAS) perspective; *3*) the networked markets perspective; and *4*) the competitive strategy perspective. The STS perspective showed that industrial systems consist of autonomous companies and facilities that are connected through supply contracts, collaborative agreements, and shipments of goods. The focal company is the company (and its facilities) for which the simulation is executed, while its environment involve all other companies and facilities in the system. Through the CAS perspective, we identified how the market interactions between companies give rise to supply contracts and shipments of goods. By considering an industrial system as a network of coupled markets, the networked markets perspective showed that the participation of companies in multiple markets coupled those markets. Through this network of markets, the prices an volumes of exchanged goods propagate through the system, which enables it to adapt. The competitive strategy perspective showed that the market interactions play a central role in the mutual influence between the focal company and its environment. A business decision of the focal company improves its operations, which influences the companies in the environment via improved product properties and/or increased production. This causes the companies to (directly) adapt their market behaviour or make structural changes that indirectly adapt their market behaviour. This adaptation subsequently influences the market interactions in the system, which then can change the prices and volumes of exchanged goods. Thereby, the environment influences the focal company's financial performance and the effects of the business decision.

Case studies The core of this research consisted of five case studies in which we developed simulation models that used a system perspective to assess resilience-enhancing business decisions. Following Nikolic (2009), each simulation model built



Dimensions of complexity used in the case studies

upon the experience gained in developing the previous models, iteratively increasing their complexity. This complexity evolved along eight different dimensions: *1*) the diameter of the industrial system; *2*) the possible market interactions; *3*) the types of changes caused by the focal company; *4*) the types of changes caused by the environment; *5*) the types of changes caused by market interactions; *6*) the detail of the environment's representation; *7*) the decision rules used to represent (inter)actions; and *8*) the features considered by companies in their decision-making. The figure below presents an overview of the complexity (indicated by the eight dimensions) of the different case studies.

An important objective of the case studies was to establish the ability of the used conceptualisations to assess the indirect effects of a business decision and how this influenced the outcomes of the assessment. In each case study, we observed that the assessed decision influenced the companies in the environment and caused them to adapt their behaviour. This gave rise to changed market interactions that led to substantially different market outcomes, in the form of higher prices, delayed price developments, decreased price differences, or decreased margins. By internalising the environment's complexity into the assessment, the assessment outcomes thus changed substantially. Thereby, the case studies demonstrated that, by account for the complexity in the insutrial system, the used conceptualisations could assess the indirect effects of a decision.

We found in all case studies that the indirect effects of the business decision changed the supply contracts of the focal company and thereby the assessment outcomes. For instance, in the second case study, the delayed price developments caused the focal company to get a lower price for its products over some period of time. This lower price had a direct effect on the company's net cash flows, and subsequently decreased the focal company's net present value by 4 %. By comparing the outcomes of an assessment with the indirect effects to the outcomes of an assessment without the indirect effects, we showed that the indirect effects of the decision caused the operating margin to increase with almost 50 %. So not only did the system perspective enable us to assess a decision's indirect effects, it also changed the assessment outcomes. The system perspective thus enabled a more comprehensive assessment of business decisions.

Synthesis The experiences of the case studies were used to develop our system perspective that can be used to comprehensively assess a company's actions. That perspective is centred around the notion that the comprehensive assessment of a focal company's action needs to include the industrial system that forms the company's environment. In that perspective, the environment is represented as a set of autonomous companies that are interacting to exchange goods with each other. Through those interactions, the prices and volumes of exchanged goods emerge. When the focal company implements an action, it changes its interactions with the companies in its environment. As those companies also interact amongst themselves, the changes caused by the focal company propagate through the environment, which thereby adapts to the focal company's action. The changed environment leads to changed prices and exchanged volumes throughout the system, which can influence the focal company's operational and financial performance.

Through our system perspective, the environment's complexity is internalised into a simulation model, which thereby can be used to assess an action's indirect effects. The level of internalised complexity is specified by eight dimensions: *1*) diameter of the industrial system; *2*) possible market interactions; *3*) types of changes caused by the focal company; *4*) types of changes caused by the environment; *5*) types of changes caused by market interactions; *6*) detail of the environment's representation; *7*) decision rules used to represent (inter)actions; and *8*) features considered by companies in their decision-making. Using those dimensions, the level of complexity internalised in a model can be chosen to align as well as possible with the problem for which the model is developed.

