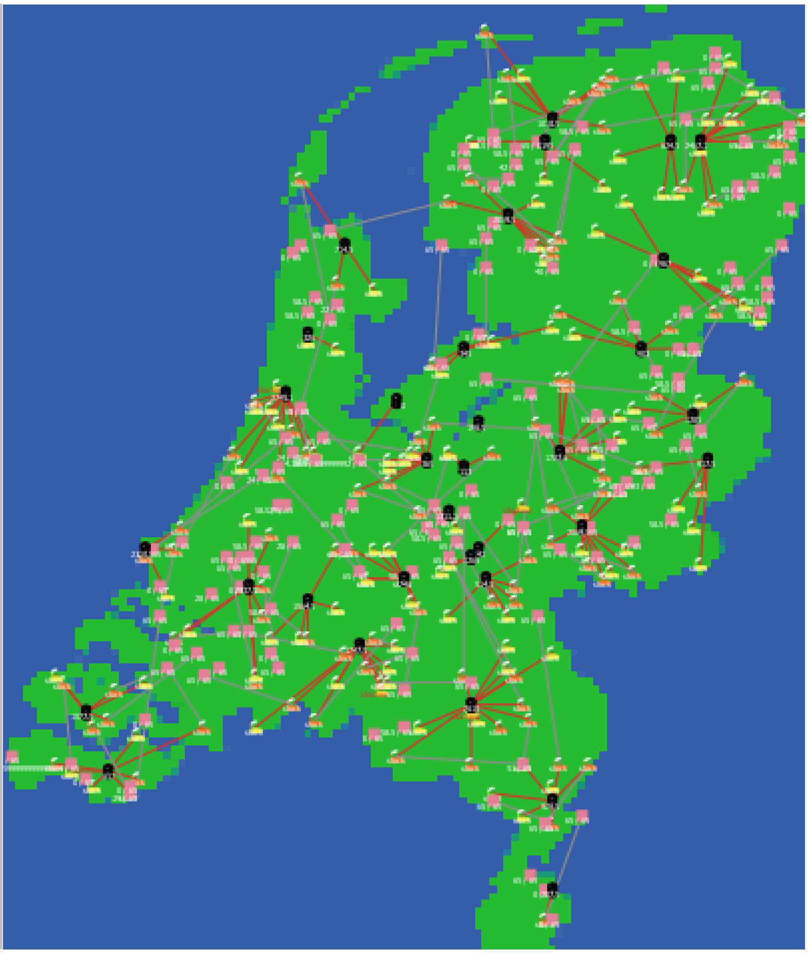
The effects of stocking configurations in industrial symbiotic networks

An agent-based simulation study



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BACHELOR THESIS INDUSTRIAL ENGINEERING AND MANAGEMENT

THE EFFECTS OF STOCKING CONFIGURATIONS IN INDUSTRIAL SYMBIOTIC NETWORKS

An agent-based simulation study

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i Foreword

Enschede, February 5th, 2019

Dear reader,

Before you lies my thesis report on the ‘effects of stocking configurations in industrial symbiotic networks’. These effects where studied using an Agent-based simulation model. This thesis is written to conclude my bachelors studies, Industrial Engineering and Management, at the University of Twente. I have started the earliest exploratory meetings that have led to this thesis in December 2017 and worked on the thesis until February 2019.

I would especially like to thank my supervisors, dr. Luca Fraccascia and Guido van Capelleveen, for introducing me to the concepts of industrial symbiosis and agent-based simulation, but also for pointing me in the right research directions, answering my many questions, and for patiently providing valuable feedback to both my approaches and reports throughout the entire project. It was very pleasant to work with these supervisors as they were always quick to respond and answered questions elaborately.

I would also very much like to thank dr. Devrim Yazan, for joining as a supervisor in September 2018, when this was required. His questioning during the meetings was always on point and made me review parts of the simulation model and reports, leading to more profound insights.

I hope you will find this proposal both enjoyable and informative, and invite you to keep me informed on any thoughts or suggestions.

Kind regards,

Wietse Harmsma

ii DEFINITIONS AND ABBREVIATIONS

BSG	Brewers Spent Grain
By-product	The term ‘by-product’ is used to describe a resource that is generated by manufacturers (type A) during production of the primary production as a by-product. In the model presented in this thesis, it is established that this by-product can be turned into a substitute resource for another manufacturer. In the case presented the by-product takes the form of brewers spent grain. The term ‘by-product’ is used throughout this thesis to describe this particular kind of resource, even if technically not a by-product of the agent that possesses the resource at that state in the model.
CO2e	‘Carbon di-oxide equivalent’, a quantity measure used to express emission of any (combination of) greenhouse gas in terms of how much global warming it may cause. Expressed as the functional equivalent amount of CO2.
EOQ	Economic Order Quantity
IS	Industrial symbiosis
KPI	Key Performance Indicator
Main product	The term ‘main product’ is used to describe the product which sales form the primary business of a manufacturing agent in the proposed model. In the case presented the main products of manufacturers of type A and type B are alcohol and compound-fertilizer respectively.
ROP	Reorder point
tkm	‘Tonne-kilometre’, a quantity measure used to express the quantity of transportation. 1 tkm is the equivalent of moving a 1-tonne payload over one kilometre.
Virgin resource	The term ‘virgin resource’ is used to describe a resource that is bought from a conventional supplier outside of the modelled network. This resource is assumed to not be previously used or consumed, or otherwise have been processed other than to its original production. The price of a virgin resource is considered to be higher than that of a by-product. In the case presented, the virgin resource is grain.

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1 CONTEXT DESCRIPTION

1.1 RESEARCH MOTIVATION

Industrial symbiosis (IS) is a subfield of industrial ecology that engages separate industries in a collective approach to competitive advantage, involving physical exchange of materials, energy, and services (M. R. Chertow, 2000). A symbiotic network is a network of companies that participate in Industrial symbiosis with each other. IS is considered a tool for production companies to guarantee profits, but also increase environmental sustainability (Jacobsen, 2008; Maillé & Frayret, 2016). The literature agrees that, while there is a number of successful examples of industrial symbiosis networks, most initiatives to start an IS network fail to succeed (Chiu & Yong, 2004; Walls & Paquin, 2015a).

A recent survey among manufacturing companies in Europe has shown that major considerations for companies to initiate in industrial symbiosis include the high initial investment cost and the equitable cost and benefit sharing, among others (Menato et al., 2017). These results are in line with a large number of studies that have argued economic incentives to be the primary driver for successful IS (V. Albino, Fraccascia, & Giannoccaro, 2016; Baas & Boons, 2004; M. R. Chertow, 2008; Ehrenfeld & Gertler, 1997; Gang, Xiao, & Chu, 2014; Lombardi & Laybourn, 2012; Paquin, Tilleman, & Howard-Grenville, 2014; Wang, Wang, & Song, 2018). Furthermore, this survey has shown that the involvement of an unbiased and fair third party in a symbiotic relationship would encourage companies to activate new symbiotic exchanges.

One potential solution that could answer to the economic issues, as well as some of the trust-related issues that prevent manufacturers from starting new IS initiatives, is to include warehouses in industrial symbiosis networks to stock by-products. These warehouses would limit the investment needed by the manufacturers and may govern the distribution of value. Furthermore, the inclusion of warehouses may be beneficial to whole IS network, as it offers the opportunity for 'inventory pooling' in which uncertainties in demand are mitigated by combining inventory at a central location and scale benefits are gotten (Eppen, 1979).

At first sight, this method is a potential solution to some of the current challenges of industrial symbiosis, but research is needed to quantify the potential of this method. This thesis investigates whether the inclusion of warehouses in IS networks is a viable means to stimulate industrial symbiosis.

This research is inspired by the SHAREBOX project, a digital platform that assists companies in the identification of suitable partners as well as to provide the means for secure sharing of the needed data. By providing such a platform, the SHAREBOX project attempts to stimulate the creation of new symbiotic links ("SHAREBOX – SECURE SHARING," 2018).

1.2 RESEARCH QUESTIONS

1.2.1 Research Question

To verify whether including stocking locations in an industrial symbiosis network is a potential means to improve the value proposition of such a network, the following research question is answered:

"What is the relation between (1a) the number of stocking locations and (1b) capacity of stocking locations and (2a) the profitability and (2b) environmental impact of an Industrial symbiosis network?"

1.2.2 Sub-questions

In order to answer this research question, a number of sub-questions need to be answered. Answering these questions will enable us to answer the research question.

a) How does the profitability of the network change if the number of stocking locations is altered?
b) How does the profitability of the network change if the capacity of the stocking locations is altered?
c) How does the amount of greenhouse gas emission of the network change if the number of stocking locations is altered?
d) How does the amount of greenhouse gas emission of the network change if the capacity of the stocking locations is altered?

1.3 Research approach

To answer the research question one would ideally study a number of existing IS networks with different warehouse-configurations and compare the performance of these networks on the selected KPI's, the profitability of the network and the amount of greenhouse gas emission. However, while there are a number of examples of successful and well-studied IS networks, including the Kalundborg symbiosis in Denmark, the Guayama symbiosis in Puerto Rico, the Styria symbiosis in Austria and the Kwinana symbiosis in Australia (M. Chertow & Ehrenfeld, 2012; Ehrenfeld & Gertler, 1997), there are no examples of IS networks that have embraced the pooling of inventory.

This is why an agent-based simulation model is used to study IS networks, as proposed by Albino et al. (2016), Batten (2009), Fraccascia & Yazan (2018), Ghali, Frayret, & Ahabchane (2017) and E. Romero & Ruiz (2014). Agent-based simulation is a simulation modeling technique in which individual agents are programmed to interact with each other and the simulation environment in order to reach a pre-defined goal. This use is advocated, as the fields of industrial symbiosis, complex systems and, therefore, agent-based simulation are closely related (Ashton, 2009; Batten, 2009; Elena Romero & Ruiz, 2013).

The framework used in this thesis to model the agents is that of the 'Enterprise Input-Output'-approach (Albino, Dietzenbacher, & Kühtz, 2003), in which manufacturers are represented as unknown entities that consume certain resources as an input to produce an output and generate waste in the process, following Albino et al., (2016) and Fraccascia (2018).

The conceptual model is presented in chapter 4.1, the experiment design is shown in chapter 4.2.

2 Context analysis

Prior to embarking on explaining the research methodology, in this chapter, we pay attention to the conceptual framework on which the thesis is founded. A complete literature review on a topic is generally very time-consuming (Webster & Watson, 2002). Given the large number of topics that this thesis touches, and the time constraints, we therefore primarily rely on directions given by authorities on the subjects and prior knowledge. The conceptual framework of this thesis includes the concepts of 'industrial symbiosis', 'behavior of symbiotic networks', '(agent-based) simulation' and 'warehouse aggregation'.

2.1 Industrial symbiosis

The concept of industrial symbiosis is an allegory drawn from the observation of natural ecosystems, applied to industrial networks, focused on the exchange of resources. A definition that covers the definition well is: "*Industrial symbiosis, a subfield of industrial ecology, engages traditionally separate industries and entities in a collaborative approach to resource sharing."* (M. Chertow & Park, 2016). The resources to be shared are primarily waste resources or by-products from production.

The concept has been around since the publishing of the article "Strategies for Manufacturing" (Frosch & Gallopoulos, 1989), around what time the industrial site of Kalundborg in Denmark was recognized as a symbiotic network. In recent years, IS has received much interest among both researchers and policy-makers. Researchers see it as a 'science of sustainability', whereas policymakers value its opportunity to combine environmental benefit, economic improvement, and local regeneration (Gibbs, 2008). However, the obvious benefits and some successes, many attempts to introduce industrial symbiosis in a network have failed to thrive (Walls & Paquin, 2015b).

2.2 Behavior of Industrial symbiosis networks

Networks of organizations that partake in industrial symbioses are named 'Industrial symbiosis networks'. As a consequence, such a network exists of, generally unrelated, organizations that exchange by-products. A symbiotic network, in its most limited form, therefore exists of two manufacturers, of which one produces a waste resource as a by-product of its production, which is exchanged to the other, which uses the resource as a raw material. Such an exchange could involve some payment, being either a 'waste disposal fee' from the supplying organization to the receiving organization or a 'purchasing price' paid by the receiving company to the supplier. Other costs, such as transportation cost and processing cost might arise. If there is a shortage of supply or demand of some waste resource this is called a 'mismatch'. Fraccascia & Yazan (2018) point to two known factors that cause a mismatch in a symbiotic relationship; being 1) the lack of either supplying or demanding firms of waste material and 2) the lack of information considering the existence of either demand or supply among the opposing party.

Boons, Chertow, Park, Spekkink, & Shi (2017) recently defined seven ways in which industrial symbiosis can manifest itself. Each of which is initiated by one of three actors; an industrial actor, a third-party organization or a governmental actor. They continue to identify conditions that trigger industrial symbiosis. These conditions are either technical, economic or geospatial of nature. However, it is sometimes suggested that industrial symbioses are in fact established over any proximity (Sterr, 2004).

2.3 AGENT-BASED SIMULATION

"*Simulation may be defined as a technique that imitates the operation of a real-world system as it evolves over time*" (Winston & Goldberg, 2004, p1145). Simulation models are either deterministic or stochastic. The former implying that the model contains no random variables. The latter implying that one or more random variables are present. Furthermore, a simulation is called "continuous" if the variables describing the state of the model change over time.

An 'agent-based simulation' or 'multi-agent simulation' refers to a specific kind of discrete simulation model, in which the model is composed of multiple computing elements, agent, are interacting (Wooldridge, 2009). Agent-based simulation has evolved from the concept of 'cellular automata'(Batten, 2009). 'Cellular automata' is a simulation concept which was created in the 1940s, but only emerged in the 1970s with 'Conway's Game of Life'. In 'cellular automata', there is a grid of cells, each cell being in one of a finite number of states. Cells change their state based on the state of the cells around it, following pre-defined rules (Kari, 2015).

Agent-based simulation emerged as computer systems became more powerful. Like in 'cellular automata', agents in an agent-based simulation interact with their environment and, using 'if-then' statements, make decisions on how to behave. Agents have a clearly defined goal and are autonomous in making decisions to reach this goal. Since the behavior of each agent is programmed at an agent-level, the 'bottom-up' approach, the collective result of an agent-based simulation during model development is open-ended (Fukuyama, Epstein, & Axtell, 1997; Grimm et al., 2005; Wooldridge, 2009).

Agent-based simulation is viewed as a useful tool for studying complex systems because such systems are most often not governed by a system-wide program, but rather by aggregation of individual behavior (Macy & Willer, 2002). Agent-based models have been developed in many different domains; including agriculture (Berger, 2001), ecology, healthcare (Segovia-Juarez, Ganguli, & Kirschner, 2004) and sociology (Macy & Willer, 2002).

2.4 INVENTORY POOLING

'Pooling' is a common term in inventory management that refers to the grouping of resources. In this case, the term refers to combining the inventory of by-product at a third-party storage-hubs (stocking location) in order to limit the total number of locations. The hypothesis of this thesis is founded on the known benefits of the pooling of inventory; the mitigation of demand variability, the decrease of transportation cost and the minimization of environmental consequences. Furthermore, methods of value allocation are discussed.

2.4.1 Mitigation of demand variability

A much recognized added value of centralization of inventory is that variability in demand per retailer is mitigated, which leads to a diminished safety-stock. This value is first recognized by Eppen (1979), for a multilocation newsvendor problem with the similarly distributed normal demand at every location. The magnitude of this value is depended on how identical and independently distributed the demand per supplier is (Eppen, 1979). This concept has since been generalized to any multivariate-dependent demand distribution (Corbett & Rajaram, 2006) and is also researched for dynamic arrivals (Benjaafar, Cooper, & Kim, 2005). It is generally agreed that a centralized system is optimal in most designs when demand is relatively certain, longer lead-times are acceptable or if customers are not easily becoming 'lost sales' in case of a stock-out (Anupindi & Bassok, 1999; Benjaafar et al., 2005; Berman, Krass, & Mahdi Tajbakhsh, 2011; Kurata, 2014; Schmitt, Sun, Snyder, & Shen, 2015). Dai, Fang, Ling, & Nuttle (2008) have shown that the costs of lost sales remain negatively correlated to the profitability of inventory pooling if decisions are not made independently, inventory control is conducted by the distribution centers, based on information of all retailers, which is confirmed in the simulation study of Qiu & Huang (2011).

2.4.2 Transportation cost

There have been multiple studies on the effects of inventory centralization on the transportation cost in a network, most of these offer calculation models.

Vidyarthi, Çelebi, Elhedhli, & Jewkes (2007) offer a model that considers capacity constraints. Ozsen, Coullard, & Daskin (2008) introduce the 'capacitated warehouse location model with risk pooling' (CLMRP), which is a location/allocation model to minimize the sum of fixed-facility location, transportation, and inventory cost, with the limitation that one retailer is always assigned to a single distribution center. This model is further developed by Al Dhaheri & Diabat (2010), to accommodate multiple products.

Note that, while such models are useful in real-time situations, they require significant computational power to be resolved, even when a Lagrangean relaxation is applied (Ozsen et al., 2008; Vidyarthi et al., 2007). This makes these models inherently unsuitable for a simulation study, in which the computations must be repeatedly performed for multiple actors.

2.4.3 Ecological benefits

The literature on ecological benefits of centralization of inventory is more limited, therefore a research synthesis is impossible. Yet, the paper of Arikan & Silbermayr (2017) gives an elaborate view on the ecological benefits of inventory pooling; It lists cases in which economic and ecological performance resolve so that profitable pooling reduces expected emissions. However, it is concluded that, while 'physical pooling' (centralization) is significantly more beneficial than virtual pooling economically, it is also significantly less beneficial in ecological performance. It is therefore stated that economic and environmental sustainability, solely from pooling, are more or less excluding each other.

2.4.4 Resource allocation

Since multiple actors, with different objectives, engage in the collaboration of inventory centralization, there needs to be a stable mechanism on how inventory and cost or profit is shared among these actors in order for a successful collaboration (Chen, 2009; Kemahlioğlu-Ziya & Bartholdi III, 2011; Oezen et al., 2012). Most researchers use game theory to analyze such scenarios. Kemahlioğlu-Ziya & Bartholdi III (2011) uses, "*one of the most celebrated*" (Karsten, Slikker, & Borm, 2017), 'Shapley-values' to extensively compare three policies a supplier might adapt to solve a single-period allocation problem if it owns the right of allocation. The study identifies Shapley values as a stable method of allocation value. Guajardo & Rönnqvist, (2015) also show that such a situation, with a centralized inventory plant planning, is stable, using the concept of core, from cooperative gaming theory and, too, consider Shapley values as a method to allocate the existing value, alternatively they mention a simple egalitarian assignment, assignment in proportion to the base-stock and 'nucleolus' (Schmeidler, 1969). Though the latter is deemed complex and often mistaken, and should, therefore, be avoided. Furthermore, the 'Equal Profit Method' is mentioned, following Frisk, Göthe-Lundgren, Jörnsten, & Rönnqvist (2010). Other alternatives to the use of Shapley values for fair allocation of value are offered by (Karsten et al., 2017); they propose the 'proportional rule', the 'serial rule' (Moulin & Shenker, 1992), a 'benefit-proportional rule', a 'concavicated increasing marginal rule' and a 'concavicated average marginal rule'.

3 SIMULATION MODEL

3.1 CONCEPTUAL MODEL

3.1.1 Agents

The model contains three types of agents, randomly spread across a geographic area; two or more manufacturers, an arbitrary number of warehouses and one or more landfills.

3.1.1.1 Manufacturers

A manufacturer is modeled as a black box using the 'Enterprise Input-Output' approach, so that it purchases and consumes resources (inputs) to produce main products and wastes (output). Manufacturers in this model are considered to produce only one main product, following Fraccascia et al. (2018). The model is further simplified to an extent that only one type of waste is considered, being the by-product of manufacturers of type A, which is also assumed to be a substitute for the sole virgin resource of manufacturers of type B. This simplification is justified, as other cost and emissions are not impacted by IS, so are not considered in this model. The daily amount of product produced and sold is simulated as a normally distributed stochastic value.

Manufacturer-agents keep an inventory of the resource, to be able to fulfill the demand of the next days. Manufacturers attempt to keep up the inventory level by ordering new resources if the inventory level is low. For more details on inventory ordering, see paragraph 4.1.2.1 'Ordering Inventory'.

An industrial symbiotic relation can be established in which manufacturers of type A are supplying by-product, while manufacturers of type B are purchasing the by-product, either directly from a manufacturer of type A or from a warehouse. Each manufacturer is assumed to be able to only concurrently establish two relationships, being the relationship with its nearest landfill and a single industrial symbiotic relationship with another agent.

3.1.1.2 Warehouses

Warehouses are optionally added to the symbiotic network. Regardless of its name, a 'warehouse' can represent different types of inventory locations, including warehouse(s), (grain-)silo(s), basin(s) or a container terminal. Warehouses will store by-product received from manufacturers of type A and redistribute the by-product to demanding manufacturers of type B or, if the maximum capacity of the warehouses is reached, the by-product is disposed at the nearest landfill. Multiple concurrent industrial symbiotic relations may be established between multiple manufacturers and a single warehouse.

Warehouses use a business model that is styled after the 'brokerage model'. In this model, the warehouses offer the service of mediating between manufacturers of type A, supplying the by-product, and manufacturers of type B, buying the by-product. For this service, warehouses receive a percentage of the price that is paid for the by-product. Therefore, if a by-product is not sold, the warehouse does not make any profit. However, all additional cost created by the warehouses, including the cost of storage and the cost of disposal of the received by-product for which there is no available storage space, are incurred to the supplying manufacturer.

Warehouse inventory is disposed of if the warehouse has a fill rate greater than its target fill rate, see also paragraph 4.1.2.5 'Paying disposal cost'

For simplicity, both maximum capacity and target fill rate are uniform for all warehouses in the network.

3.1.1.3 Landfills
One or more landfill-agents are present in the network to receive excess by-products of type A manufacturers. Excess can occur when warehouse capacities are exceeded, when the warehouse fill rate is higher than the target fill rate or when type A manufacturer is (temporarily) not in an industrial symbiotic relationship. The landfill-agent will store the received by-product until the simulation is terminated. When receiving a by-product, landfill-agents will incur disposal cost.