The answer to our research question on *how we can conduct a more comprehensive assessment of a companys actions that can enhance its resilience* had three elements: *1*) the used theoretical perspectives, *2*) the built models, and *3*) the developed system perspective. Those three elements built on each other to collectively address the main research question. With regard to the theoretical perspectives, we concluded that we needed four different theoretical perspectives that highlighted different aspects at different levels. Only by combining those perspectives, we were able to capture and understand the industrial systems' complexity. The built models enabled us to conclude that the internalisation of the environment's complexity enabled the assessment of action's indirect effects. Moreover, the experiments conducted with those models showed that those indirect effects had a substantial influence on the assessment outcomes. So, internalising the environment's complexity enabled a more comprehensive assessment of an action. Our system perspective described how the environment's complexity can be internalised in an assessment and thus formed the final element of our answer.

We identified two main directions in which future research can further develop our system perspective: explore and advance the perspective's application, and extend the captured complexity. This research focused on developing the perspective and demonstrate its use for a variety of actions. With those two objectives completed, the two direction of future research can advance the perspective to be applied more efficiently and effectively by companies. In that regard, we argued that companies – in order to face the increasing complexity in industrial systems – should internalise complexity in their assessments. We recommended companies to be aware of the complexity of developing models with our system perspective. The development of those models will require considerable time and resources, and is an iterative process that may not always directly lead to the desired outcomes. Therefore, we recommended companies to consider thoroughly whether they are ready as an organisation to develop highly complex models and whether they actually need such complex models. When this turns out to be the case, the system perspective presented in this thesis can be used to support business decisions that can enhance the company's resilience in the face of increasing volatile and complex industrial systems.

Curriculum vitae

Gerben Bas was born on February 8, 1988 in Dordrecht, the Netherlands. After completing his high school in 2006, he started his scientific education at Delft University of Technology. He finished his Bachelor's studies *Technische Bestuurskunde* in 2011 with a study of the costs and benefits of subsidising private home improvement for the Municipality of Rotterdam. Quickly thereafter, he completed his Master's studies *Systems Engineering, Policy Analysis, and Management* in 2012. In his MSc thesis, he presented an agent-based model of the natural gas trade in Europe that could be used to study the emergence of functioning natural gas wholesale markets. The choice for this subject – driven by his enthusiasm for agent-based models – deviated substantially from the specialisation in his Master's studies, which focused on land use and development.

In hindsight, the choice for that Msc thesis subject proved to be pivotal for his pursuits in the years that followed. Directly after graduating from Delft University of Technology, he started working at the Energy & Industry section of the Technology Policy and Management faculty in Delft. In his first year, he studied the concept of (physically) close collaboration among small-scale plants in the chemical industry through the modelling of an industry as a set of negotiating agents. The second year, he picked up his graduation topic and studied the interconnection of natural gas and electricity markets and infrastructures through agent-based models. Building on the successes of his first year, he spent his third and fourth year elaborating and formalising the concept of industrial networks as negotiating agents. In those years, he also began applying that perspective to the assessment of business decisions in general and assessing the additional insights that could be derived from including that complexity into those decisions.

Currently, he works as a technical consultant for Widget Brain where he focuses on data analysis, machine learning, and algorithm development to optimise and automate operational decisions. An up to date profile is available on `https://www.linkedin.com/in/gerbenbas`.

Gerben Bas

Resilient Industrial Systems

A Complex System Perspective to Support Business Decisions

Industrial systems increasingly need to become more resilient to developments in their environment. To take the right decisions and improve their resilience, those companies need insight into the effects of resilience-enhancing actions. A substantial part of those actions' effects follow from the adaptation of the focal company's environment in response to its actions. The current, predominantly inward focused, perspective used to assess actions cannot be used to capture those indirect effects of an action. Therefore, this thesis addresses how we can conduct a more comprehensive assessment of a company's actions that can enhance its resilience. This research develops and tests a novel combination of theoretical perspectives to execute such a comprehensive assessment. In five case studies, with increasing complexity along several variables, we develop simulation models to assess a variety of possible resilience-enhancing actions. The outcomes of the case studies indicate that our combination of theoretical perspectives, operationalized in our models, can indeed capture the indirect effects of the assessed actions, and that including those indirect effects substantially influences the performance of the focal company. With this approach, companies can assess their proposed actions more comprehensively, enabling them to take actions that improve their resilience to the increasing volatility in industrial systems.

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