3.1.2 Model dynamics

3.1.2.1 Ordering inventory
A reorder point (ROP) is estimated for every manufacturing agent using Equation 1. This estimate is based on the safety stock, equal to the expected daily demand, and the expected demand during lead time.

$$ROP(manufacturer\ a) = (leadtime\ (days) + 1) * E(daily\ demand)_a * \delta \tag{1}$$

where 'δ' is the weight in tonnes of resources needed to produce one unit of main product.

If the inventory level of a manufacturer-agent drops below its ROP, and the manufacturer is not receiving by-product from an industrial symbiotic partner in a direct symbiotic relationship, new by-product or virgin resource is ordered. The order quantity (EOQ) is estimated as:

$$EOQ(manufacturer\ a) = (E(daily\ demand)_a + 2\sigma(daily\ demand)_a) * \delta \tag{2}$$

where 'δ' is the weight in tonnes of resources needed to produce one unit of main product and σ(daily demand) is the standard deviation of daily demand.

Given the normal-distribution of daily demand, the empirical rule is applied to assume that this quantity is sufficient in 97.5% of all cases of daily demand.

When no warehouses are present in the network, manufacturers of type B will either receive the complete amount of by-product generated by its industrial symbiotic partner or order all as a virgin resource at a conventional supplier outside of the Industrial symbiosis network.

If warehouses are present in the network, three situations might emerge. The manufacturer might order all resources at a conventional supplier, establish an industrial symbiotic relation with a warehouse to purchase all of the demanded resources at a warehouse, or purchase a share of the demanded resource at a warehouse and complement the order at a conventional supplier.

For each received resource, procurement costs are incurred, these costs are calculated using Equation 4.

$$Sales\ at\ day\ T\ (supplier\ a, buyer\ b) = Sales(a, b)$$

$$= \min(SupplyLimit, DemandLimit)$$

$$= \min(\begin{cases} 'Output\ of\ a' & if\ a \in A \\ 'Assigned\ share' & if\ a \in W \end{cases}, \begin{cases} 'resources\ demanded\ by\ b' & b \in B \\ 'available\ inventory' & b \in W \end{cases}) =$$

$$\min(\begin{cases} Demand_a * \gamma(a) & if\ a \in A \\ EOQ_b * \frac{\sum Input_a}{\sum Output_a + EOQ_b} & if\ a \in W \end{cases}, \begin{cases} Demand_b * \delta & b \in B \\ \min(\varepsilon * Capacity, \sum Input_b - \sum Output_b) & b \in W \end{cases})$$

(3)

with A and B are the sets of all manufacturers of type A and B respectively, W is the set of all warehouse-agents in the IS network, 'ϒ' the tonnes of by-product generated per tonne of main product produced, 'δ' the weight in tonnes of resources needed to produce one unit of main product and ε the objective fill rate of the warehouse. More insight in 'assigned share' is provided in paragraph 4.1.2.3.

So that;

$$Procurement\ cost\ of\ manufacturer\ b\ when\ in\ IS\ relation\ with\ agent\ a = c_{procurement}(a,b) = \begin{cases} EOQ * \delta * P_{virgin.res} & a \in \{nobody\} \\ (Sales(a,b) * P_{byproduct}) + (EOQ - Sales(a,b) * P_{virgin.res}), & a \in W \\ Demand_a * \gamma * P_{byproduct} & a \in A \end{cases} \tag{4}$$

where 'ϒ' the tonnes of by-product generated per tonne of main product produced, 'δ' the weight in tonnes of resources needed to produce one unit of main product, $P_{virgin.res}$ the price of a tonne of virgin resource bought at a conventional supplier, $P_{byproduct}$ the price of a tonne of by-product.

3.1.2.2 Stockouts

The demand that is observed by manufacturers is stochastically defined and therefore has a certain margin of uncertainty, the size of which is defined by the market dynamicity. While manufacturers take this uncertainty into account when calculating ROP and EOQ, there is a risk that the amount of resources needed to produce the observed demand at a certain day is greater than the inventory level of a manufacturer. This means the manufacturer is unable to produce the amount of main product needed to fulfill demand. In this case, a stockout occurs. During a stockout, all inventory of the affected manufacturer-agent is consumed to produce as much of the demand as possible. The remaining demand is considered to be lost; resulting in stockout cost for the manufacturer to be incurred. Therefore:

$$Stockoutcost\ at\ time\ t\ of\ manufacturer\ a = c_{stockout}(t)_a = \begin{cases} (D(t)_a - I(t)_a * \delta) * P_{stockout} & if\ (D(t)_a - I(t)_a * \gamma) < 0 \\ 0 & otherwise \end{cases} \tag{5}$$

where $D(t)_a$ is the demand at manufacturer a at time t in units , $I(t)_a$ the inventory of manufacturer a at time t in units, 'δ' the weight in tonnes of resources needed to produce one unit of main product and $P_{shortage}$ the cost of being one unit short.

Furthermore, as a stockout restricts the amount that a manufacturer is able to produce, it will also limit the output of by-product of this manufacturer. Therefore, if a manufacturer of type A is the supplying party in an IS relationship, a stockout at this manufacturer will often also cause a stockout at the receiving party of the IS relationship.

3.1.2.3 Assigned share

Once all orders are placed, inventory will be sent from warehouses to manufacturers. It may occur that aggregate demand for the by-product at a specific warehouse is greater than the available inventory at this warehouse on a specific moment. In such a case, each manufacturer is sending a share of the available inventory to the ratio of the ordered demand, see Equation 6.

$$Assigned\ Stock\ at\ day\ T\ (man\ \alpha) = min \begin{cases} Demand\ of\ Man. \alpha \\ (\frac{Demand\ of\ Man.\alpha \times Total\ Available\ Stock}{Aggregate\ demand\ at\ day\ T}) \end{cases} \quad (6)$$

3.1.2.4 Paying warehouse storage cost

At the end of each day, manufacturers of type A, that have supplied by-product to a warehouse, pay warehouse storage cost. These costs are calculated based on the weight of by-product stored at that warehouse, see Equation 7.

$$Cost\ for\ manufacturer\ a\ of\ storing\ byproduct\ at\ warehouse\ w =$$

$$c_{storage}(t)_a = \frac{Inventory(t)_w}{Capacity_w} * P_{storage} + P_{maintenance} \quad (7)$$

where $P_{storage}$ is the cost of storing one tonne of by-product for one day and $P_{maintenance}$ is the upkeep cost for one warehouse for one day.

3.1.2.5 Paying disposal cost

In a number of cases, the by-product is not processed but disposed of. Agents will always dispose of inventory at the nearest landfill. As manufacturers supplying the by-product wield any of the cost involved with the storage, sales, and risk of no sale, the costs that are incurred due to disposal are paid by the manufacturer that generated the by-product. The model considers the following cases:

- If a manufacturer of type A is not in an IS relationship, it will dispose of any by-product that is generated at the nearest landfill.
- Warehouses dispose of any inventory that is received while there is no more storage capacity. This is the case if the inventory level of the warehouse is equal to the capacity of the warehouse.
- At the end of each day, warehouses will clear part of the inventory if the inventory level is above the inventory level corresponding to the target fill-rate. This is to simulate the 'no-sales' scenario.
- At the end of a model run, all manufacturer- and warehouse-agents will dispose of any left inventory. This is so that an unbiased comparison can be made between runs where large amounts of inventory are kept and runs where little inventory is kept. This dynamic prevents model runs where inventory is permanently stored in a warehouse, to have a better performance because less inventory is disposed.

The disposal costs are computed with the following Equation:

$$Cost\ of\ disposal\ for\ manufacturer\ a =$$

$$c_{disposal}(t)_a = w_{disposed} * P_{disposal} \quad (7)$$

where T is the day for which disposal costs are calculated, $w_{disposed}$ the weight of by-product disposed of, directly by the manufacturer or by the warehouse that received the by-product, in tonnes and P the cost of disposing of one tonne of the resource.

3.1.2.6 Transportation

For every resource transported between agents in the Industrial symbiosis network, transportation cost and increased emission are incurred.

$$c_{transport}(t) = \sum_{a,b}\big(Dist(a,b) * Sales(a,b)\big) * 2P_{trans.var.} + \sum_{a,b} Dist(a,b) * P_{trans.fix.} \quad (8)$$

$$e_{transport}(t) = \sum_{a,b}\big(Dist(a,b) * Sales(a,b)\big) * 2E_{transport} \quad (9)$$

where T is the day for which transportation cost and emission are calculated, 'Dist(a,b)' is the distance between agents a and b, 'Sales(a,b)' is the weight of resources sold by agent a and bought by agent b in tonnes and '$P_{transport.var}$' is the variable cost of moving one tonne of the resource for one kilometer, '$P_{transport.fix}$' the fixed cost of moving any amount of resource for one kilometer and '$E_{transport}$' is the emission rate in CO2e of moving one tonne of the resource for one kilometer.

If disposing by-products, manufacturers will be taxed with the cost of transporting the by-product to the landfill, even if this by-product is moved through a warehouse. In a network without warehouses, manufacturers of type B are burdened with the transport cost of the by-product between the two manufacturers. In networks with warehouses, manufacturers of type B still pay for the transport of the by-product from a warehouse to its own location, but manufacturers of type A are burdened with the cost of transport to the warehouse.

3.1.2.7 Establishing industrial symbiotic relations

3.1.2.7.1 Without warehouses

If no warehouses are present in the industrial symbiosis network, manufacturers of type B will continuously attempt to establish direct IS relationships with manufacturers of type A. If the manufacturer of type B is already in an IS relationship, it will attempt to find more profitable IS relationships.

Every day, manufacturers of type B will select a random manufacturer of type A. The manufacturer of type B will then calculate the expected profitability of an IS relationship with the selected manufacturer, using Equation 13. If the manufacturer of type B is currently not in an IS relationship and the expected profitability is higher than the expected profitability without an IS relationship, calculated using Equation 11, an offer is sent to the selected manufacturer. If the manufacturer is currently in an IS relationship, the expected profitability is higher than the expected profitability of its current relationship, calculated using Equation 13, and the expected profitability is higher than the expected profitability without an IS relationship, calculated using Equation 11, an offer is also sent. If no offer is sent, the manufacturer will maintain its current situation.

Manufacturers of type A will value each offer they received, using Equation 12, and select the offer that is expected to be most profitable. If the offer is also expected to be more profitable than not being in an IS relationship, calculated using Equation 14, the offer is excepted and a, IS relationship between the two manufacturers is initiated.

If a new IS relationship is initiated, any previous IS relationships of both parties are terminated.

$$\begin{aligned} &E.profit(buy, without\ IS) \\ &= -('Expected\ resource\ cost' + 'Expected\ transport\ cost' + 'Expected\ shortage\ cost') \\ &= -((P_{virgin.res.} * E(Sales) + 0 + P_{shortage} * \ E(Shortage)) \\ &= -(P_{virgin.res.} * E(Sales) + 0 + P_{shortage} * \ L\left(\frac{EOQ - E(Demand)}{market\ dynamicity}\right)) \end{aligned} \tag{10}$$

with $P_{virgin.res}$ is the procurement price of one tonne of virgin resource, $P_{shortahe}$ is the cost of a shortage of one tonne of main product, 'market dynamicity' is the standard deviation of demand and L(z) is the density of normal loss function with z the standardized variate.

$$\begin{aligned} &E.profit(sell, without\ IS) = \\ &'Expected\ profit\ from\ sales' - \\ &\qquad ('Expected\ disposal\ cost' + 'Expected\ transportcost\ to\ landfill') \end{aligned}$$

$$= 0 - (('Expected\ byproduct\ generation * P_{disposal}) + (E(tonnekilometres\ of\ transport) * P_{transport}))$$
$$= -(('E(Demand) * \gamma * P_{disposal}) + E(Demand) * \gamma * 2Distance(self, nearest\ landfill) * P_{trans.var} + 2Distance(self, nearest\ landfill) * P_{trans.fix}) \quad (11)$$

with 'ϒ' being the tonnes of by-product generated per tonne of main product produced, $P_{disposal}$ the rate of disposing one tonne of waste at a landfill, $P_{trans.var}$ the average variable cost of transportation per tonne-kilometer and $P_{trans.fix}$ the average fixed cost of transportation per kilometer.

$$E.profit(buy, IS\ relation\ with\ manufacturer\ \alpha) = -('Expected\ resource\ cost' + 'Expected\ transport\ cost' + 'Expected\ shortage\ cost')$$
$$= -((P_{byproduct} * E(Sales) + E(Sales) * 2Distance(self, \text{man. } \alpha) * P_{trans.var} + 2Distance(self, nearest\ \text{man. } \alpha) * P_{trans.fix} + P_{shortage} * E(Shortage))$$
$$= -(P_{byproduct} * E(Sales) + 0 + P_{shortage} * L\left(\frac{EOQ - E(Demand)}{market\ dynamicity}\right)) \quad (12)$$

with $P_{byproduct}$ the price for which the by-product is sold to the manufacturer, $P_{trans.var}$ the average variable cost of transportation per tonne-kilometer and $P_{trans.fix}$ the average fixed cost of transportation per kilometer., $P_{shortahe}$ is the cost of a shortage of one tonne of main product, 'market dynamicity' is the standard deviation of demand and L(z) is the density of normal loss function with z the standardized variate.

$$E.profit(sell, IS\ relation\ with\ manufacturer\ \beta)$$
$$= 'Expected\ profit\ from\ sales' - ('Expected\ disposal\ cost' + 'Expected\ transportcost\ to\ landfill')$$
$$= (='Profit\ margin\ per\ sale' * E(Sales)) - (('Expected\ byproduct\ generation * P_{disposal}) + E(tonnekilometres\ of\ transport\ to\ landfill) * P_{transport}))$$
$$= \left(P_{byproduct} * E(Sales)\right) - ((('E(Demand) - \text{E(Sales)}) * \gamma * P_{disposal}) + (E(Demand) - \text{E(Sales)}) * \gamma * 2Distance(self, nearest\ landfill) * P_{trans.var} + 2Distance(self, nearest\ landfill) * P_{trans.fix}) \quad (13)$$

with 'ϒ' being the tonnes of by-product generated per tonne of main product produced, $P_{byproduct}$ the price for which the by-product is sold to the manufacturer, $P_{disposal}$ the rate of disposing one tonne of waste at a landfill, $P_{trans.var}$ the average variable cost of transportation per tonne-kilometer and $P_{trans.fix}$ the average fixed cost of transportation per kilometer.

3.1.2.7.2 With warehouses

In networks with warehouses, manufacturers of both types will select a random warehouse in the network and calculate the expected profitability of an IS relationship with this warehouse. In this case, direct IS relationships between manufacturers will not occur. If an IS relationship with this warehouse is expected to be more profitable than the current relationship the manufacturer is in and expected to be more profitable than no IS relation, an IS relation with this warehouse is initiated.

Notice that this translates to warehouses accepting any offer of any manufacturer. This is justified since it is always profitable for warehouses to be in an IS relationship. Due to the brokerage-model, any variable cost of storing the extra by-product is assumed to be incurred at the supplying manufacturer.

In such a network, manufacturers of type B and manufacturers of type A will also use Equation 11 and 12 respectively to calculate the expected profitability without an IS relationship and will use Equation 15 and 16 to calculate expected profitability with the prospected partner.

$$
\begin{aligned}
&E.profit(buy, IS\ relation\ with\ warehouse\ \alpha) = \\
&-('Expected\ resource\ cost' + 'Expected\ transport\ cost' + 'Expected\ shortage\ cost') \\
&= -((P_{byproduct} + P_{warehouse}) * E(Sales) + E(Sales) * 2Distance(self, \text{ware.}\,\alpha) * \\
&\quad P_{trans.var} + 2Distance(self, nearest\ \text{ware. } \alpha) * P_{trans.fix} + P_{shortage} * \\
&\quad E(Shortage)) \\
&= -((P_{byproduct.} + P_{wareprofit} + P_{warecost}) * E(Sales) + E(Sales) * \\
&\quad 2Distance(self, \text{ware.}\,\alpha) * P_{trans.var} + 2Distance(self, nearest\ \text{ware. } \alpha) * \\
&\quad P_{trans.fix} + P_{shortage} * L\left(\frac{EOQ - E(Demand)}{market\ dynamicity}\right))
\end{aligned} \tag{14}
$$

with $P_{byproduct}$ the price for which the by-product is sold to the manufacturer, $P_{warehouse}$ the aggregate price of storing one tonne of by-product at a warehouse, $P_{wareprofit}$ the amount of profit taken per tonne of by-product stored at a warehouse, $P_{warecost}$ the cost beared by a warehouse to store one tonne of byproduct, $P_{trans.var}$ the average variable cost of transportation per tonne-kilometer and $P_{trans.fix}$ the average fixed cost of transportation per kilometer., $P_{shortahe}$ is the cost of a shortage of one tonne of main product, 'market dynamicity' is the standard deviation of demand and L(z) is the density of normal loss function with z the standardized variate.

$$
\begin{aligned}
&E.profit(sell, IS\ relation\ with\ warehouse\ \alpha) \\
&= 'Expected\ profit\ from\ sales' \\
&\qquad - ('Expected\ disposal\ cost' + 'Expected\ transportcost\ to\ landfill') \\
&= 'Profit\ margin\ per\ sale' * E(Sales)) - (('Expected\ byproduct\ generation * P_{disposal}) + \\
&\quad (E(tonnekilometres\ of\ transport\ to\ warehouse) * P_{transport} + \\
&\quad E(tonnekilometres\ of\ transport\ to\ landfill) * P_{transport})) \\
&= \left((P_{byproduct} - P_{ware.}) * E(Sales)\right) - ((('E(Demand) - \text{E(Sales)}) * \gamma * P_{disposal}) + \\
&\quad E(Sales) * \gamma * 2Distance(self, \text{ware.}\,\alpha) * P_{trans.var} + 2Distance(self, ware.\,\alpha) * \\
&\quad P_{trans.fix} + (E(Demand) - \text{E(Sales)}) * \gamma * 2Distance(self, nearest\ landfill) * \\
&\quad P_{trans.var} + 2Distance(self, nearest\ landfill) * P_{trans.fix})
\end{aligned} \tag{15}
$$

with 'ϒ' being the tonnes of by-product generated per tonne of main product produced, $P_{byproduct}$ the price for which the by-product is sold to the manufacturer, $P_{ware.}$ the rate of the warehouse for intermediating the transaction, $P_{disposal}$ the rate of disposing one tonne of waste at a landfill, $P_{trans.var}$ the average variable cost of transportation per tonne-kilometer and $P_{trans.fix}$ the average fixed cost of transportation per kilometer.

3.1.3 Performance Indicators

This thesis builds on the assumption that economic incentives are a precondition for a successful IS network. It, therefore, aims to verify the viability of a solution that might increases the profitability of an Industrial symbiosis network while also limiting the environmental consequences of implementing this solution. Therefore, the key performance indicators are network profitability and the increase in emission due to symbiosis. In order to conclude whether a symbiotic network is beneficial to reducing greenhouse gas emission, the increase in emission should be compared to the emission that is saved due to the decrease in produced and transported virgin resource. The network profitability and the increase in emission due to industrial symbiosis are computed using Equations 17 and 18.

$$Network\ profitability = \sum_{t=1}^{365}\left(w_{main}(t) * P_{main} - c_{procurement}(t) - c_{disposal}(t) - c_{stockout}(t) - c_{storage}(t) - c_{transport}(t)\right) \quad (16)$$

$$Increase\ in\ emission = \sum_{t=1}^{365}(e_{transport}(t) + e_{storage}(t)) \quad (17)$$

The other indicators in the proposed model are the number of stockouts, the average number of established symbiotic relations and the total weight of by-product traded are reported. These indicators are added to be able to assess the key performance indicators and follow directly from the simulation.

3.2 EXPERIMENT CASE

3.2.1 Simulation model

The conceptual model is implemented into a simulation model using NetLogo 6.0.3 (Wilensky, 2018). Simulations with and without warehouses follow the flowcharts found in Appendix A and Appendix B respectively. The code used in the experiment is shown in Appendix C. The design decisions on the geographical area and processing order are especially notable.

3.2.1.1 Geographical area

The world of the simulation model consists of tiles of two categories: ‘land’-tiles and ‘not land’-tiles, the latter consist of ‘water’-tiles and ‘other’-tiles. Agents can only exist on ‘land’-tiles. We assume there are no manufacturers or warehouses on ‘water’-tiles. This model is therefore not suitable for simulating IS networks that include oil-rigs or ships, given their unique nature.

When calculating the distances between the various agents, the model will use Euclidean distances. Practical restrictions like the need for roads or not being able to transport resources through ‘water’-tiles are relaxed for simplicity purposes and to limit the needed computing power.

In the experiment, a simplified version of a map of the Netherlands is used to distribute the tiles. See Appendix D for this world’s design.

3.2.1.2 Processing order

Whereas real-world scenarios are assumed to occur at random in a continuous and parallel environment, NetLogo is a “simulated parallel” environment, meaning that true parallel computing is not supported and the simulation operates deterministically. This means that if a function calls multiple agents simultaneously, the processing order is set deterministically (Tisue & Wilensky, 2004). Furthermore, parallelism is reduced due to the way the code is built. The simulation is set to follow a specific pattern; each repetition represents the time period of a single day. Each repetition, the functions, ‘order-inv’, ‘supply-demand’, ‘Evaluate_existing_relations’, ‘Evaluate_pending_offers’, ‘Offer_Partnership’, ‘Clear_inventory’ and ‘Update_Values’, are processed in series. While processing a function, the applicable sets of agents are processed in the order; manufacturers, warehouses, landfills. If there is a need to further separate the agent set of manufacturers, manufacturers of type A will be called before manufacturers of type B.

While such a fixed processing order does not represent a real-life scenario, the time period of a single day is assumed to be small enough for the effects of this limitation to be neglectable. A similar study has used larger time periods (Fraccascia, 2018).

3.2.2 Case description

The hypotheses are tested for a hypothetical IS network in the Netherlands in which manufacturers of type A produce alcohol and the manufacturers of type B produce compound-fertilizer. The symbiotic process of using Brewers Spent Grain (BSG), a by-product of the production of alcohol from sugar molasses, to fuel fertilizer production, has been studied in a case study by Yang & Feng (2008).

3.2.2.1 Input data

To simulate this network, data from a variety of sources is put in the simulation model. An overview of the data used is found in Table 1. As this model describes a hypothetical network, there is a number of parameters of which the values cannot be estimated due to a lack of precedent cases. The sensitivity of these parameters, the price of by-product, resource storage cost and warehouse profit margin, on the key performance indicators is tested in a sensitivity analysis. The input values for these parameters are therefore varying in a reasonable range.

Table 1 Input data on ethanol and fertilizer producers, with '-' is not applicable.

	Alcohol production	**Fertilizer production**	**Warehouses**
Number of agents[1]	101	97	{5, 25, 45, 65, 85, 105}
Average demand per manufacturer[2]	10000 t / year	20000 t / year	-
Standard deviation of demand	{100,200,500}	{200,400,1000}	-
Input resource[3]	-	(Brewers') grain	-
Resource price (virgin resource)[4]	-	€ **70** /t	-
Resource price (by-product)	-	{€0/t, €3.5/t, €7/t, €10.5/t, €14/t, €17.5/t}	-
By-product production[5]	0.8 $t_{brewers\ spent\ grain}$ / $t_{alcohol}$	-	-
Resource required[5]	-	0.4 $t_{brewers\ spent\ grain}$ / $t_{fertilizer}$	-
Resource order cost	-	€ 0 /t	-
Transport emission[6]	0.259 kgCO2e /tkm	0.259 kgCO2e /tkm	-
Fixed transport cost[6]	€ 0.27 /km	€ 0.27 /km	-
Variable transport cost[6]	€ 0.1095 /tkm	€ 0.1095 /tkm	-
Cost of stockout (per tonne short)	€ 0 /t	€ 0 /t	-
Yield of main product[4]	€ 350 /t	€ 350 /t	-

[1] KvK Open data, SBI 20149 and 2015 respectively, 45% of Producers of Organic chemicals, via: RIVM briefrapport 609021123/2012 'De keten van oplosmiddelen in kaart' in 2011, calculated to be 56,25% of all producers
[2] Fraccascia (2018)
[3] Yang & Feng (2008)
[4] Agrimatie, University of Wageningen
[5] Fraccascia (2018)
[6] See paragraph Transport emission
[7] See paragraph Transport cost
[8] See paragraph Storage

Disposal cost	€ 30 /t	-	-
Resource storage emission[7]	-	-	0 kgCO2e/t
Resource storage cost[7]	-	-	{€ 2.45/ t, € 4.9/ t , €7.35/ t }
Warehouse profit margin	-	-	{€ 2.45/ t, € 4.9/ t, €7.35/ t}
Lead times of outside suppliers	-	2 days	-
Lead times between agents	1 day	1 day	1 day
Capacity	-	-	{5t, 20t, 35t, 50t, 65t}
Target fill-rate	-	-	90%

3.2.2.1.1 Transport cost

For low-margin products such as the brewers spent grains in the example case, transportation cost can play an important part when determining whether a symbiotic relationship can be profitable. Research has repeatedly that the transportation cost of a biomass, such as brewers spent grains, depends on three factors (Gold & Seuring, 2011), namely 'travel time', 'mass and volume', 'capacity of carrier', 'labour cost', 'cost of vehicle and fuel' and 'environmental and social burdens. '

3.2.2.1.1.1 Travel time

An average speed of 60 km/h is assumed, following Yazan et al. (2016).

3.2.2.1.1.2 Mass and volume

By multiplying the average daily demand by the waste generation factor, 8 tonnes is found to be the average amount of by-product generated by each alcohol producer. It is read in the 'Handboek Melkveehouderij 2014' (Remmelink, van Middelkoop, Ouweltjes, & Wemmenhove, 2014) that the density of brewers spent grains averages around 225 kg/m^3, so that the average supply of each alcohol producer is determined to have a volume of around 35, 56 m^3.

Likewise, the average demand for fertilizer producers is found to be also around 8 tonnes and determined to have the same average volume of around 35,56 m^3. '

It is assumed that, while in a symbiotic relationship, neither the alcohol nor the fertilizer producers will keep inventory. Therefore, the maximum amount of by-product ordered will equal to the economic order quantity, set to be the sum of the average demand intensity and twice the standard deviation and the supply of by-product produced by the manufacturer is picked from a normal distribution where the mean is the average demand and the standard deviation is varying per assumed market dynamicity. Given a respective market dynamicity of 0.1, 0.2 and 0.5, this would result in a maximum weight of by-product transported of 9.6t, 11.2t, and 16t. And the supply is calculated using Equation

$$w_{byproduct} = \gamma * \varphi(\mu_{demand}, \sigma_{demand}) \tag{18}$$

Using this equation, the chance of a supply exceeding the 20 tonnes loading-limit for medium-weight trucks is calculated.

Table 2 Probabilities of supply exceeding truck capacity for individual alcohol manufacturer

Market dynamicity	$P(0.8 * \varphi(10t, market\ dyn. * 10t) < 10t$	$P(0.8 * \varphi(10t, market\ dyn * 10t) < 20t$
0.1	0.006	0
0.2	0.106	0
0.5	0.309	0.001

3.2.2.1.1.3 Capacity of the carriers

Using the classification model following the Task Force on Transportation (Klein et al., 2016), CE Delft ('t Hoen, den Boer, & Otten, 2017) and CBS (2018), semi-trailers are classified based on their loading capacity. Semi-trailers with a loading capacity of <10t are classified as lightweight semi-trailers, 10t-20t as medium-weight semi-trailers and >20t as heavy semi-trailers.

In the calculations on mass and volume it is shown that the load in most cases may pass the 10t-limit, but rarely passes the 20t-limit. We, therefore, assume that in all cases a medium-weight semi-trailer for distribution is used to move by-product between agents.

3.2.2.1.1.4 Labor cost

The labor cost of a self-employed truck driver in the Netherlands range about €2000,- per month (mijnzzp.nl, n.d.). The Dutch collective labor agreement for 2019 in the transport sector, prescribes a drivers salary per month or for 174 hours (CNV Vakmensen, FNV, Transport en Logistiek Nederland, De Unie, & Vereniging Verticaal Transport, 2017). Therefore, the proposed case assumes an average rate of €11.50 per hour and assumes an average driving speed of 60 km/h. Therefore labor cost is assumed to be €0.19 per kilometer.

3.2.2.1.1.5 Cost of vehicles and fuel

To calculate the replacement cost of a medium-heavy distribution semi-trailer, equation 20 was applied to 32 observation of real-time online offers of occasion VOLVO FL 240, a typical distribution trailer seen in the Netherlands. Note that trucks with a mileage of more than 500.000 km are excluded as it is a widely excepted rule of thumb that commercial semi-trailer trucks last for 500.000 km. The rest value of a VOLVO FL 240 with a mileage of 500.000 km is estimated to be €12.000. Based on the results, the replacement costs are assumed to be €0.06 per kilometer.

$$replacement\ cost\ per\ km = \frac{Purchase\ Cost - €12000}{500000\ km - \ advertised\ milage} \tag{19}$$

Fuel consumption is derived from dividing the energy-usage per tonne-kilometer as stated by CE Delft ('t Hoen et al., 2017) by the energy density of standard diesel oil (35.86 MJ/L). With an average energy usage of 2.8 MJ/tkm ('t Hoen et al., 2017) average diesel consumption is estimated to be 2.8/35.86 = 0.0781 L/tkm. In November 2018 average fuel prices for Diesel at Shell in the Netherlands are set around €1.402/L ("Historisch prijzenoverzicht | Shell Nederland," n.d.). So that the estimated costs for fuel in this model are set at 0.0781 * €1.402 = €0.1095 /tkm.

3.2.2.1.1.6 Environmental and social burdens

Both regular and heavy-truck road tax is to be paid for using trucks on Dutch highways. Likewise, a party is obliged to be insured. Depending on the situation, these costs may fluctuate between 2000 to 7000 euros. However, since we are only interested in the price per kilometer and we assume one truck to drive 174 hours per month at a speed of 60 kilometers per hour, resulting in 125.280 kilometers per year, these costs are negligible.

3.2.2.1.2 Transport Emission
Emission per kilometer is calculated via the principle of 'well-to-tank' ('t Hoen et al., 2017), meaning the allocated emission includes both direct emission due to diesel consumption as well as all environmental effects caused by the production of the fuel. Transport emission is set to 259g/tkm, following 't Hoen et al. (2017)

3.2.2.1.3 Storage
In the presented case, the 'warehouses' is assumed to be a concrete or asphalt covered surface on which the BSG is piled and covered in plastic or put in silage bags (ALLEN, STEVENSON, & BUCHANAN-SMITH, 1975; Johnson, Huber, & King, 1987; Matthiesen, Wagner, & Büscher, 2006).

Loss of matter due to mold or seepage are common issues with BSG. However, the average throughput time of the by-product in the presented model is no more than 3 days. Regardless of the silage method, loss of material can be prevented for at least 3 days (Allen & Stevenson, 1975), these costs are therefore considered to be neglectable.

Furthermore, while some initial investment is needed to place the concrete or asphalt surface, these pads are very durable and need almost no maintenance (Koons & Agri-King, 2000). Maintenance costs are therefore also regarded neglectable.

The remaining costs primarily consist of the cost of silage bags, handling, and chemicals for preparation. These costs are very situational, which is why a range of values is experimented with.

4 RESULTS

4.1 PERFORMANCE INDICATORS
The parameters 'warehouse capacity' and 'number of warehouses' relate directly to the research question.

In this chapter, we discuss the sensitivity of these parameters and the linear trend of the average results per input value.

4.1.1 Warehouse capacity

4.1.1.1 Network profitability
Figure 1 visualizes how the resulting network profitability and increase in emission develop as the capacity of the warehouses increases. It is observed that as the capacity of the warehouses increases, the kurtosis of the result for network profitability is decreasing.

Furthermore, increasing the capacity of the warehouses has a positive effect on the average network profitability. To add to this, the results, presented in Appendix F, show that also the amount of by-product that is traded increases substantially, as the capacity of the warehouses increases. Also, the p values, given in Table 3, all show values that are in the critical area.

So, the null hypothesis is rejected; the distributions for network profitability are assumed to be significantly different and increasing the capacity of the warehouses seems to be beneficial to the profitability of the network.

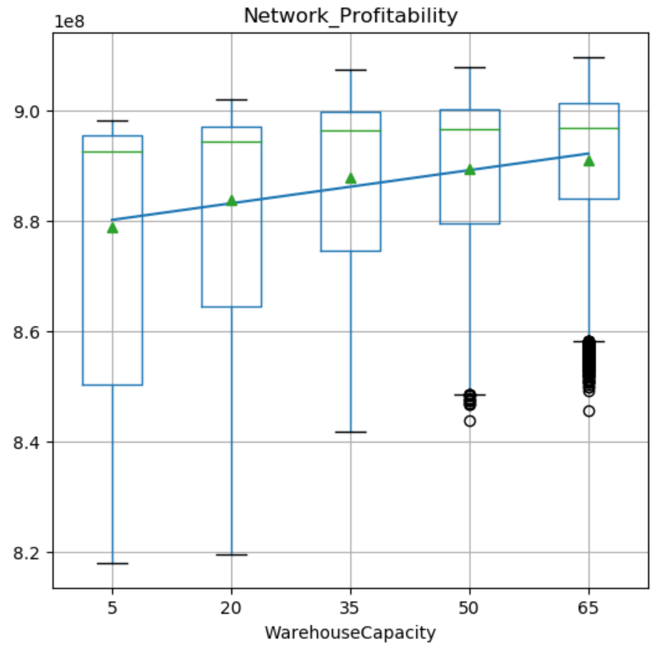

Figure 1 Boxplot results on network profitability in relation to the number of warehouses mean depicted as a triangle, linear regression line drawn through means.

P values (Warehouse capacity, network profitability) *lin. coefficient ≈ 203460 (X < Y)*

Table 3 p values of Mann-Whitney u test for network profitability in relation to warehouse capacity in tonnes.

X\Y	20t	35t	50t	65t
5t	8.26E-223	0	0	0
20t		1.98E-115	1.04E-284	0
35t			1.70E-71	6.85E-165
50t				1.07E-33

4.1.1.2 Changes in emission

Figure 2 shows how the distribution of increases in emission develops. It is observed that both the mean and median increase substantially as the capacity of the warehouses increase. Furthermore, the kurtosis is increasing at a high rate. But, as the capacity increases the initial skewness of the distribution mitigates. The distribution that relates to a capacity of 65 tonnes is almost symmetrical as it has a skewness of -0.04.

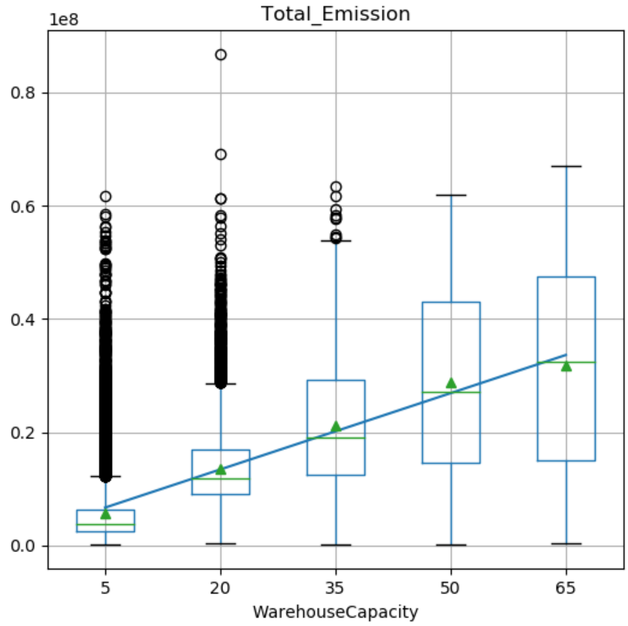

Figure 2 Boxplot results on increase in emission in relation to the number of warehouses, mean depicted as a triangle, linear regression line drawn through means.

The respective increase in kgCO2e per tonne of weight product traded for the number of warehouses = 5, 25, 45, 65, 85 and 105 is found by dividing the results averages of increase in emission by the weight of by-product traded, found in Appendix F. The results are found in Table 4.

Table 4 Respective increase in greenhouse gas emission in relation to tonnes of by-product traded

Warehouse capacity	5t	20t	35t	50t	65t
kgCO2e/t by-product	1932.7	321.0	254.1	251.4	241.3

The p values that correspond to these results, found in Table 5, are all below the critical value of 0.05. Therefore, the null hypothesis is assumed to be dismissed. The distributions are assumed to be different and the parameter of warehouse capacity is, therefore, a defining parameter in the model for the presented case to predict increases in emission.

P values (Warehouse capacity, increased emission) *lin. coefficient ≈ 453435 (X < Y)*

Table 5 p values of Mann-Whitney u test for the increase in emission in relation to warehouse capacity in tonnes.

X\Y	20t	35t	50t	65t
5t	1.49E-219	8.07E-58	0	0
20t		0	0	0
35t			0	0
50t				1.78E-124

4.1.2 Number of warehouses

4.1.2.1 Network profitability

Similar to the capacity of the warehouses, the number of warehouses also shows a positive effect on the profitability of the network and the amount of by-product that is traded, as is shown in Figure 3 and Appendix F. Furthermore, the kurtosis is decreasing as the number of warehouses is increasing.

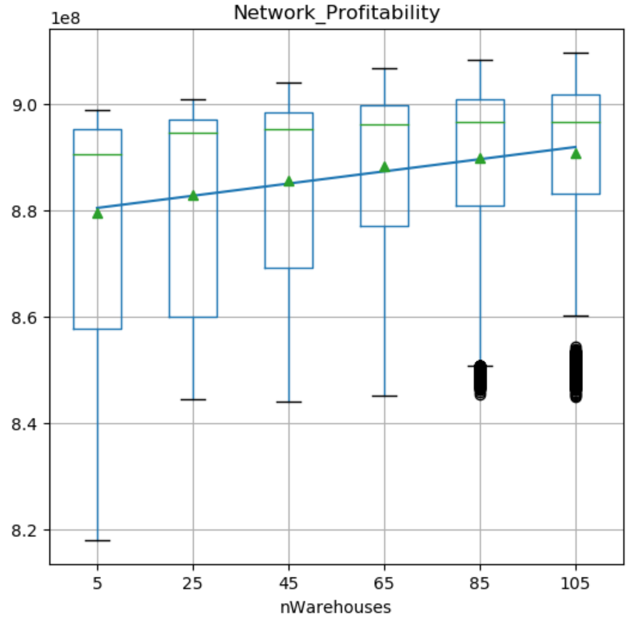

Figure 3 Boxplot results on network profitability in relation to the number of warehouses, mean depicted as a triangle, linear regression line drawn through means.

The p values, found in Table 6, suggest a significant difference in the distributions, which will be assumed.

P values (nWarehouses, network profitability) *lin. coefficient ≈ 115130 (X < Y)*

Table 6 p values of Mann-Whitney u test for the increase in network profitability in relation to warehouse capacity in tonnes.

X\Y	25	45	65	85	105
5	8.26E-223	0	0	0	0
25		1.98E-115	1.04E-284	0	0
45			1.70E-71	6.85E-165	2.69E-211
65				1.07E-33	1.03E-69
85					1.56E-11

4.1.2.2 Changes in emission

The results, visualized in Figure 4, show that an increase in emission does not necessarily relate to the number of warehouses in a linear fashion. We observe that, during the experiment, the results are initially decreasing when more warehouses are added to the network. The mean, median and upper quartile are lowest when the number of warehouses is 25. After the number of warehouses increases further from 25, the weight of distribution follows a positive trend.

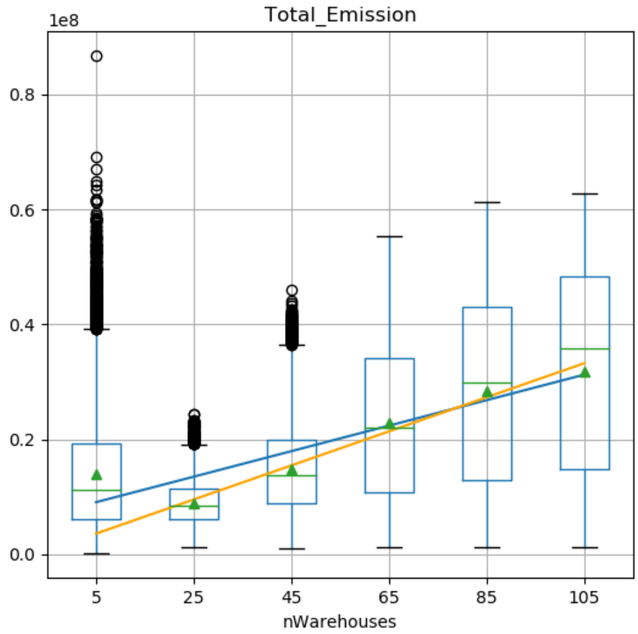

Figure 4 Boxplot results on increase in emission in relation to the number of warehouses, mean depicted as triangle, linear regression line drawn through means. Orange line for regression without nWarehouses = 5.

The respective increase in kgCO2e per tonne of weight product traded for the number of warehouses = 5, 25, 45, 65, 85 and 105 is found by dividing the results averages of increase in emission by the weight of by-product traded, found in Appendix F. The results are found in Table 7.

Table 7 Increase in emission per tonne by-product in relation to the number of warehouses.

nWarehouses	5	25	45	65	85	105
kgCO2e/t by-product	817.4	320.0	243.9	239.7	242.2	244.8

The p values, found in Table 8, indicate a significant difference in distributions for all combinations of input values.

P values (nWarehouses, increased emission) *lin. coefficient ≈ 227935 (X < Y)*

Table 8 p values of Mann-Whitney u test for the increase in emission in relation to warehouse capacity in tonnes.

X\Y	25	45	65	85	105
5	8.26E-223	0	0	0	0
25		1.98E-115	1.04E-284	0	0
45			1.70E-71	6.85E-165	2.69E-211
65				1.07E-33	1.03E-69
85					1.56E-11

4.2 Sensitivity analysis

The basic descriptive statistics of individual parameters in relation to a KPI are shown in Appendix F.

The variable input values other than the number of warehouses and warehouse capacity do not relate directly to the research question. Therefore, we decide on whether it is needed to take any of the other variable parameters into account. To achieve this, the Mann-Whitney U test was applied in order to find whether a change in any of these parameters results in a significant change in the experiment scores on performance indicators. The test size α_0 is set to 0.05.

The null-hypothesis for any Mann-Whitney u test is that both series of input values have a similar distribution. The alternative hypothesis is that the series face a different distribution. As we are interested in any significant effect, positive or negative, the two-tailed test will be used.

4.2.1 Cost of by-product

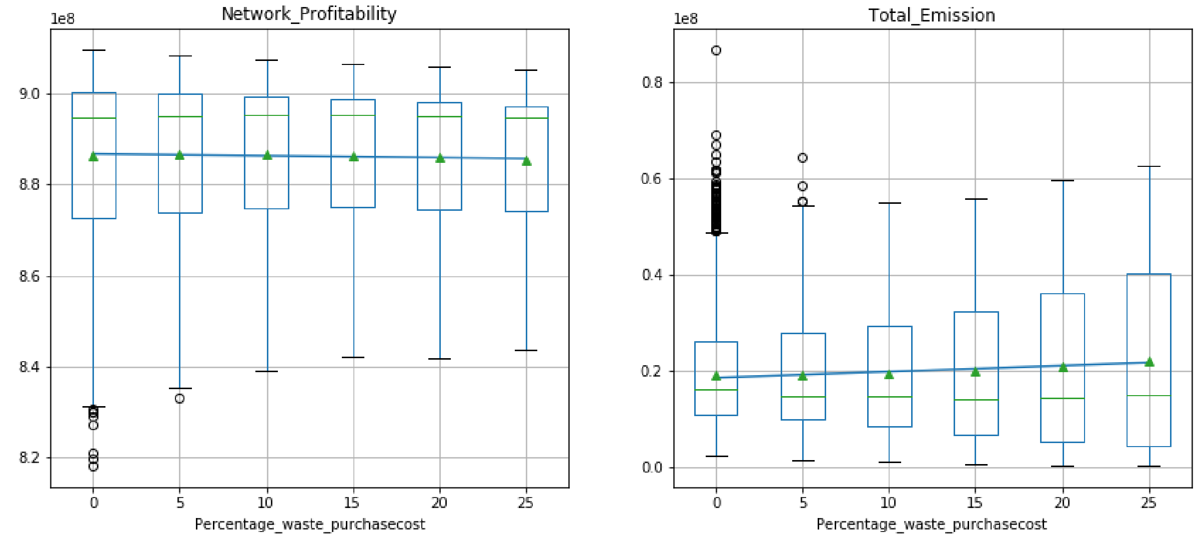

Figure 5 Boxplot results on network profitability (left) and increase in emission (right) in relation to cost of by-product as a percentage of the cost of a virgin resource, mean depicted as triangle, linear regression line drawn through means.

The descriptive statistics of both network profitability and the increase in emission in relation to the input value for the cost of by-product are visualized in Figure 5.

It is observed that as the cost of by-product increases, the kurtosis of the distribution of network profitability also increases. Furthermore, as the cost of by-product increase, the distribution is more skewed towards higher values of network profitability. The respective p values, resulting from the Mann-Whitney u test, are mostly higher than the critical value of 0.05. These p values are found in Table 9. Exceptions are the tests for the cost of by-product of 0% and 5% of the virgin resource and for 5% and 10% of the virgin resource. Since most p values are below the predefined critical value, we regard the null-hypothesis dismissed, meaning that the resulting network profitability is taken as significantly different as the input values for cost of by-product change. Therefore, the parameter 'cost of by-product' has to be taken into account when predicting network profitability in this and similar cases.

P values (Cost of by-product, network profitability) *lin. coefficient ≈ 114459 (X < Y)*

Table 9 p values of Mann-Whitney u test for network profitability in relation to the cost of by-product, expressed as a percentage of the cost of virgin resource.

X\Y	5%	10%	15%	20%	25%
0%	0.612367	0.037825	1.33E-06	1.10E-17	3.66E-40
5%		0.082642	1.66E-06	9.50E-19	1.86E-44
10%			0.000539	3.72E-16	7.16E-45
15%				1.43E-07	5.86E-34
20%					1.57E-15

The right graph of Figure 5 visualizes how the increase in emission is distributed for each input value for the cost of by-product. It is found that the kurtosis of this distribution decreases as the cost of by-product increases and that the distribution is increasingly more skewed towards the lower values of emission. The respective p values, found in Table 10, are below the critical value for the tests for lower values, 0% and 5%, 5% and 10% and 10% and 15%. For the tests for higher values; 15% and 20% and 20% and 25%, the resulting p value is not below 0.05. However, in the Mann-Whitney u tests in which there are one or more input values jumped, the p value is again below 0.05, therefore there is no significantly uniform distribution that describes all results. Therefore, the parameter 'cost of by-product' has to be taken into account when predicting the increase in emission in this and similar cases.

P values (Cost of by-product, increase in emission) *lin. coefficient ≈ 126047 (X < Y)*

Table 10 p values of Mann-Whitney u test for increase in emission in relation to the cost of by-product, expressed as a percentage of the cost of virgin resource.

X\Y	5%	10%	15%	20%	25%
0%	3.90E-05	4.12E-15	6.95E-22	7.06E-27	7.57E-24
5%		0.000419	6.37E-09	6.38E-14	1.95E-14
10%			0.019925	8.40E-06	3.50E-08
15%				0.150404	0.003499
20%					0.412109

4.2.2 Warehouse profit margin

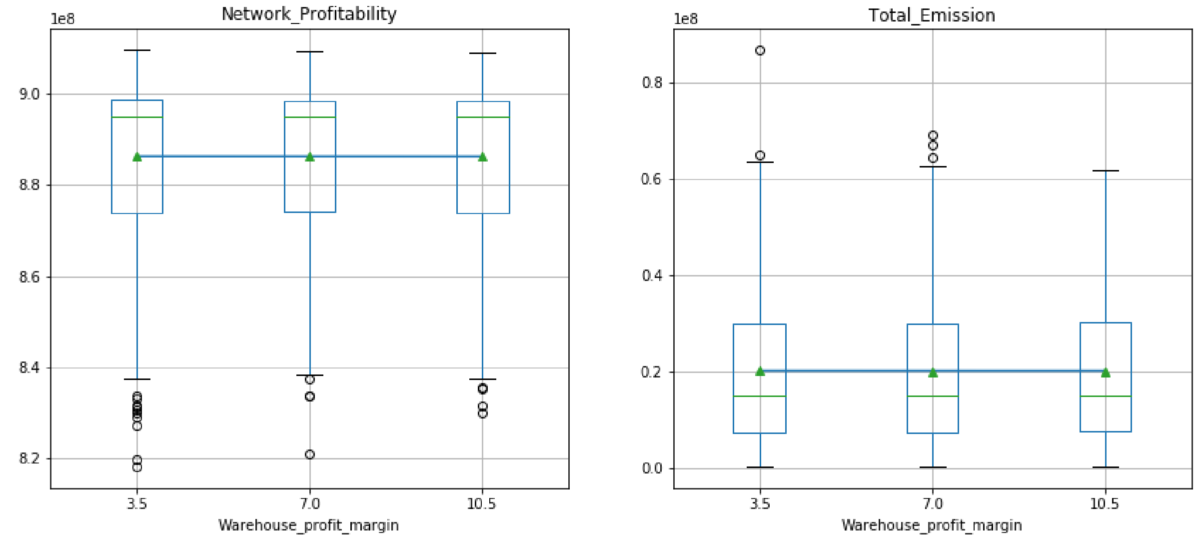

Figure 6 Boxplot results on network profitability (left) and increase in emission (right) in relation to profit margin of warehouses as a percentage of the cost of a virgin resource, mean depicted as triangle, linear regression line drawn through means.

The descriptive statistics of both network profitability and the increase in emission in relation to the input value for cost of by-product are visualized in Figure 6.

The graphs of Figures 6 show that for each of the values of warehouse profit margin, the resulting outcomes are distributed fairly similar. Both the median and mean, as well as the first and third quartile, seem to remain constant. This observation is confirmed by the p values of each combination of input values, shown in Tables 11 and 12. These p values show that, with a test size of 0.05, there is no reason to dismiss the null-hypothesis. Meaning that, with a test-size of 0.05, the network profitability and increase in emission are regarded significantly robust to changes in the warehouse profit margin. This parameter is therefore excluded from estimates for network profitability and emission in this model.

P values (Warehouse profit margin, network profitability) *lin. coefficient ≈ -276867 (X > Y)*

Table 11 p values of Mann-Whitney u test for network profitability in relation to the warehouse profit margin, expressed as a percentage of the cost of virgin resource.

X\Y	3.5	7	10.5
3.5		0.532297	0.150204
7			0.41469
10.5			

P values (Warehouse profit margin, increase in emission) *lin. coefficient ≈ 22481 (X < Y)*

Table 12 p values of Mann-Whitney u test for an increase in emission in relation to the warehouse profit margin, expressed as a percentage of the cost of virgin resource.

X\Y	3.5	7	10.5
3.5		0.982275	0.897373
7			0.914926
10.5			

4.2.3 Storage cost

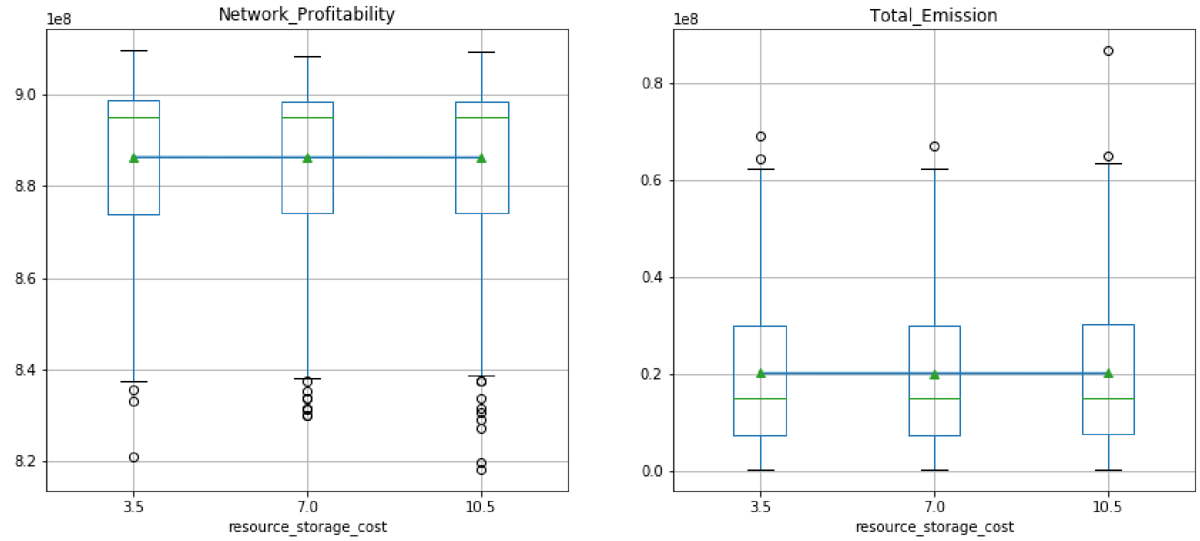

Figure 7 Boxplot results on network profitability (left) and increase in emission (right) in relation to storage cost as a percentage of the cost of a virgin resource, mean depicted as triangle, linear regression line drawn through means

The descriptive statistics of both network profitability and the increase in emission in relation to the input value for resource storage cost are visualized in Figure 7.

The graphs of Figures 7, too, show fairly similarly distributed outcomes. The p values in Tables 13 and 14 show that, with a test size of 0.05, there is no reason to dismiss the null-hypothesis. Meaning that, with a test-size of 0.05, the network profitability and increase in emission are regarded insignificantly sensitive to changes in resource storage cost. This parameter is therefore excluded from estimates for network profitability and emission in this model.

P values (Storage cost, network profitability) *lin. coefficient ≈ -11005 (X > Y)*

Table 13 p values of Mann-Whitney u test for network profitability in relation to the storage cost, expressed as a percentage of the cost of virgin resource.

X\Y	3.5	7	10.5
3.5		0.623377	0.138768
7			0.320422
10.5			

P values (Storage cost, increased emission) *lin. coefficient ≈ 2111 (X < Y)*

Table 14 p values of Mann-Whitney u test for increase in emission in relation to the storage cost, expressed as a percentage of the cost of virgin resource.

X\Y	3.5	7	10.5
3.5		0.427737	0.976015
7			0.444543
10.5			

4.2.4 Market dynamicity

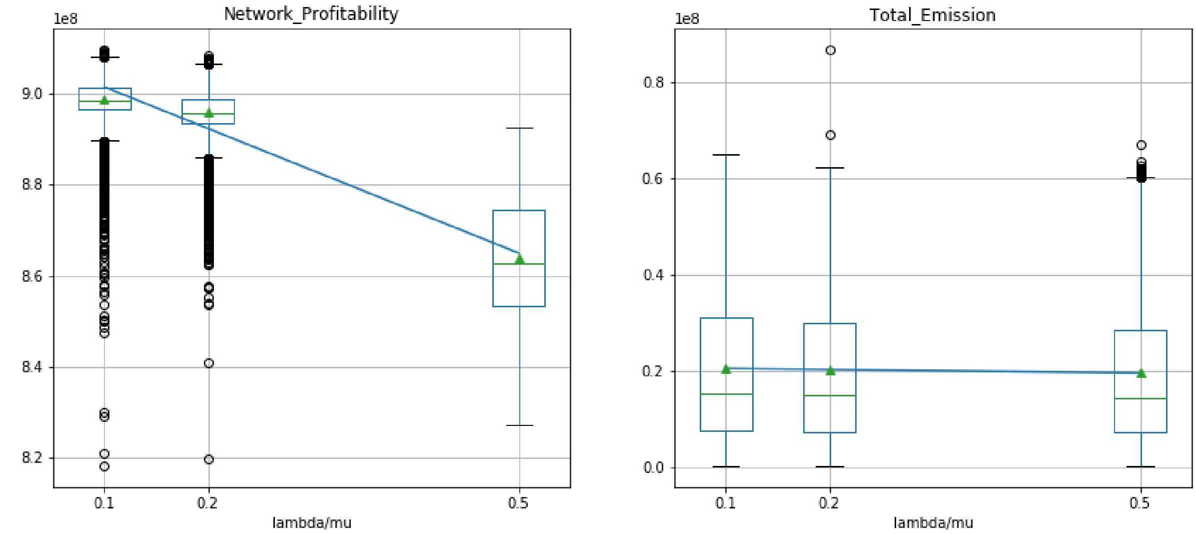

Figure 8 Boxplot results on network profitability (left) and increase in emission (right) in relation to 'market dynamicity', mean depicted as triangle, linear regression line drawn through means

The left graph of Figure 8 shows a decreasing average result for network profitability as the input value for market dynamicity is increased. Furthermore, it is observed that the kurtosis is strongly decreasing and the distributions are increasingly more skewed towards lower network profitability values as the market dynamicity increases. For each combination of input values tested, the p values, shown in Table 15, are 0. There is no statistical chance that any of the resulting distributions follow the same distribution. Therefore, the parameter 'market dynamicity' has to be taken into account when predicting the network profitability in this and similar cases.

P values (Market dynamicity, network profitability) *lin. coefficient ≈ -90606049 (X > Y)*

X\Y	0.1	0.2	0.5
0.1		0	0
0.2			0
0.5			

Table 15 p values of Mann-Whitney u test for network profitability in relation to the market dynamicity.

The right graph of Figure 8 shows the same values for market dynamicity and the resulting distributions for the increase in emission. For each increase in dynamicity, the mean and median decrease. Furthermore, there is a slight increase in kurtosis. Studying the p values, shown in Table 16, it is found that none of the p values are larger than the critical value; each distribution is significantly different from the others. The parameter 'market dynamicity' is so also to be taken into account when predicting the increase in emission in this and similar cases.

P values (Market dynamicity, increased emission) *lin. coefficient ≈ -2553263 (X > Y)*

Table 16 p values of Mann-Whitney u test for increase in emission in relation to the market dynamicity.

X\Y	0.1	0.2	0.5
0.1		0.044884	1.09E-08
0.2			0.000148
0.5			

5 DISCUSSION OF RESULTS

There is a number of the results presented in chapter 4, that require further explanation. In this chapter, the most notable experiment results are explained.

Firstly, a notable result is the initial drop in the average increase of emission as the number of warehouses increases, visualized in figure 4. This results is notable as the amount of by-product sold, shown in appendices E and F, does not show a similar development. The amount of by-product has a positive correlation with the number of warehouses for all of the values experimented with. Therefore, on average, a larger amount of by-product is traded whereas the increase in emission is dropping as the number of warehouses increases.

An explanation is found in the other performance indicator, the average number of concurrent symbiotic relations. A similar limiting effect is apparent as the average number of concurrent symbiotic relations is measured in relation to the number of warehouses in the network, as shown in Appendices E and F. These results show that, on average, more by-product is traded per IS relation. This is likely to have a limiting effect on the increase in emission, as with more by-product per relation, the trucks transporting the by-product between the agents are better utilized. The part of emission from transport that is irrelevant to the amount of by-product transported is distributed over more by-product, resulting in a slightly more environmentally sustainable IS network.

Due to this result, the relation between the number of warehouses and the amount of by-product traded is not linear for the input values that are experimented with. However, it is observed that if the number of warehouses increases further from 25, the resulting amount of by-product traded and the average number of concurrent is relations also increase linearly to the number of warehouses. Therefore, a second linear regression is applied over the results in which the number of warehouses is greater or equal to 25.

Secondly, the results of the Mann-Whitney u test on different input values of warehouse profit margin, suggest that both the resulting network profitability and the increase in emission are not significantly sensitive to changing warehouse profit margins. This indicates that the profit margins of the warehouses do not affect the performance of the network.

Similar results are found for the warehouse storage cost. Warehouse storage cost, combined with warehouse profit margin, form an additional margin to the price of by-product that is paid by the manufacturers of type B, these two parameters are therefore aspects of the same model dynamic. The primary difference between the two parameters is that warehouse profit margin is a shift in the distribution of profit and would, in principle, not affect the network profitability. Whereas an increase in actual storage cost implies an additional cost to the complete network and will restrain profitability. The fact that no significant differences are observed shows that these costs are, in the case presented, negligible in relation to the profit generated in the network.

This is in contrast to what is expected when Equation 10 and Equation 14 are studied. Equation 10 returns the expected profit of a manufacturer that is buying virgin resources from a conventional supplier. Equation 14 returns the expected profit of a manufacturer that is buying by-product from a warehouse. A comparison between these functions shows that the buying manufacturer will choose to not initiate an industrial symbiotic relationship the expected additional transport cost while in the industrial symbiotic relationship exceed the savings in resource procurement cost of the industrial symbiotic relationship, given that the expected number of shortages is the same in both cases. The profit margin of the warehouses, the cost of storage at the warehouses and the additional transport cost could all be described as the ‘additional cost of warehousing’.

The experiment results, therefore, show that, with the current input values, the additional cost of warehousing does not limit the general profitability of an industrial symbiotic relationship. This suggestion is underpinned by the experiment results on the weight of by-product sold, given in Appendix E. The average of the weight of by-product sold is also fairly constant as the warehouse profit margin or the warehouse storage cost increase. These results, therefore, suggest that, in similar experiments, higher storage cost, higher warehouse profit margins, and higher transport cost may be incurred before these cost limit the amount of by-product sold, which will also limit the network profitability and the increase in emission.

6 CONCLUSIONS AND FURTHER RESEARCH

The goal of this thesis has been to introduce intermediary warehouses to the concept of industrial symbiosis networks and gain insight in the relation between (1a) the amount and (1b) capacity of such warehouses and (2a) the profitability and (2b) environmental impact of the industrial symbiosis network. Since no real-world industrial symbiosis networks exist to study, an 'agent-based simulation model' is proposed.

As a proof of concept, the proposed model has been developed in NetLogo 6.0.3 (Wilensky, 2018) and an experiment was run for an industrial symbiosis network consisting of alcohol-manufacturers and manufacturers of compound fertilizer. Input data from a number of sources have been used to estimate the parameter values for the presented case.

The results of this simulation experiment indicate that both the number of warehouses as well as the capacity of the warehouses have a positive effect on the profitability of the network in the case presented. Increasing the values of these parameters lead to an increase in average network profitability.

Furthermore, the results indicate that an increase in the number of warehouses and capacity of warehouses will lead to an absolute increase in emission. However, these results have been normalized to show that the increase in emission per tonne of by-product traded is actually decreasing as the number of warehouses is increasing.

However, as proposed by Ghali et al. (2017), one of the limitations of agent-based simulation models on industrial symbiosis is the lack of data to validate the models. This is no different for this model. No complete real-world data is available to validate the model against. While much effort is put in the checking of assertions, insertion of test-data and structural analysis of the simulation model, we cannot be sure that the model can accurately predict a real-world situation, until such a network is established and the model is validated.

Also, it should be noted that the findings of this thesis project are specific to the industries presented; alcohol-manufacturers and manufacturers of compound fertilizer. Significance has been proven under the parameter values that correspond to this specific case. Therefore, a concluding answer to the research question cannot be given at this stage, neither should policy decisions be based on the observations from this thesis.

In order to be able to take a conclusive decision on whether the introduction of warehouses in Industrial symbiosis networks further research should focus on studying similar setups in other industries and geographic areas, to see if similar conclusions are drawn using different inputs.

Another needed subject of further research is the location of warehouses. In the current model, warehouses are located at random locations throughout the world. Therefore, the warehouses are not necessarily placed at the most optimal locations. Improving the method of location, for example by minimizing the aggregate distance between manufacturers and warehouses, could likely reduce the amount of transport needed. It follows that the warehouse-location method used is expected to yield sub-optimal results, both in profitability and emission. Some indication of these sub-optimal results is already given by the large number of outliers, in emission results. The current warehouse-location method also leads to some warehouses being located at locations at which few or no manufacturers will initiate a relationship with that warehouse, so that the warehouse becomes obsolete.

Furthermore, the prize-setting mechanism of warehouses, only shortly discussed in this thesis, is a subject that could generate new insights on how to make networks such as the one presented in this thesis work.

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Appendix A FLOWCHART OF MODEL FOR IS NETWORK WITHOUT WAREHOUSES

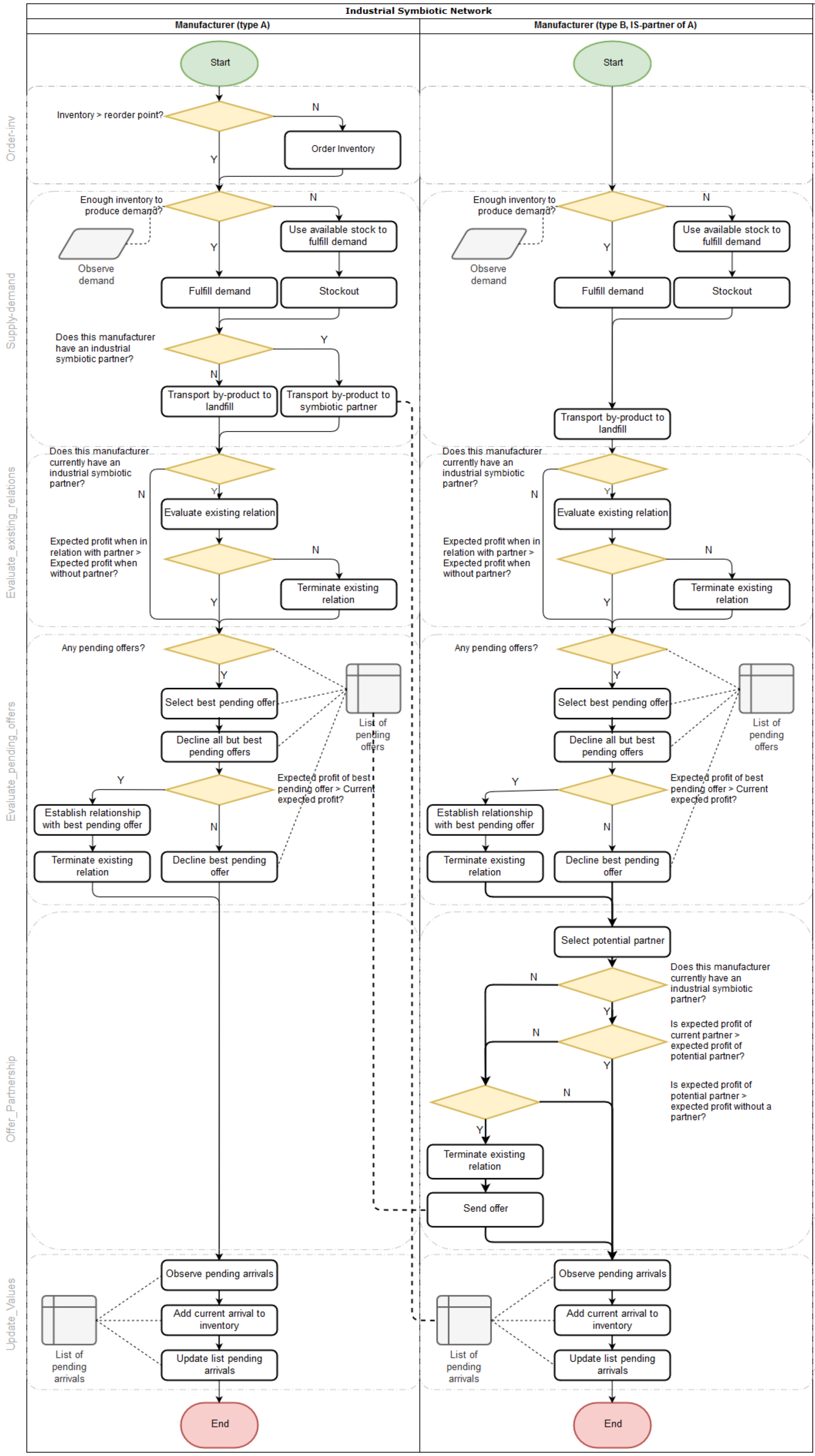
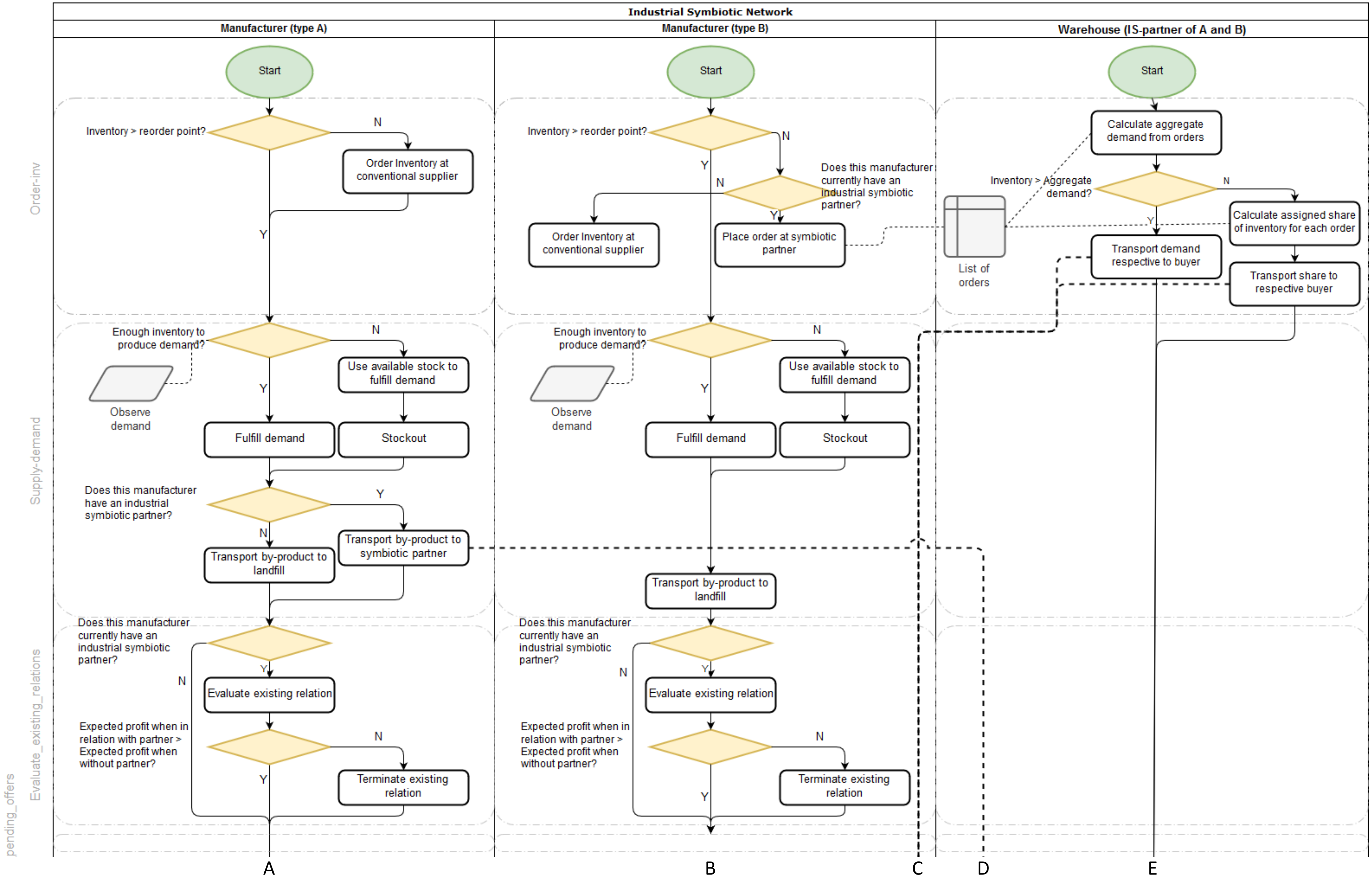


Figure 9, Flowchart of model without warehouses, the flowchart represents a single 'day' in the simulation model and is repeated till the simulation is finished. Left, the function that operationalizes the respective segment of the flowchart is shown.

Appendix B FLOWCHART OF SIMULATION MODEL FOR IS NETWORK WITH WAREHOUSES



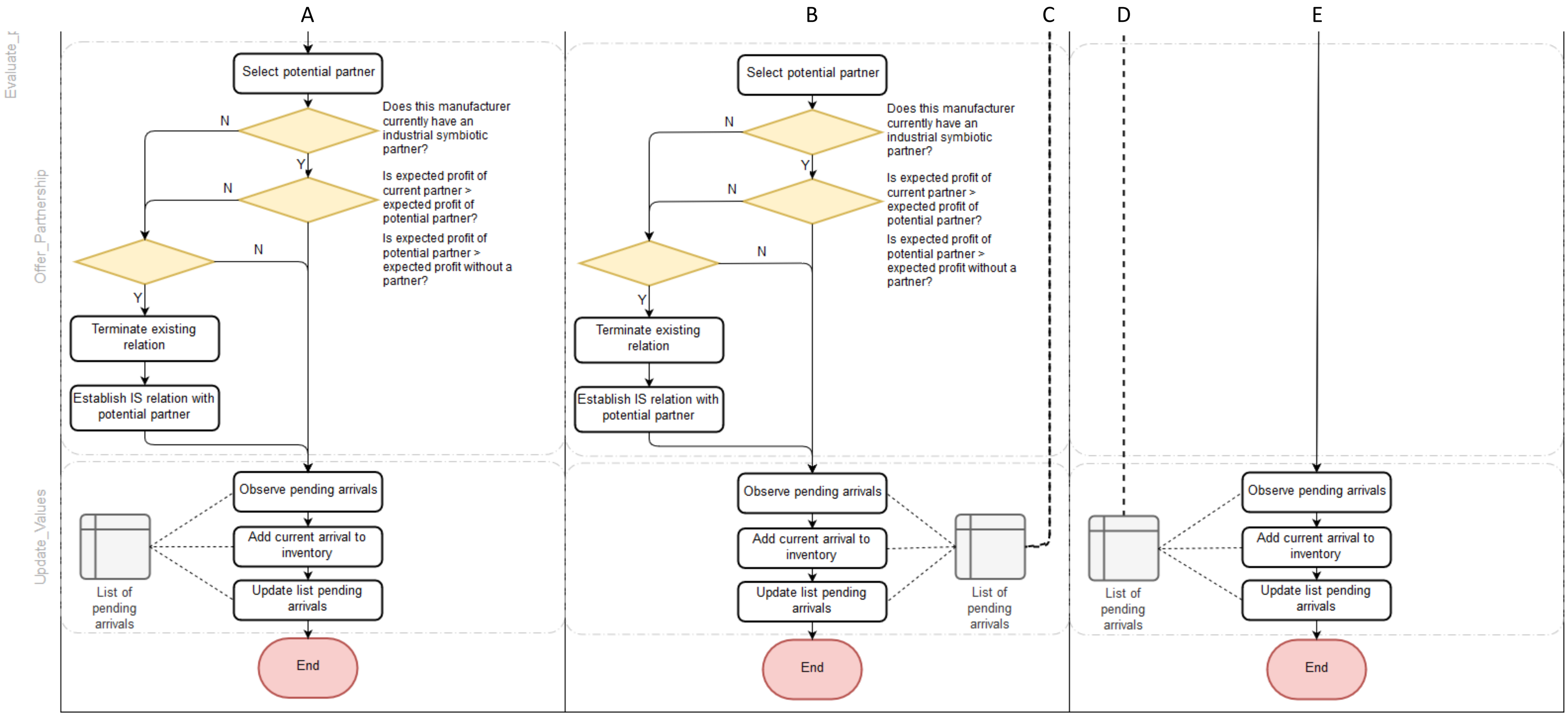


Figure 10, Flowchart of model with warehouses, the flowchart represents a single 'day' in the simulation model and is repeated till the simulation is finished. Left, the function that operationalizes the respective segment of the flowchart is shown.

Appendix C NetLogo code of simulation model

```
;; version 1.2 cleaned and commented.

Globals [
;General Variables
  nStockouts ; This variable tracks the aggregate weight of shortages by all second-order manufacturers in the network.
  nEstablished_relations
  remaining_inventory
  landcolor ; This constant defines the color of tile (patch) that is treated as a 'land'-tile.
  seacolor ; This constant defines the color of tile (patch) that is treated as a 'water'-tile.
  distancefactor ; This constant is used to translate the distances between agents, as acquired by the build-in 'distance'-function, to perceptible values. Factor is 3.5
  Unit_refinement_cost ; This constant gives the cost for refining one unit of by-product into the resource.
  Unit_refinement_emission ; This constant gives the emission weigth for refining one unit of by-product into the resource.
  Manufacturers-A ; This is the agentset containing all manufacturers that generate the by-product.
  Manufacturers-B ; This is the agentset containing all manufacturers that use the resource that can be derived from the by-product.
  Normalcdf_list ; this is a list of a list of floats, containing a wide range of z-values and the corresponding probability that the cumulative of a standard normally distributed variable is smaller or equal to that value.
  nm.loss_list ; this is a list of tuples, containing a wide range of z-values and the corresponding expected loss (in terms of the standard deviation).
  Sum_Byproduct_Traded ; This is a variable representing the total weight in tonnes of byproduct traded.

;Profitability Variables
  Network_Profitability
  Sum_Sales_Profit ; The aggregate of the profit of all manufacturers in the network due to normal sales.
  Sum_Procurement_Cost ; The aggregate of the cost of all manufacturers for buying raw materials from parties external of the network.
  Sum_Transport_Cost ; The aggregate of the cost of all manufacturers for transporting: a) by-products from the manufacturing plant to the landfill, b) by-products from the manufacturing plant to the warehouse and c) resources from the warehouses to the manufacturing plant.
  Sum_Disposal_Cost ; The aggregate of the cost of all manufacturers for disposing by-product at the landfill, either directly or via a warehouse.
  Sum_storage_cost ; The actual expenses of all warehouses for providing the storage capacity.
  Sum_Maintenance_Cost ; The aggregate of the cost of maintaining the warehouses.
  Sum_Stockout_Cost ; The aggregate of the cost of all manufacturers of not being able to fulfill demand.
  Sum_Refinement_Cost ; The aggregate of the cost of all manufacturers for refining waste-material to resource-material.

; Emission Variables
```

```
  Total_Emission
  Sum_Transport_Emission ; the aggregate of all emission due to transport of the by-product or the derivative of the by-product.
  Sum_Storage_Emission ; the aggregate of all emission due to storing of the by-product or the derivative of the by-product.
  Sum_Refinement_Emission ; the aggregate of all emission due to the refinement of the by-product (not included in this model).
  Sum_Construction_Emission ; the aggregate of all emission due to the construction of warehouses.
]

; Here all types of agents in this model are defined.
breed [ manufacturers manufacturer ]
breed [ warehouses warehouse ]
breed [ customers customer ]
breed [ landfills landfill ]

manufacturers-own [
  ticks_since_Stockout; counts the number of "days" since the last "day" a manufacturer had enough inventory to fullfill all its
demand of that day.

  ;Constants
  resource_materials ; A "list" (in this case length = 1) in which the resource materials the manufacturer needs to produce a
single unit of its product are stored. Is either 0 or 1, for each resource.
  waste_materials ;  A "list" (in this case length = 1) in which the by-products the manufacturer generates when producing a
single unit of its product are stored. Is either 0 or 1, for each resource.
  demand_intensity ; This constant represents the average arrival intensity of customers at the manufacturers. Demand is
Normally-distributed. The average demand intensity is a random integer between 1 and 99.
  standard_deviation ; This is the standard deviation of demand per day, set by the user-defined variable "lambda/mu" as a
percentage of the demand_intensity.
  threshold-value_sell ; This constant represents the lowest acceptable economic benefit a manufacturer requires to form a
symbiotic relationship. Initialized at 0.
  threshold-value_buy ; This constant represents the highest acceptable cost a manufacturer accepts to form a symbiotic
relationship. Initialized at the cost of ordering at the conventional (external to the model) supplier.

  ; Variables
  inventory ; Represents the current inventory levels of a manufacturer.
  EOQs ; This is the number of units a manufacturer aims to buy, the EOQ is approached by: expected daily demand + 2 * expected
standard deviation of daily demand )
  resource_input_ratio
  waste_output_ratio
  Reorder_points ; This is the inventory level for which a manufacturer will order new inventory, fixed at: lead time of an
inventory order * expected daily demand
  symbiotic_buyers ; The current partners to which the agent supplies its by-products. If "nobody", the by-product is disposed
at the nearest landfill directly after it is generated.
  symbiotic_suppliers ; The current partners from which the agent buys its by-products. If "nobody", all of the needed resource
```

```
is bought from a conventional supplier.
  non_symbiotic_OQ ; This is the amount of goods ordered from the conventional supplier, ranging from 0 to the EOQ.
  pending_buyers ; This list represents other manufacturers that are interested in buying the resource from the manufacturer.
  pending_arrivals ; This list represents all resources that are ordered by the manufacturer but still in transport. So that the
n-th element of this list represents the aggregate of all transports that are still n days away from being delivered.
  ]

warehouses-own[
  aggregate_demand ; The aggregate of the demand intensities of all manufacturers that buy from this warehouse; included to
limit computation complexity.
  inventory ; Represents the current inventory levels of the warehouse.
  pending_orders ; This list represents all the orders of the product under investigation that have been placed at the warehouse
at the current day, an element in this list is a tuple of an amount and a manufacturer.
  pending_arrivals ; This list represents all resources that are send to the warehouse, but are still in transport. So that the
n-th element of this list represents the aggregate of all transports that are still n days away from being delivered.
  symbiotic_buyers ; The current partners to which the warehouse sells the by-products.
  symbiotic_suppliers ; The current partners for which the warehouse facilitates trades and storage.
]

landfills-own[
  Exploiter ; The name of the exploiting company on this landfill. Data from Rijkswaterstaat Bodem+ (n.d.).
  Location_name ; The name the exploiter has assigned to this location. Data from Rijkswaterstaat Bodem+ (n.d.).
  Location ; The town in/near which the landfill is located. Data from Rijkswaterstaat Bodem+ (n.d.).
  Hazardous_material ; Whether this landfill will process hazordous material. Data from Rijkswaterstaat Bodem+ (n.d.). !! This
feature is currently not included in the model.
  inventory ; This list represents the current inventory levels of the landfill, e.g. the n-th element in this list represents
the current inventory of waste-product n. Landfills in this model to not process waste, thus the values in this list will ever
increase, until the model is terminated.
]

extensions [
  csv  ; Included to import data for landfills and the probability tables.
  ;py ; Included for testing purposes. (not included in the model)
  ;profiler ; Included for testing purposes.
]

;;;; Setup procedures ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to setup ;; Setup function, accessable from dashboard. (Controls -> Setup, hotkey: S)
  clear-all
  reset-ticks
  Setup-environment
```

```
  Setup-normcdftable
  Setup-losstable
  Setup-landfill
  Setup-warehouses
  Setup-manufacturers
end

to Setup-environment
  ;; Here the patches are colored to represent the Netherlands and specific values are assigned to identify land and sea.
  import-pcolors "nederland3.png"
  set landcolor 64.4
  set seacolor 105

  ; Set some global constants
  set distancefactor 3.5
  set unit_refinement_cost 0
  set unit_refinement_emission 0
end

to Setup-normcdftable
  ;; Import normalcdf probability table from csv file.
  set normalcdf_list []
  file-close
  file-open "Norm_cdf.csv"
  while [not file-at-end?] [
    let data csv:from-row file-read-line
    set normalcdf_list lput data normalcdf_list
  ]
  file-close
  set normalcdf_list replace-item 0 normalcdf_list (replace-item 0 item 0 normalcdf_list 0.5) ;This line is added to correct an unexplainable error in reading the csv (item (0,0) contains an unknown symbol)

end

to Setup-losstable
  ;; Import normal loss probability table from csv file.
  set nm.loss_list []
  file-close
  file-open "Standard_normal_loss.csv"
  while [not file-at-end?] [
    let data csv:from-row file-read-line
    set nm.loss_list lput data nm.loss_list
```

```
  ]
  file-close
  set nm.loss_list replace-item 0 nm.loss_list (replace-item 0 item 0 nm.loss_list 0.398942280401433) ;This line is added to correct an unexplainable error in reading the csv (item (0,0) contains an unknown symbol)

end

to setup-warehouses
  ;; Here, warehouses are set up, if applicable. Warehouses are represented by pink squares.

  If use_warehouses? [
  set-default-shape warehouses "square"
  create-warehouses nWarehouses [
      set color pink
      set inventory 0
      set size 2
      set label word "/ " WarehouseCapacity

      ; Set initiation values
      set symbiotic_buyers [nobody]
      set symbiotic_suppliers [nobody]
      set pending_orders []
      set pending_arrivals n-values (  Lead_times_Man-Ware + 1 )  [0]
      set aggregate_demand 0
    ]

  ;; Warehouses should be spread across the space
  ;; Move each warehouse to a random patch that has the color associated to land.
  ask warehouses [
    move-to one-of patches with [ pcolor = landcolor ]
    ]
  ]

end

to setup-manufacturers
  ;; Here manufacturers are set up. Manufacturers are of either type A or type B and are represented by orange and yellow factories respectively.

  set-default-shape manufacturers "factory"
  create-manufacturers nManufacturers_A [
```

```
    ; A-type manufacturers specific setup
    set resource_materials 0 ; A-type manufacturers do not use any raw materials that are included in this model. So that it is assumed that these manufacturers do never stock out.
    set waste_materials  1  ; A-type manufacturers produce the by-product that can be used to derive a raw material needed by B-type manufacturers.
    set color orange

    ; General manufacturer setup, set initialisation values.
    set symbiotic_buyers [nobody]
    set symbiotic_suppliers [nobody]
    set pending_arrivals n-values (  max (list Lead_times_to_Man Service_times_conventional ) + 1 )  [0] ; the list "pending arrivals" is extended based on the user-input lead times, so that any positive integer of lead times in days fits in the model.
    set pending_buyers []
    set demand_intensity (10000 / 365)
    set standard_deviation demand_intensity * lambda/mu
    set resource_input_ratio 1
    set waste_output_ratio (ManA_waste/product)
    set EOQs EOQ ; EOQs is calculated in the "EOQ"-function
    set non_symbiotic_OQ EOQs ; Initially, all reosurces are bought from the conventional supplier.
    set reorder_points reorder_point service_times_conventional Demand_intensity ; Reorder points are calculated using the "reorder_point"-function.
    set threshold-value_sell 0 ; This is set after the manufacturers are placed at their respective positions
    set threshold-value_buy 0 ; This is set after the manufacturers are placed at their respective positions
    set inventory (EOQs + reorder_points) ; All manufacturers start with a filled inventory.
  ]

    create-manufacturers nManufacturers_B [

    ; B-type manufacturers specific setup
    set resource_materials 1 ; B-type manufacturers need the one raw material included in this model to produce their product.
    set waste_materials 0 ; B-type manufacturers are assumed to not produce any by-product relevant to this symbiosis.
    set color yellow

    ; General manufacturer setup, set initialisation values.
    set symbiotic_buyers [nobody]
    set symbiotic_suppliers [nobody]
    set pending_arrivals n-values (  max (list Lead_times_to_Man Service_times_conventional ) + 1 )  [0] ; the list "pending arrivals" is extended based on the user-input lead times, so that any positive integer of lead times in days fits in the model.
    set pending_buyers []
    set demand_intensity (20000 / 365)
    set standard_deviation demand_intensity * lambda/mu
    set resource_input_ratio (1 / ManB_product/resource)
```

```
    set waste_output_ratio 0
    set EOQs EOQ  ; EOQs is calculated in the "EOQ"-function
    set non_symbiotic_OQ EOQs ; Initially, all reosurces are bought from the conventional supplier.
    set reorder_points reorder_point service_times_conventional Demand_intensity ; Reorder points are calculated using the "reorder_point"-function.
    set threshold-value_sell 0 ; This is set after the manufacturers are placed at their respective positions
    set threshold-value_buy 0 ; This is set after the manufacturers are placed at their respective positions
    set inventory (EOQs + reorder_points) ; All manufacturers start with a filled inventory.
  ]

  ; increase visual agents size, move to a random tile of land, add label and link with closest landfill
  ask manufacturers [
    set size 2
    set label "initiating"
    set label-color blue
    move-to one-of patches with [ pcolor = landcolor ]
    create-link-with min-one-of landfills [distance myself] [
      set color red
      If not show_landfills? [ hide-link ]
    ]
    set threshold-value_buy (fitness_buy (nobody))
    set threshold-value_sell (fitness_sell (nobody))
  ]

  ; add both kinds of manufacturers to their respective agentset (based on color).
  set Manufacturers-A Manufacturers with [ color = orange ]
  set Manufacturers-B Manufacturers with [ color = yellow ]
end

to setup-landfill
  ;; Here, the landfills are set up. Landfill agents are represented by grey carbage cans and can be set to invisable in the Interface. Data from Rijkswaterstaat Bodem+ (n.d.)

  set-default-shape landfills "garbage can"
  file-close
  file-open "Stortplaatsen.csv"
  while [not file-at-end?] [
    let data csv:from-row file-read-line
    create-landfills 1 [
      set color gray
      set size 2
      set Exploiter item 0 data
```

```
      set Location_name item 1 data
      set Location item 2 data
      set Hazardous_material item 3 data
      set xcor item 4 data
      set ycor item 5 data
      set inventory 0
      set label 0
      If not show_landfills? [ hide-turtle ]
    ]
  ]
  file-close
end

;;;; Go procedures ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to go
    order-inv
  debug "order_inv"
    supply-demand
  debug "supply-demand"
    Evaluate_existing_relations
  debug "Evaluate existing"
    Evaluate_pending_offers
  debug "Evaluate pending"
    Offer_Partnership
  debug "Offer partnership"
    Clear_inventory
  debug "clear inv"
    Update_Values
  debug "Update values"
    tick
end

to debug [operation]
  ask manufacturers [
    if (count my-links > 1) AND ((symbiotic_suppliers = [nobody]) and (symbiotic_buyers = [nobody]))[
        print operation
      stop
      ]
    stop
    ]
  stop
end
```

```
to order-inv
  ;; Any manufacturer that buys inventory from a warehouse in the model does so in this function. The function for buying from outside the network is also called in this function.
  ask manufacturers  [
    let latest_item_transport 0
    let quantity EOQs
    if (resource_materials = 1) and (inventory < reorder_points) [    ; If the resource is consumed and inventory is below the reorder point:
      If (first symbiotic_suppliers != nobody) [                      ; If there is a supplier other than the conventional supplier:
        If [breed] of first symbiotic_suppliers = warehouses [        ;  and that supplier is a warehouse
          ask first symbiotic_suppliers [
            set pending_orders lput list quantity myself pending_orders  ; Place an order at the warehouse for the EOQ of resource.
          ]
      ]]
      external-order-inv         ; This function is called to buy (additional/any) inventory from outside the network, at the conventional supplier. See; "Auxilary functions"
    ]
  ]

  ;; The next part of the function makes the warehouses fullfill the orders
    If use_warehouses? [
      ask warehouses [
      let latest_item_transport 0        ; initiate a variable "latest_item_transport"
        If not empty? pending_orders [   ; If there are any pending orders:
        let sum_demand sum map first pending_orders  ; Sum all demand
          foreach pending_orders [ a -> ; In case not enough stock for fulfilling all orders, calculate 'assigned_share' for each order and send that share to manufacturers.
            let assigned_share floor((inventory)*(item 0 a) / sum_demand )
            let amount min list assigned_share ( item 0 a )       ; (What actually happens is that an assigned share is always calculated, but if it is more than the demanded quantity, the demanded quantity is send. )
            set inventory (inventory - amount)     ; Recalculate inventory after fullfilling an order.

            ; Some byproduct is traded to the end-user, the counter of total by-product traded is upadated.
            set Sum_Byproduct_traded (Sum_Byproduct_traded + amount)

            ; Orders are send; update Transport related KPI's and if a product needs refinement; update refinement KPI's
            set Sum_Transport_Cost (Sum_Transport_Cost + ([distance item 1 a] of self * distancefactor * 2 * tonne_kilometer_price * amount ))
```

```
            set Sum_Transport_Cost (Sum_Transport_Cost + ([distance item 1 a] of self * distancefactor * 2 * kilometer_price))
            set Sum_Transport_Emission Sum_Transport_Emission + ([distance item 1 a] of self * distancefactor * 2 *
tonne_kilometer_emission * amount )
            set Sum_refinement_Emission Sum_refinement_Emission + ( Unit_Refinement_Emission * amount )
            set Sum_refinement_Cost Sum_refinement_Cost +  ( Unit_Refinement_Cost * amount )

          ; Put the order on transport (pending arrivals is a variable of the receiving party).
          ask item 1 a [
            set latest_item_transport amount
            set pending_arrivals (replace-item ( Lead_times_to_Man - 1) pending_arrivals (item (Lead_times_to_Man - 1)
pending_arrivals + latest_item_transport ))
          ]
        ]
        set pending_orders []    ; All orders are processed, clear the list of pending orders
      ]
      set label (word inventory " / " WarehouseCapacity)     ; Label is updated
      set aggregate_demand (sum [demand_intensity] of manufacturers with [symbiotic_suppliers = myself])
    ]
  ]
end


to supply-demand ;; This function is used to simulate arrivals and manufacturers trying to serve demand.
  ask manufacturers [
    let demand round random-normal demand_intensity standard_deviation

    ;; If there is stock available
      IfElse demand * resource_materials * resource_input_ratio <= inventory [
      set inventory (inventory - (demand * resource_materials * resource_input_ratio))
      send-waste (demand * resource_input_ratio)
      set Sum_Sales_Profit Sum_Sales_Profit + ( demand * Price_Final_Product )
      set label "stock"
      set label-color white
      set ticks_since_Stockout 0
    ]
    ;; If stock is empty
    [set label "stockout"
      If inventory * resource_materials > 0 [
        let sales (inventory / resource_input_ratio)
        set inventory 0
        send-waste sales
        set Sum_Sales_Profit Sum_Sales_Profit + ( sales * Price_Final_Product )
```

```
        set label-color red
        set ticks_since_Stockout ticks_since_Stockout + 1
        set nStockouts nStockouts + ( demand - sales )
        set Sum_Stockout_Cost Sum_Stockout_Cost + ( Cost_of_Stockout * ( demand - sales )) ]
    ]
  ]
end

to Evaluate_existing_relations
  ask manufacturers [
    ;; Evaluate whether current supplier is still 'cheaper' (taking all costs into account) as buying from the conventional supplier, if not, terminate relationship.
      If first symbiotic_suppliers != nobody [
        If (fitness_buy (first symbiotic_suppliers)) > threshold-value_buy [
          terminate_relation (first symbiotic_suppliers)(self)
        ]
      ]

    ;; Evaluate whether it is still more beneficial to sell by-product to current buyers than to dispose it at the landfill, if not, terminate relationship.
      If first symbiotic_buyers != nobody [
        If (fitness_sell (first symbiotic_buyers)) < threshold-value_sell [
          terminate_relation (self)(first symbiotic_buyers)
        ]
      ]
    ]
end

to Evaluate_pending_offers
  ;; In the function "offer_Partnership" manufacturers will send offer to suitable partners to buy their by-products (in case of manufacturers) or inventory (in case of warehouses), in this function these offers are considered and accepted or declined.
  ask manufacturers [  ; As a manufacturer
    while [ not empty? pending_buyers ][   ; If there is any offer,
      let potential_buyer (first pending_buyers)
      let current_buyer first symbiotic_buyers
      set pending_buyers but-first pending_buyers

      IfElse current_buyer != nobody [                    ; but there is a previous agreement with another manufacturer
        If (fitness_sell (potential_buyer) > fitness_sell (current_buyer))[   ; and this offer is more beneficial as the current agreement.
          terminate_relation (self)(current_buyer) ; Terminate previous relationship

```

```
          establish_relation (self)(potential_buyer) ; and accept pending offer.
        ]

        let transportc (transportcost self potential_buyer 1)
        set EOQs EOQ
        set reorder_points reorder_point lead_times_to_man Demand_intensity
      ]
      [If (fitness_sell potential_buyer > threshold-value_sell) [     ; If there is no previous agreement and the offer is more beneficial than having no buyer:
        establish_relation (self)(potential_buyer)                    ; accept the pending offer
        let transportc transportcost self first symbiotic_buyers 1
        set EOQs EOQ
        set reorder_points reorder_point lead_times_to_man Demand_intensity
        ]
      ]
    ]
  ]
end

To Offer_Partnership
  ;; In this function manufacturers will send offer to suitable partners to buy their by-products (in case of manufacturers) or inventory (in case of warehouses)
  ask manufacturers-B [  ; For all type-B manufacturers
    let potential_supplier (nobody)
    let fitting_partners []

    If resource_materials > 0 [  ; If the resource is consumed:
      IfElse not use_warehouses? [ ; In case no warehouses are used, the range of potential partners consists of the type-A manufacturers
        Set fitting_partners manufacturers-A
        If any? fitting_partners [
          set potential_supplier one-of fitting_partners   ; a random partner is chosen from this range.
        ]
      ]
      [ Set fitting_partners warehouses ; In case warehouses are used, the range of potential partners consists of all warehouses.
        If any? fitting_partners [
          Set potential_supplier one-of fitting_partners   ; A random partner is chosen from this range.
        ]
      ]

      let current_relation_check? false    ; This check is used to determine whether the potential new agreement is better than
```

```
the current agreement.
      IfElse first symbiotic_suppliers != nobody [
        If fitness_buy (potential_supplier) > fitness_buy (first symbiotic_suppliers)[ ; If an agreement exists, and it is more
expensive than the potential new agreement, terminate this relationship.
          terminate_relation (first symbiotic_suppliers)(self)
          set current_relation_check? true   ; Enable the possibility for a new relationship
      ]]
      [set current_relation_check? true]   ; If no current agreement exists, it is always possible to initiate a relationship.

      If potential_supplier != nobody [
        If fitness_buy (potential_supplier) > threshold-value_buy and current_relation_check? [   ; If the potential new
agreement is more beneficial than the threshold value and any previous agreement:
          IfElse use_warehouses? [    ;  And the supplier is a warehouse,
            establish_relation (potential_supplier)(self)    ;  form an agreement with this warehouse.
            let transportc transportcost self potential_supplier 1
            set EOQs EOQ
            set reorder_points reorder_point lead_times_to_man Demand_intensity
          ]
          [ ask potential_supplier [set pending_buyers lput myself pending_buyers ]]   ; If the partner is another manufacturer,
send an offer to form an agreement.
        ]
      ]
    ]
  ]
  debug("Offer_partnership - buy")

; Sell - If using warehouses
  ;; for warhouses do not initiate any agreements, manufacturers of type-A need to push their product to the warehouses, if
these are used.
If use_warehouses? [
  Ask Manufacturers-A [
    If waste_materials > 0 [   ; If a by-product is generated.
      let potential_buyer one-of warehouses   ; Select a warehouse
      let current_relation_check? false
      IfElse first symbiotic_buyers != nobody [   ; Test whether selling the by-product to this warehouse is more beneficial
than the current agreement.
        If fitness_sell (potential_buyer) > fitness_sell (first symbiotic_buyers)[
          terminate_relation (self)(first symbiotic_buyers)
          set current_relation_check? true ]]
      [set current_relation_check? true]
      If fitness_sell (potential_buyer) > threshold-value_sell and current_relation_check? [   ; If the new agreement is more
beneficial than the current agreement, and the threshold value, the new relation is established.
```

```
          establish_relation (self)(potential_buyer)
        ]
      ]
    ]
  ]
debug("Offer_partnership - sell")
end

to clear_inventory
  ;; This function is used to simulate a warehouse inventory-keeping policy. For this it calls the function
"Dispose_excess_inventory" to make the warehouses dispose any inventory that
  ask warehouses [
    Dispose_excess_inventory FillRate
  ]
end

to update_Values
  ;; This function is called to update labels and aggregate globals. Also, the movement and arrival of transports is simulated
in this function.
  ; Update globals
  Ask landfills [ set label inventory ]
  Set sum_maintenance_cost (sum_maintenance_cost + ( MaintenanceCost * nWarehouses ))
  Set sum_storage_cost (sum_storage_cost + (WarehouseCapacity * tonne_storage_cost / 365))
  Set Network_Profitability ( Sum_Sales_Profit - Sum_Procurement_Cost - Sum_storage_cost - Sum_Transport_Cost -
Sum_Disposal_Cost - Sum_Maintenance_Cost - Sum_Stockout_Cost )
  Set Total_Emission ( Sum_transport_emission + Sum_storage_emission + Sum_refinement_emission + Sum_construction_emission )


  ;; Here transport (pending arrivals) is updated
  ask manufacturers [
    set inventory ( inventory + ( first pending_arrivals )) ;; the earliest sending is added to the inventory of the
manufacturer
    set pending_arrivals but-first pending_arrivals   ;; other sendings are set one day closer to arriving
    set pending_arrivals (lput 0 pending_arrivals )  ;;  an empty transport is added to the tail of the list, so that the length
the list doesn't decrease in size.
  ]

  If use_warehouses? [
    ask warehouses [
      set inventory (inventory + first pending_arrivals) ;; the earliest sending is added to the inventory of the warehouse
      set pending_arrivals but-first pending_arrivals   ;; other sendings are set one day closer to arriving
      set pending_arrivals (lput 0 pending_arrivals )  ;;  an empty transport is added to the tail of the list, so that the
```

```
length the list doesn't decrease in size.
      if inventory >= WarehouseCapacity [
        Dispose_Excess_Inventory 100   ;; if the arriving resource does not fit in the warehouse, the resource is send to the nearest landfill.
      ]
    ]
  ]
end

;;;; Auxilary procedures ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to external-order-inv
  ;; This function is called by manufacturers to order inventory from the conventional supplier
  let latest_item_transport non_symbiotic_OQ   ;; Add the ordered resource to the latest transport
  set Sum_Procurement_Cost Sum_Procurement_Cost + ( non_symbiotic_OQ * Resource_cost_conventional )  ;; Update global economic performance indicator.
  set pending_arrivals (replace-item ( Service_times_conventional - 1) pending_arrivals (item ( Service_times_conventional - 1) pending_arrivals + latest_item_transport ))  ;; Add latest arrival to list of pending arrivals.
end

to send-waste [amount] ;; This function is called by 'supply-demand' by type-A manufacturers, to update the inventory of the type-B symbiotic-partner, warehouse or landfill if waste is send.
  If waste_materials > 0 [
    IfElse first symbiotic_buyers != nobody [ ; If the receiving party is not a landfill;
      ; show first symbiotic_buyers
      Let lead_time 0    ;Initiate the integer 'lead_time'
      IfElse [breed] of first symbiotic_buyers = manufacturers [

          ; Some byproduct is traded to the end-user, the counter of total by-product traded is upadated.
          set Sum_Byproduct_traded (Sum_Byproduct_traded + amount)

          set lead_time lead_times_to_Man ]  ; If the receiving party is a manufacturer, set 'lead_time' to the corresponding value
        [ set lead_time lead_times_Man-Ware ]  ; Otherwise, the receiving party is a warehouse, set 'lead_time' to the corresponding value.
      ask first symbiotic_buyers [  ;
        let latest_pending_arrival (item (lead_time - 1) pending_arrivals) ;; Add the resource to the pending arrivals of the receiving party.
        set latest_pending_arrival (latest_pending_arrival + amount)
        set pending_arrivals (replace-item (lead_time - 1) pending_arrivals latest_pending_arrival)
      ]
      Update_transport_KPIs (first symbiotic_buyers)(amount)
```

```
    ]
    [ let NearLandfill (min-one-of landfills [distance myself])
      ask NearLandfill [  ; If there is no reveiving party, send the waste directly to the nearest landfill and the disposalcost
KPI's are updated.
      set inventory (inventory + amount )
      set Sum_Disposal_Cost Sum_Disposal_Cost + ( Disposalcost_Landfill * amount )

      Update_transport_KPIs (NearLandfill)(amount)
      ]
    ]
  ]
end

to Dispose_Excess_Inventory [Level]
  ;; This function is called when warehouses dispose inventory to keep the stocklevel below the put in percentage.
  while [ inventory > ( Level / 100 * WarehouseCapacity )][
    let excess_inventory (inventory - (level / 100 * WarehouseCapacity))  ;; Calculate excess inventory
    let NearLandfill (min-one-of landfills [ distance myself ])
    Ask NearLandfill [   ; Send excess inventory to the nearest landfill
      Set inventory ( inventory + excess_inventory )
      Set Sum_Disposal_Cost Sum_Disposal_Cost + ( Disposalcost_Landfill * excess_inventory)  ; Update disposalcost KPI's
    ]
    Set inventory ( inventory - excess_inventory )  ; Update warehouse inventory level.

    ; This is new
   Update_transport_KPIs (NearLandfill)(excess_inventory)
  ]
end

to terminate_relation [seller buyer]
  ;; update sellers list of symbiotic buyers - remove buyer
  ifelse [breed] of seller = warehouses [ ; for warehouses
    ask seller [
      if length symbiotic_buyers = 1 [ ; If the list contains only the symbiotic buyer to remove
        set symbiotic_buyers (lput nobody symbiotic_buyers) ; Add an empty agent 'nobody''to this list (for the list would
otherwise disappear)
      ]
      set symbiotic_buyers (remove buyer symbiotic_buyers) ; remove the symbiotic buyer to remove
    ]
  ]
  [ ask seller [  ; If seller is a manufacturer
    set symbiotic_buyers ([nobody])  ; Set the symbiotic buyer to 'nobody'
```

```
    ]
  ]

  ;;update buyers list of symbiotic suppliers - remove seller (Similar to above)
  ifelse [breed] of buyer = warehouses [
    ask buyer [
      if length symbiotic_suppliers = 1 [
        set symbiotic_suppliers (lput nobody symbiotic_suppliers)
      ]
      set symbiotic_suppliers (remove seller symbiotic_suppliers)
    ]
  ]
  [ ask buyer [
    set symbiotic_suppliers ([nobody])
    set non_symbiotic_OQ (EOQ) ; If the relation with the symbiotic supplier is terminated, all inventory needs to be bought from the conventional supplier.
    ]
  ]

  ;;delete link
  if is-link? link-with buyer
  [ask link-with buyer [
            die
  ]]

  if is-link? link-with seller
    [ask link-with seller [
      die
  ]]
end

to establish_relation [seller buyer]
  ;; update sellers list of symbiotic buyers
  ;show (word "Seller is: " seller ", buyer is: " buyer)
  ifelse [breed] of seller = warehouses [   ; for warehouses
    ;show ("debug 1")
    ask seller [
      set symbiotic_buyers (lput buyer symbiotic_buyers)   ; Add the buyer to the list with symbiotic buyers.
      ;show ("debug 2")
      if member? nobody symbiotic_buyers [   ; If there where previously no buyers for this warehouse, a 'nobody' is in this list. If this is the case, remove this 'nobody'
        set symbiotic_buyers (remove nobody symbiotic_buyers)
```

```
        ;show ("debug 3")
      ]
    ]
  ]
  [ask seller [   ; for manufacturers
    set symbiotic_buyers (lput buyer [])  ; Set the list of symbiotic_buyers, with buyer.
    ;show ("debug 4")
    ]
  ]

  ;;update buyers list of symbiotic suppliers (As above)
  ifelse [breed] of buyer = warehouses [
    ;show ("debug 5")
    ask buyer [
      ;show ("debug 6")
      set symbiotic_suppliers (lput seller symbiotic_suppliers)
      if member? nobody symbiotic_suppliers [
        ;show ("debug 7")
        set symbiotic_suppliers (remove nobody symbiotic_suppliers)
      ]
    ]
  ]
  [ask buyer [
    ;show ("debug 8")
    set symbiotic_suppliers (lput seller [])
    set non_symbiotic_OQ ceiling(EOQs - Expected_Sales (seller)(buyer))   ; If it is expected that not all resources can be bought from the symbiotic supplier,
                                                                          ; use the function 'Expected_Sales' to calculate how many remaining resources need to be bought from the conventional supplier.
    ]
  ]

  Ask buyer [  ; Create link
    create-link-with seller
    ;show ("debug 9")
  ]

  IfElse Use_Warehouses? [
    ; If warehouses are enabled, two links form one full relation; one between the first-order manufacturer and the warehouse and one between the warehouse and the second-order manufacturer.
    set nEstablished_relations (nEstablished_relations + 0.5)
  ][
```

```
      ; If warehouses are disabled, one link between manufacturers forms a full relationship.
      set nEstablished_relations (nEstablished_relations + 1)
      ]
  end

  to Update_transport_KPIs[receiver amount]
     ; Orders are send; update Transport related KPI's and if a product needs refinement; update refinement KPI's
      set Sum_Transport_Cost (Sum_Transport_Cost + ([distance receiver] of self * distancefactor * 2 * tonne_kilometer_price *
  amount ))
      set Sum_Transport_Cost (Sum_Transport_Cost + ([distance receiver] of self * distancefactor))
      set Sum_Transport_Emission Sum_Transport_Emission + ([distance receiver] of self * distancefactor * 2 *
  tonne_kilometer_emission * amount )
      set Sum_refinement_Emission Sum_refinement_Emission + ( Unit_Refinement_Emission * amount )
      set Sum_refinement_Cost Sum_refinement_Cost +  ( Unit_Refinement_Cost * amount )
  end

  to Clear_left_inventory
    ask turtles with [breed != landfills] [
      let excess_inventory (inventory)  ;; Calculate excess inventory
      let NearLandfill (min-one-of landfills [ distance myself ])
      Ask NearLandfill [   ; Send excess inventory to the nearest landfill
        Set inventory ( inventory + excess_inventory )
        Set Sum_Disposal_Cost Sum_Disposal_Cost + ( Disposalcost_Landfill * excess_inventory)  ; Update disposalcost KPI's
      ]
      Set inventory ( inventory - excess_inventory )  ; Update warehouse inventory level.

     Update_transport_KPIs (NearLandfill)(excess_inventory)
    ]
  end

  ;;;; Auxilary report functions ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

  to-report fitness_sell[partner]
    ; Initialize
    let ESales_profit 0
    let ELandfill_cost 0
    let ETransport_Landfill 0
    let ETransport_partner 0

    ; Calculate ESales; Expected units sold
    let ESales Expected_Sales self partner

```

```
  ; Profit of sales = (price * % waste purchasecost)*(1 - warehouse fees)*ESales
  let warehouse_fee 0
  ifelse partner != nobody [
    if [breed] of partner = warehouses [set warehouse_fee (tonne_storage_cost)]
    set ESales_profit ((Resource_cost_conventional * (percentage_waste_purchasecost / 100))*(1 - (warehouse_fee / 100)) * ESales )
    set ELandfill_cost ((demand_intensity * waste_output_ratio - ESales) * disposalcost_landfill) ; landfill cost - is the tonnes of unsold by-product, times the price to dispose a tonne of by-product

    ; transportationcost - consists of transport of by-product sold (if warehouses) and transport of unsold by-product to the nearest landfill.
    if [breed] of partner = warehouses [set ETransport_partner (TransportCost (self)(partner)(ESales))]
    set ETransport_landfill (TransportCost (self)(min-one-of landfills [distance self])(demand_intensity * waste_output_ratio - ESales))
  ][
    set ESales_profit 0
    set ELandfill_cost (demand_intensity * waste_output_ratio * disposalcost_landfill)
    set ETransport_landfill (TransportCost (self)(min-one-of landfills [distance self])(demand_intensity * waste_output_ratio))
    ]

  ; transportationcost - consists of transport of by-product sold (if warehouses) and transport of unsold by-product to the nearest landfill.
  set ETransport_landfill (TransportCost (self)(min-one-of landfills [distance self])(demand_intensity * waste_output_ratio - ESales))
  let ETransportation_cost (ETransport_partner + ETransport_landfill)

  ; "Fitness" is defined as the sum of these costs and profits
  report ESales_profit - (ELandfill_cost + ETransportation_cost)
end

to-report fitness_buy[partner]
  ; Initiate
  Let ESales_cost 0

  ; Calculate ESales; Expected units bought
  let ESales Expected_Sales partner self

  ; Procurement cost = (price * % waste purchase)* ESales
  ifelse partner != nobody [
    ifelse use_warehouses? [
      set ESales_cost (Resource_cost_conventional * ((percentage_waste_purchasecost + warehouse_profit_margin +
```

```
resource_storage_cost) / 100) * ESales)]
    [ set ESales_cost (Resource_cost_conventional * (percentage_waste_purchasecost / 100) * ESales)]]
  [ set ESales_cost (Resource_cost_conventional * ESales) ]

  ; Transportation cost - consists of transport of by-product bought from any source from inside the network.
  let ETransport_cost 0
  if partner != nobody [set ETransport_cost (transportCost (partner)(self)(ESales))]

  ; Expected Stockout_cost; from the normal loss function
  let expected_shorts (standard_deviation * nm.loss(EOQ)(Demand_intensity)(standard_deviation))
  let EShortage_cost (expected_shorts * cost_of_stockout)

  ; "Fitness" is defined as the negative of the sum of all cost above.
  report 0 - (ESales_cost + ETransport_cost + EShortage_cost)

end

to-report TransportCost[start destination quantity]
  ; Used to calculate the daily transportcost of a relation for a certain quantity from start to finish.
  let dist ([distance start] of destination * distancefactor)
  let price/km (quantity * tonne_kilometer_price + kilometer_price)
  report (dist * price/km * 2)
end

to-report expected_sales [seller buyer]
  ; This function is used to estimate the daily amount of sales from the seller that the buyer can expect when being in a
relationship with the seller.
  let limitin 0
  let limitout 0

  if seller = nobody [  ; Conventional suppliers can always deliver all resources.
    report [EOQs] of buyer]

  ifelse [breed] of seller != warehouses [
    set limitin ([demand_intensity * waste_output_ratio] of seller )] ; Manufacturers are assumed to accept any resources that
are generated by their symbiotic partner.
  [ let olddem (sum ([EOQs] of turtle-set ([symbiotic_buyers] of seller))) ; Warehouses are able to deliver up to the assigned
share (defined as: Demand of buyer * (All supply that day / Total demand that day (including that of the buyer))
    let newdem (([EOQs] of buyer))
    let agrsup (sum ([demand_intensity * resource_input_ratio] of turtle-set ([symbiotic_suppliers] of seller)))
    set limitin (newdem * (agrsup / (newdem + olddem))) ]

```

```
  if buyer = nobody [ ; If there is no one to buy the resources, all resources are send to the landfill. Landfills always exept resources.
    report [demand_intensity * waste_output_ratio] of seller]

    ifelse [breed] of buyer != warehouses [
      set limitout ([demand_intensity * resource_input_ratio] of buyer)]
  [ let agrin (sum ([demand_intensity * waste_output_ratio] of turtle-set ([symbiotic_suppliers] of buyer)) + [demand_intensity * waste_output_ratio] of seller)
      let agrout (sum ([demand_intensity * resource_input_ratio] of turtle-set ([symbiotic_buyers] of buyer)))
      set limitout ( min (list ((FillRate / 100) * WarehouseCapacity) (agrin)) - agrout)]  ; Warehouses are able to accept the increased load of supply as long as the aggregate of the rest of supply after fullfilling demand fits the warehouse.

  report min(( list limitin limitout ))  ; The expected number of sales is the smallest of the two values calculated.
end

to-report EOQ  ; Manufacturers are assumed to aim for a service level of 97.5%, which is approximately reached when ordering the mean demand intensity + twice the standard deviation.
  report floor(demand_intensity + (2 * standard_deviation)) * resource_input_ratio
end

to-report Reorder_point [ lead_time demand ] ; The reorder point is chosen as such that the manufacturer is expected to be able to fullfill all demand while the order for resources is arriving.
  report ((lead_time + 1) * demand * resource_input_ratio)
end

to-report normcdf2 [x mmean deviation]
  ;; This function is used to interpret the normalcdf z-table that is loaded in the model.

  let z ((x - mmean) / deviation )  ; calculate the z-value
  let item1 0  ; initiate some integers
  let item2 0
  let prob 0
  set z (word (precision z 2))  ; convert the z-value to a string of maximal two decimals
  ifelse ((first z != "-") and (length z = 4)) or ((first z = "-") and (length z = 5)) [  ; if the z-value has a second decimal:
    set item2 read-from-string (last z)  ; set 'item2' the value of the second decimal
    set z but-last z  ; strip the second decimal from the z-value
  ]
  [set item2 0]  ; if the z-value has only one decimal, set 'item2' to 0

  set item1 (10 * (read-from-string z))  ; the imported table increments the z-value by 0.1 for each row, so that the row number is corresponding to the absolute of the z-value * 10
                                         ; set item1 the stripped z-value * 10, which is the rownumber in which the
```

```
corresponding probabilities are found or its negative.
  ifelse (abs item1) <= 51 [              ; if the abs(z-value) <= 5:
    set prob item item2 (item (abs item1) normalcdf_list)]  ; find the approximate probability in row "item1" and collumn
"item2" of the table.
    [set prob 1]  ; if the z-value > 5, the table is not sufficiently large, however, these values approach 1, set the
probability to '1'
  ifelse item1 >= 0 [ ; for positive z-values, the wanted probability is the found probability
    report prob ]
  [ report 1 - prob ]  ; for negative z-values, the wanted probabilty is (1 - the found probabilty)
end

to-report nm.loss [x mmean vvariance]
  ;; This function is used to interpret the normal loss function that is loaded in the model.
  let z ((x - mmean) / vvariance )  ; calculate the z-value
  let item1 0  ; initiate some integers
  let item2 0
  let result 0
  set z (word (precision z 2))  ; convert the z-value to a string of maximal two decimals
  ifelse ((first z != "-") and (length z = 4)) or ((first z = "-") and (length z = 5)) [  ; if the z-value has a second decimal:
    set item2 read-from-string (last z)  ; set 'item2' the value of the second decimal
    set z but-last z  ; strip the second decimal from the z-value
  ]
  [set item2 0]  ; if the z-value has only one decimal, set 'item2' to 0

  ifelse (first z != "-") [  ; the imported table has the unit loss for both positive and negative z-values, with two rows for
the natural number '0' (one for the range [0, -0.09] and one for the range [0, 0.09])
    set item1 (10 * (read-from-string z) + 50)]  ; results for positive z-values start at row 50 (0.00 up to 0.09), so that the
result for z = 0.01 is found in row 50, collumn 1.
    [set item1 (10 * (read-from-string z) + 49)] ; results for negative z-values start at row 0 (-4.90 down to -4.99) up until
row 49 (-0.00 down to -0.09), so that the result for z = -0.01 is found in row 49, collumn 1.
  ifelse (item1) <= 99 [ ; if z > 4.99, the table is not sufficiently large, however, these values approach 0
    set result item item2 (item (abs item1) nm.loss_list)]
    [set result 0]
  ifelse item1 >= 0 [ ; if z > 4.99, the table is not sufficiently large, however, these values approach the z-value itself.
    report result ]
  [ report abs (read-from-string z) ]
end

;; Harmsma, W.H. (2018) 'Nedereiland', Model of a symbiotic network with stock-keeping facilities. (Version 1.2) [Agent-based
simulation Model]. In context of the course 2017-201500022-JAAR: Bachelor Thesis TBK (2017-JAAR) at the University of Twente. ;;
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Appendix D Experiment world design

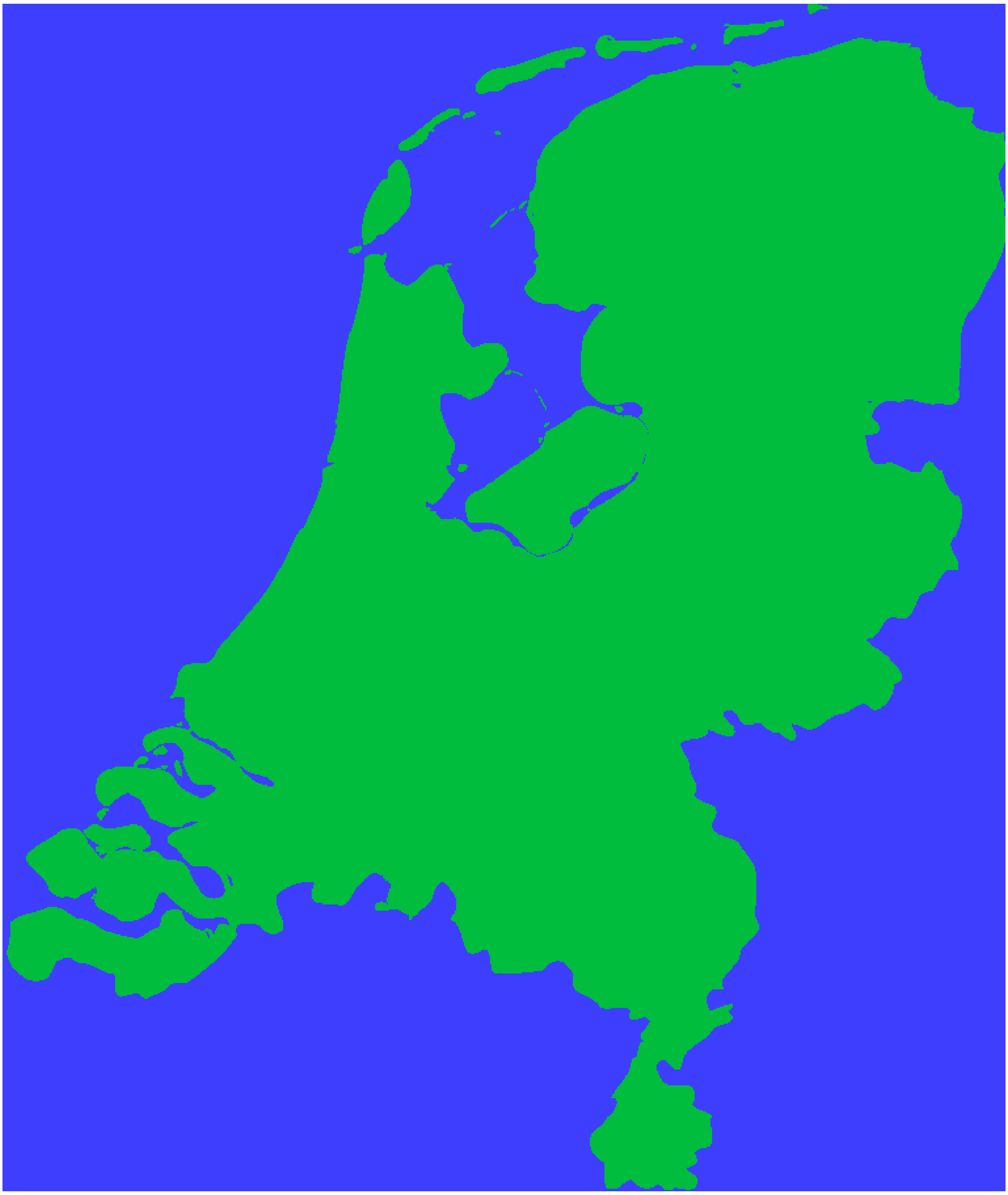

Figure 11 Design of geographic area for experiment

Appendix E Boxplots of results for the number of established relations and the weight of by-product moved.

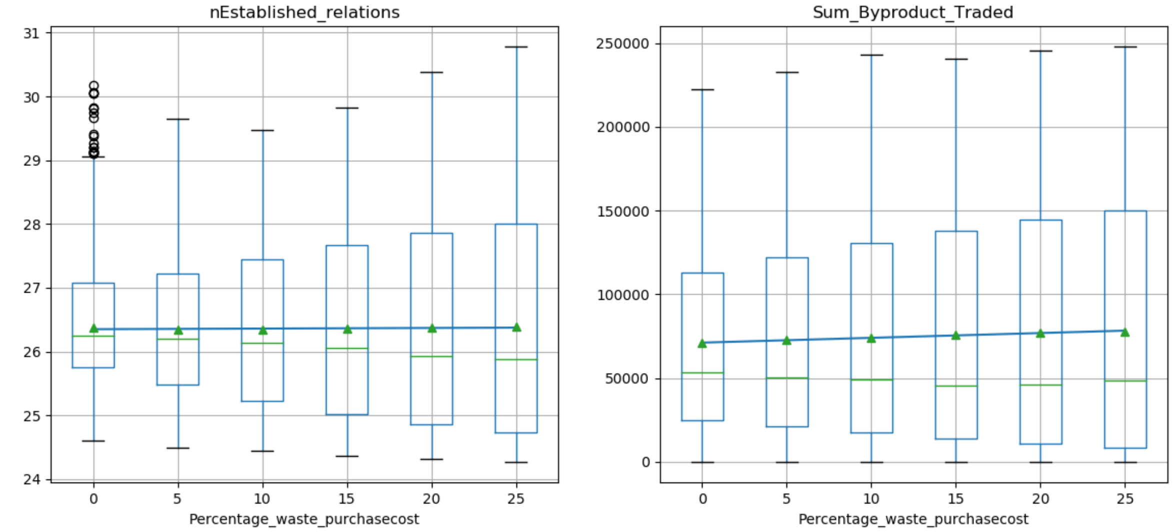

Figure 12 Boxplot results on the average number of simultaneously established IS relation in the network (left) and aggregate weight of by-product traded (right) in relation to the cost of by-product as a percentage of the cost for a virgin resource, mean depicted as triangle, linear regression line drawn through means.

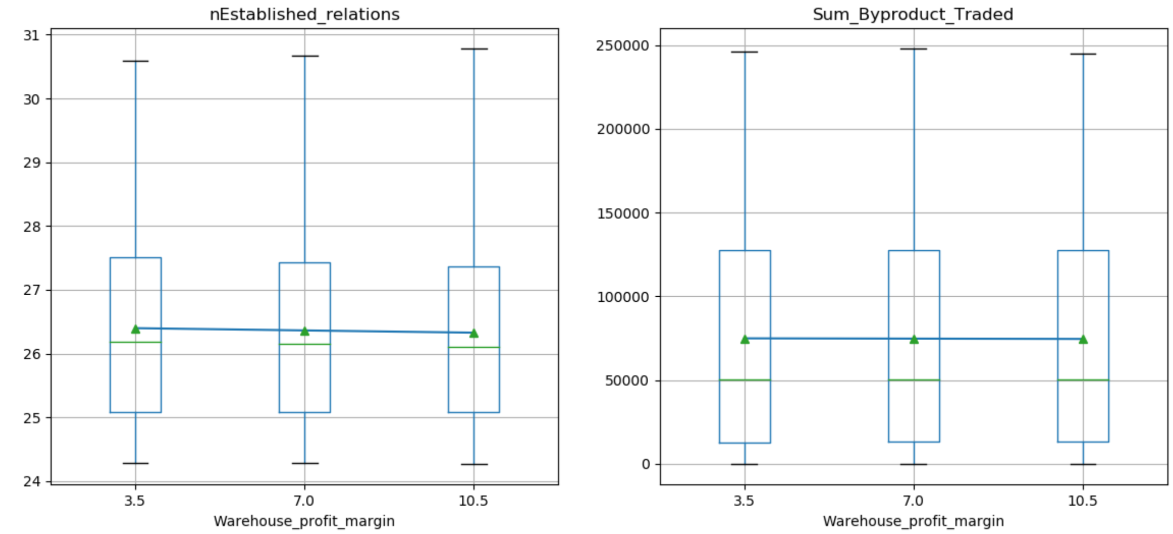

Figure 13 Boxplot results on the average number of simultaneously established IS relation in the network (left) and aggregate weight of by-product traded (right) in relation to the profit margin of the warehouse as a percentage of the cost for a virgin resource, mean depicted as triangle, linear regression line drawn through means.

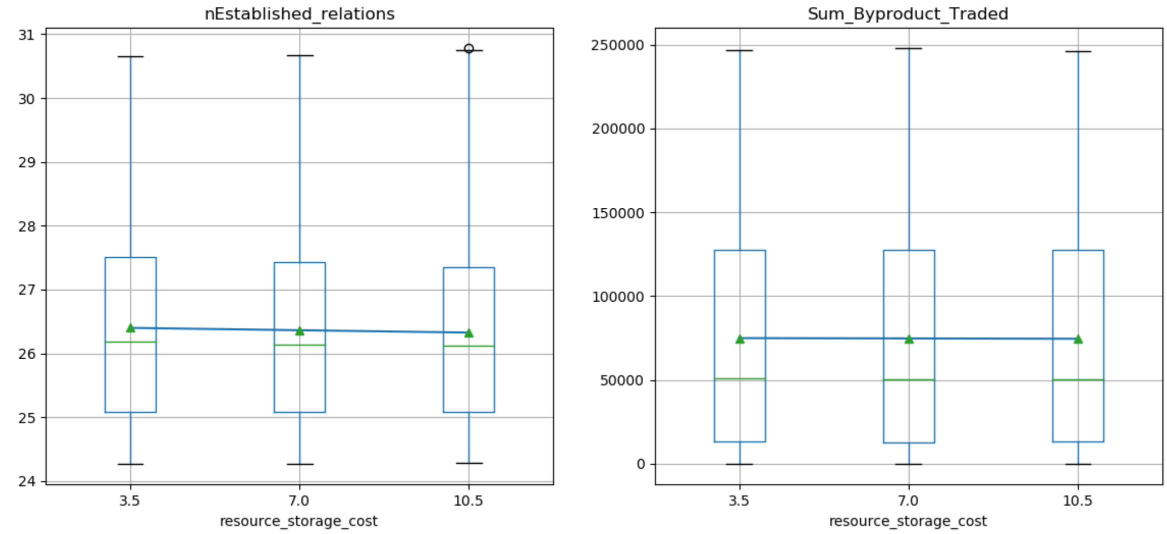

Figure 14 Boxplot results on the average number of simultaneously established IS relation in the network (left) and aggregate weight of by-product traded (right) in relation to the cost of storage as a percentage of the cost for a virgin resource, mean depicted as triangle, linear regression line drawn through means.

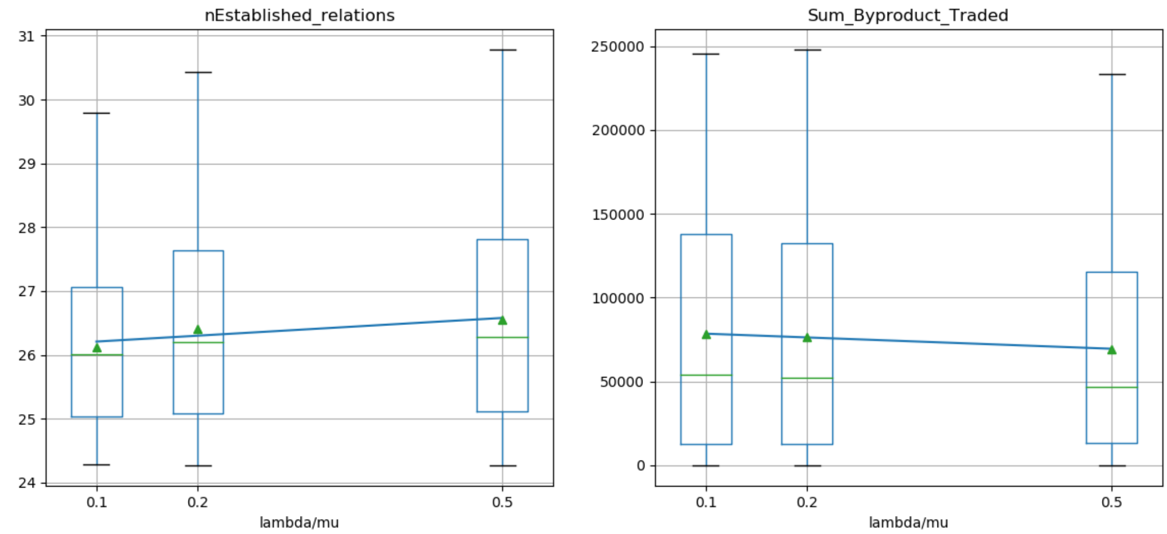

Figure 15 Boxplot results on the average number of simultaneously established IS relation in the network (left) and aggregate weight of by-product traded (right) in relation to dynamicity of the market, mean depicted as triangle, linear regression line drawn through means.

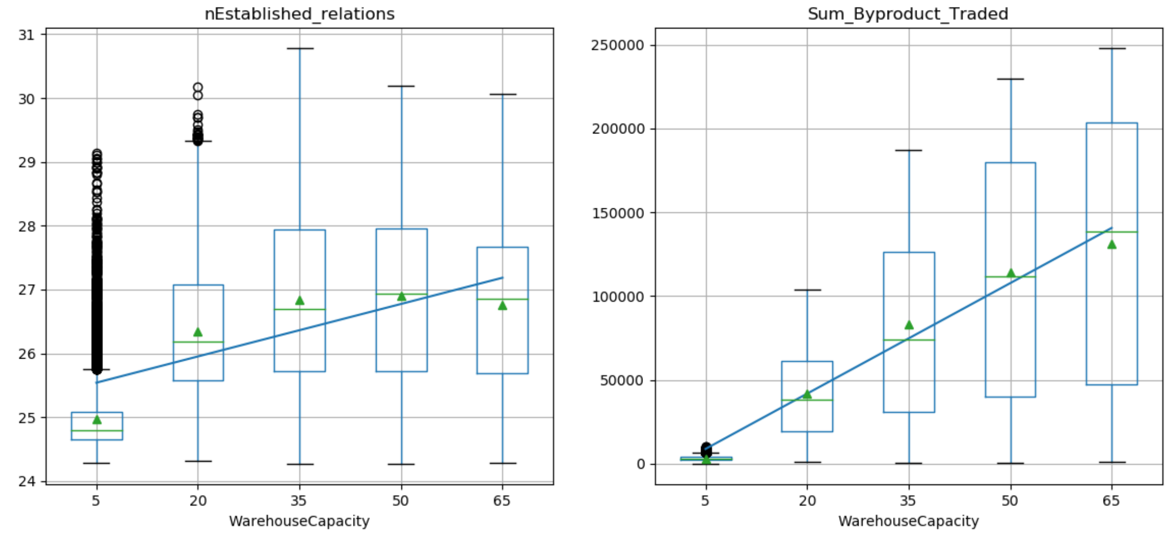

Figure 16 Boxplot results on the average number of simultaneously established IS relation in the network (left) and aggregate weight of by-product traded (right) in relation to the capacity of the warehouses in tonnes, mean depicted as triangle, linear regression line drawn through means.

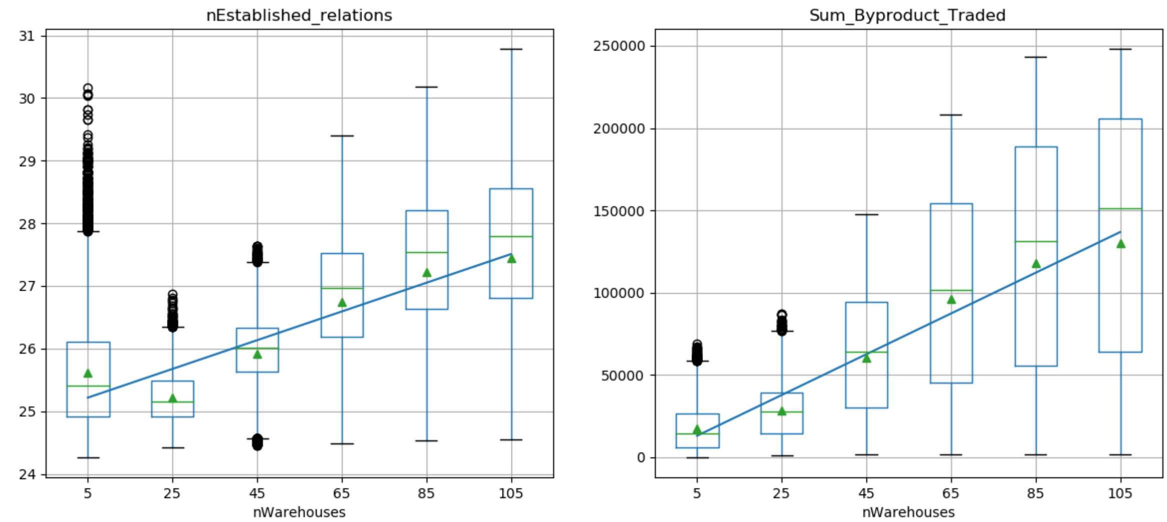

Figure 17 Boxplot results on network profitability (left) and increase in emission (right) in relation to the number of warehouses, mean depicted as triangle, linear regression line drawn through means.

APPENDIX F CLASSICAL DESCRIPTIVE STATISTICS OF EXPERIMENT RESULTS

Table 17 Classical descriptive statistics of experiment results

	Parameter	Value	Unit	KPI	N. of observations	Mean	First Quartile	Median	Third Quartile	St. deviation	Skewness	Kurtosis
0	By-product_Cost	0	% of virgin resource	Aggr_Weight_of_By-product	12150	70869.19	24971.25	53668.2	113091.8	60134.68	0.77	-0.52
1	By-product_Cost	5	% of virgin resource	Aggr_Weight_of_By-product	12150	72670.58	21220.25	50480	122010.4	64917.86	0.78	-0.61
2	By-product_Cost	10	% of virgin resource	Aggr_Weight_of_By-product	12150	74320.4	17705.5	48931.9	130724.6	69101.93	0.77	-0.72
3	By-product_Cost	15	% of virgin resource	Aggr_Weight_of_By-product	12150	75770.85	14154.1	45333.5	137809.4	72667.12	0.74	-0.84
4	By-product_Cost	20	% of virgin resource	Aggr_Weight_of_By-product	12150	77005.11	11075.5	46295.7	144387.4	75515.31	0.70	-0.94
5	By-product_Cost	25	% of virgin resource	Aggr_Weight_of_By-product	12150	78013	8501.6	48453	149892.9	77597.72	0.66	-1.04
6	By-product_Cost	0	% of virgin resource	Ave_nRelations	12150	26.37549	25.74675	26.25548	27.08288	0.87017	0.21	-0.57
7	By-product_Cost	5	% of virgin resource	Ave_nRelations	12150	26.34075	25.48219	26.20514	27.22397	1.042209	0.25	-1.07
8	By-product_Cost	10	% of virgin resource	Ave_nRelations	12150	26.34001	25.2226	26.14041	27.44247	1.252004	0.37	-1.15
9	By-product_Cost	15	% of virgin resource	Ave_nRelations	12150	26.35879	25.01233	26.05822	27.66233	1.458505	0.43	-1.20
10	By-product_Cost	20	% of virgin resource	Ave_nRelations	12150	26.37546	24.85908	25.92534	27.85685	1.637894	0.47	-1.21
11	By-product_Cost	25	% of virgin resource	Ave_nRelations	12150	26.38523	24.72534	25.88836	28.00616	1.790443	0.52	-1.16
12	By-product_Cost	0	% of virgin resource	Increase_in_Emission	12150	19073283	10855489	16118189	26103395	11040378	0.80	-0.06
13	By-product_Cost	5	% of virgin resource	Increase_in_Emission	12150	19079021	9967143	14823943	28037650	12369574	0.77	-0.50
14	By-product_Cost	10	% of virgin resource	Increase_in_Emission	12150	19456488	8406004	14646181	29347503	14281707	0.80	-0.56

15	By-product_Cost	15	% of virgin resource	Increase_in_Emission	12150	20147218	6851214	14075866	32428306	16335058	0.77	-0.73
16	By-product_Cost	20	% of virgin resource	Increase_in_Emission	12150	21018022	5451046	14473981	36090721	18361722	0.72	-0.92
17	By-product_Cost	25	% of virgin resource	Increase_in_Emission	12150	22132996	4352034	14979804	40285012	20300247	0.64	-1.11
18	By-product_Cost	0	% of virgin resource	Network_Profitability	12150	8.86E+08	8.73E+08	8.95E+08	9E+08	18025064	-0.89	-0.48
19	By-product_Cost	5	% of virgin resource	Network_Profitability	12150	8.87E+08	8.74E+08	8.95E+08	9E+08	17731860	-0.95	-0.48
20	By-product_Cost	10	% of virgin resource	Network_Profitability	12150	8.87E+08	8.75E+08	8.95E+08	8.99E+08	17566551	-1.00	-0.46
21	By-product_Cost	15	% of virgin resource	Network_Profitability	12150	8.86E+08	8.75E+08	8.95E+08	8.99E+08	17432990	-1.03	-0.45
22	By-product_Cost	20	% of virgin resource	Network_Profitability	12150	8.86E+08	8.75E+08	8.95E+08	8.98E+08	17311212	-1.07	-0.44
23	By-product_Cost	25	% of virgin resource	Network_Profitability	12150	8.85E+08	8.74E+08	8.95E+08	8.97E+08	17172462	-1.08	-0.44
24	Market_Dynamicity	0.1	λ/μ	Aggr_Weight_of_By-product	24300	78113.8	12531.75	54008.5	137752.5	72737.73	0.68	-0.91
25	Market_Dynamicity	0.2	λ/μ	Aggr_Weight_of_By-product	24300	76827.34	12938.15	52417	132526.2	72090.9	0.74	-0.78
26	Market_Dynamicity	0.5	λ/μ	Aggr_Weight_of_By-product	24300	69383.42	13395.75	46776.8	115409.1	65504.95	0.81	-0.61
27	Market_Dynamicity	0.1	λ/μ	Ave_nRelations	24300	26.12566	25.04041	26.01301	27.07055	1.145912	0.37	-0.89
28	Market_Dynamicity	0.2	λ/μ	Ave_nRelations	24300	26.41096	25.08836	26.20205	27.64247	1.394594	0.37	-1.05
29	Market_Dynamicity	0.5	λ/μ	Ave_nRelations	24300	26.55125	25.11575	26.28151	27.80822	1.536917	0.45	-0.97
30	Market_Dynamicity	0.1	λ/μ	Increase_in_Emission	24300	20593404	7618928	15317647	31284619	16036500	0.77	-0.60
31	Market_Dynamicity	0.2	λ/μ	Increase_in_Emission	24300	20258150	7485273	15049272	30039219	15929545	0.85	-0.37
32	Market_Dynamicity	0.5	λ/μ	Increase_in_Emission	24300	19601960	7415330	14494718	28563266	15484938	0.91	-0.22
33	Market_Dynamicity	0.1	λ/μ	Network_Profitability	24300	8.99E+08	8.97E+08	8.98E+08	9.01E+08	4128899	-2.79	32.15
34	Market_Dynamicity	0.2	λ/μ	Network_Profitability	24300	8.96E+08	8.94E+08	8.96E+08	8.99E+08	4724279	-1.50	9.34
35	Market_Dynamicity	0.5	λ/μ	Network_Profitability	24300	8.64E+08	8.53E+08	8.63E+08	8.74E+08	12022718	0.29	-1.05

36	Storage_Cost	3.5	% of virgin resource	Aggr_Weight_of_By-product	24300	74998.03	13121.75	50718.2	127550.1	70654.3	0.76	-0.73
37	Storage_Cost	7	% of virgin resource	Aggr_Weight_of_By-product	24300	74732.15	12821.25	50259	127898.5	70296.9	0.75	-0.76
38	Storage_Cost	10.5	% of virgin resource	Aggr_Weight_of_By-product	24300	74594.39	13171	50647	127443	69924.47	0.74	-0.77
39	Storage_Cost	3.5	% of virgin resource	Ave_nRelations	24300	26.40114	25.08767	26.18801	27.51507	1.402048	0.45	-0.85
40	Storage_Cost	7	% of virgin resource	Ave_nRelations	24300	26.35926	25.07603	26.13904	27.43356	1.380097	0.49	-0.78
41	Storage_Cost	10.5	% of virgin resource	Ave_nRelations	24300	26.32746	25.08082	26.11301	27.35548	1.356853	0.52	-0.69
42	Storage_Cost	3.5	% of virgin resource	Increase_in_Emission	24300	20183509	7492318	15002350	30055743	15837818	0.85	-0.39
43	Storage_Cost	7	% of virgin resource	Increase_in_Emission	24300	20091592	7478608	14878627	30119615	15821480	0.85	-0.40
44	Storage_Cost	10.5	% of virgin resource	Increase_in_Emission	24300	20178413	7534020	14959971	30310250	15812991	0.84	-0.42
45	Storage_Cost	3.5	% of virgin resource	Network_Profitability	24300	8.86E+08	8.74E+08	8.95E+08	8.99E+08	17586077	-0.99	-0.47
46	Storage_Cost	7	% of virgin resource	Network_Profitability	24300	8.86E+08	8.74E+08	8.95E+08	8.99E+08	17548994	-1.00	-0.46
47	Storage_Cost	10.5	% of virgin resource	Network_Profitability	24300	8.86E+08	8.74E+08	8.95E+08	8.98E+08	17506745	-1.01	-0.43
48	Warehouse_Capacity	5	tonnes	Aggr_Weight_of_By-product	14580	2940.62	2121	2745	3908	1838.16	0.43	0.33
49	Warehouse_Capacity	20	tonnes	Aggr_Weight_of_By-product	14580	41898.19	19527.75	38257.5	61210.75	25034.55	0.21	-0.96
50	Warehouse_Capacity	35	tonnes	Aggr_Weight_of_By-product	14580	83117.89	30986	74151.5	126623.1	50663.52	0.14	-1.30
51	Warehouse_Capacity	50	tonnes	Aggr_Weight_of_By-product	14580	114479.4	39903.85	111678.2	179899.5	68388.18	-0.06	-1.52
52	Warehouse_Capacity	65	tonnes	Aggr_Weight_of_By-product	14580	131438.2	47157.35	138361.4	203816.4	75721.01	-0.16	-1.54
53	Warehouse_Capacity	5	tonnes	Ave_nRelations	14580	24.97597	24.64932	24.79041	25.0911	0.530738	2.67	9.68
54	Warehouse_Capacity	20	tonnes	Ave_nRelations	14580	26.34216	25.58545	26.18767	27.08562	1.085777	0.48	-0.48
55	Warehouse_Capacity	35	tonnes	Ave_nRelations	14580	26.84542	25.72055	26.69041	27.93904	1.445197	0.33	-0.85

56	Warehouse_Capacity	50	tonnes	Ave_nRelations	14580	26.8956	25.71627	26.9274	27.95223	1.377745	0.09	-0.99
57	Warehouse_Capacity	65	tonnes	Ave_nRelations	14580	26.75395	25.69658	26.84795	27.67226	1.217679	-0.02	-0.96
58	Warehouse_Capacity	5	tonnes	Increase_in_Emission	14580	5683288	2434727	3787350	6373270	5868042	3.46	16.19
59	Warehouse_Capacity	20	tonnes	Increase_in_Emission	14580	13450357	9001256	11891120	16877438	6855061	1.32	3.69
60	Warehouse_Capacity	35	tonnes	Increase_in_Emission	14580	21121270	12529192	19091086	29200403	11571750	0.49	-0.62
61	Warehouse_Capacity	50	tonnes	Increase_in_Emission	14580	28784157	14562160	27218136	42997976	16398445	0.15	-1.25
62	Warehouse_Capacity	65	tonnes	Increase_in_Emission	14580	31716786	15041755	32352504	47480475	17444937	-0.04	-1.36
63	Warehouse_Capacity	5	tonnes	Network_Profitability	14580	8.79E+08	8.5E+08	8.93E+08	8.95E+08	21315638	-0.67	-1.49
64	Warehouse_Capacity	20	tonnes	Network_Profitability	14580	8.84E+08	8.65E+08	8.94E+08	8.97E+08	17640176	-0.74	-1.19
65	Warehouse_Capacity	35	tonnes	Network_Profitability	14580	8.88E+08	8.75E+08	8.96E+08	9E+08	16153816	-0.88	-0.70
66	Warehouse_Capacity	50	tonnes	Network_Profitability	14580	8.89E+08	8.8E+08	8.97E+08	9E+08	14821492	-1.02	-0.25
67	Warehouse_Capacity	65	tonnes	Network_Profitability	14580	8.91E+08	8.84E+08	8.97E+08	9.01E+08	14044698	-1.15	0.20
68	Warehouse_Profit_Margin	3.5	% of virgin resource	Aggr_Weight_of_By-product	24300	74950.82	12907	50690.5	127686.9	70637.66	0.76	-0.74
69	Warehouse_Profit_Margin	7	% of virgin resource	Aggr_Weight_of_By-product	24300	74779.16	13078.5	50445.4	127683.3	70305.16	0.75	-0.75
70	Warehouse_Profit_Margin	10.5	% of virgin resource	Aggr_Weight_of_By-product	24300	74594.58	13085.75	50489	127597.3	69933.13	0.74	-0.77
71	Warehouse_Profit_Margin	3.5	% of virgin resource	Ave_nRelations	24300	26.39786	25.0863	26.18767	27.50839	1.403417	0.45	-0.85
72	Warehouse_Profit_Margin	7	% of virgin resource	Ave_nRelations	24300	26.36292	25.08151	26.14658	27.43699	1.379564	0.49	-0.78
73	Warehouse_Profit_Margin	10.5	% of virgin resource	Ave_nRelations	24300	26.32708	25.07671	26.1089	27.35822	1.356062	0.52	-0.70
74	Warehouse_Profit_Margin	3.5	% of virgin resource	Increase_in_Emission	24300	20159045	7454262	14980992	30112663	15852027	0.85	-0.39
75	Warehouse_Profit_Margin	7	% of virgin resource	Increase_in_Emission	24300	20145153	7499570	14930098	30081527	15824887	0.85	-0.40
76	Warehouse_Profit_Margin	10.5	% of virgin resource	Increase_in_Emission	24300	20149317	7542225	14940507	30234957	15795499	0.84	-0.42
77	Warehouse_Profit_Margin	3.5	% of virgin resource	Network_Profitability	24300	8.86E+08	8.74E+08	8.95E+08	8.99E+08	17603249	-0.99	-0.45

78	Warehouse_Profit_Margin	7	% of virgin resource	Network_Profitability	24300	8.86E+08	8.74E+08	8.95E+08	8.99E+08	17551655	-1.00	-0.46
79	Warehouse_Profit_Margin	10.5	% of virgin resource	Network_Profitability	24300	8.86E+08	8.74E+08	8.95E+08	8.98E+08	17486852	-1.00	-0.45
80	nWarehouses	5	warehouses	Aggr_Weight_of_By-product	12150	17146.8	5486.5	14525.2	26656.25	14457.45	0.68	-0.30
81	nWarehouses	25	warehouses	Aggr_Weight_of_By-product	12150	28007.04	14339.5	27790.1	39323.9	17250.96	0.32	-0.50
82	nWarehouses	45	warehouses	Aggr_Weight_of_By-product	12150	60408.23	30261.5	64051.9	94275.45	39264.79	-0.04	-1.21
83	nWarehouses	65	warehouses	Aggr_Weight_of_By-product	12150	95788.25	45196.5	101687.3	154240.8	63700.23	-0.12	-1.33
84	nWarehouses	85	warehouses	Aggr_Weight_of_By-product	12150	117590.9	55723	131185.6	188915.2	76227.25	-0.27	-1.35
85	nWarehouses	105	warehouses	Aggr_Weight_of_By-product	12150	129707.9	63674.25	151153.1	205821.3	81992.16	-0.38	-1.33
86	nWarehouses	5	warehouses	Ave_nRelations	12150	25.60806	24.91712	25.4089	26.10274	0.895223	1.07	1.10
87	nWarehouses	25	warehouses	Ave_nRelations	12150	25.2227	24.91781	25.14795	25.4911	0.389523	0.63	-0.18
88	nWarehouses	45	warehouses	Ave_nRelations	12150	25.92009	25.62757	26.01884	26.33151	0.639977	-0.44	-0.19
89	nWarehouses	65	warehouses	Ave_nRelations	12150	26.75016	26.18767	26.96884	27.53288	1.17068	-0.47	-0.59
90	nWarehouses	85	warehouses	Ave_nRelations	12150	27.22765	26.63425	27.54623	28.2149	1.43645	-0.64	-0.61
91	nWarehouses	105	warehouses	Ave_nRelations	12150	27.44707	26.8137	27.79521	28.55274	1.578821	-0.63	-0.61
92	nWarehouses	5	warehouses	Increase_in_Emission	12150	14015716	6029869	11146598	19321372	10508525	1.28	1.70
93	nWarehouses	25	warehouses	Increase_in_Emission	12150	8962937	6183563	8401395	11359736	3724407	0.63	0.10
94	nWarehouses	45	warehouses	Increase_in_Emission	12150	14732701	8782998	13812105	19881344	8077665	0.57	-0.08
95	nWarehouses	65	warehouses	Increase_in_Emission	12150	22964291	10719572	22063851	34061147	14677803	0.26	-1.02
96	nWarehouses	85	warehouses	Increase_in_Emission	12150	28481694	12860631	29969235	43092539	17911514	-0.05	-1.26
97	nWarehouses	105	warehouses	Increase_in_Emission	12150	31749690	14859182	35845429	48249690	19302775	-0.27	-1.28
98	nWarehouses	5	warehouses	Network_Profitability	12150	8.8E+08	8.58E+08	8.91E+08	8.95E+08	18837429	-0.65	-1.31
99	nWarehouses	25	warehouses	Network_Profitability	12150	8.83E+08	8.6E+08	8.95E+08	8.97E+08	18948593	-0.76	-1.28

100	nWarehouses	45	warehouses	Network_Profitability	12150	8.86E+08	8.69E+08	8.95E+08	8.98E+08	17282578	-0.89	-0.79
101	nWarehouses	65	warehouses	Network_Profitability	12150	8.88E+08	8.77E+08	8.96E+08	9E+08	16070434	-1.13	0.07
102	nWarehouses	85	warehouses	Network_Profitability	12150	8.9E+08	8.81E+08	8.97E+08	9.01E+08	15605010	-1.29	0.68
103	nWarehouses	105	warehouses	Network_Profitability	12150	8.91E+08	8.83E+08	8.97E+08	9.02E+08	15425169	-1.38	1.05