MSc Thesis Industrial Ecology

Sustainability Value Creation Through Circular Business Model Experimentation

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Improving Industrial Symbiosis Networks through a Case Study in the Netherlands

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Acronyms and abbreviations

ABM – Agent Based Modelling

BSG – Brewer’s Spent Grain

CBM – Circular Business Model

EIP – Eco-Industrial Parks

FF – Floating Farm

IS – Industrial Symbiosis

ISN – Industrial Symbiosis Network

M4H – Merwe Vierhavens

SNFailure – Symbiotic Network Failure

SVC – Sustainability Value Creation

TPB – Theory of Planned Behaviour

WP – Waste Processor

WS – Waste Supplier

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1. Introduction

Core concepts and problem statement

Circular economy is a concept which often comes up in discussions on how to reduce the environmental impacts of businesses. The Netherlands is no different and aims to be fully circular by the year 2050 (The Ministry of Infrastructure and the Environment 2016), a goal which will require major changes to current business practices in large industries.

In the Netherlands there are several so called 'eco-industrial parks'(EIPs), each of which strive to reduce the environmental impact of their respective businesses primarily through circularity (Sakr et al. 2011). Arguably the most important factor of success for an EIP is the application of industrial symbiosis (IS) on a large scale (Gibbs and Deutz 2007). IS is the concept which describes various actors (or industries) working together in networks in order to minimize their collective environmental impact and maximize economic and societal gains. These actor networks are often described as 'Complex Adaptive Systems' (CAS), as their interactions and subsequent emergent behaviour are highly susceptible to change due to only minor variations in the network. The study of such systems is one method used by Industrial Ecologists. The IS can be achieved through various methods which include, but are not limited to, collective utility management, establishing of material/energy flows in between previously unconnected industries and adding new industries to utilize streams currently regarded as waste (Lambert and Boons 2002; Pellenbarg 2004; UNIDO 2017).

Another concept that is central to EIPs is sustainability, a term used so liberally and broad that it does not have one definition in science. Kuhlman and Farrington (2010) discuss the historical change in meaning of the word at length and debate that this evolution has somewhat led our way of thinking on the subject astray. The focus used to be on the three 'pillars' of sustainability: social, economic and environmental. However, the environmental aspect has arguably lost attention compared to the other two over time. One of the primary goals of an EIP is to increase the level of sustainability of the network as a whole, in all three of these pillars. Something which most EIPs in the Netherlands do not succeed at (Valladolid Calderón 2021). To clarify how sustainability can be measured in an EIP, this study will provide a critical analysis of what it means to 'increase sustainability value', as it is not the same as 'increase value sustainably' which focuses on the economic aspect.

The question of how to 'increase sustainability value' can be linked to the concept of sustainability value creation (SVC). SVC describes how a system's level of sustainability might be improved through redesigning or adapting the system. However, as mentioned before however, the term 'sustainable' is associated with a wide array of other concepts such as global warming, resource depletion and pollution to name a few. It is therefore difficult to establish a single common means of measurement to determine how sustainable a system actually is. Furthermore, this makes predicting the 'sustainability value' created in a system nigh impossible to measure due to the lack of a common denominator. Therefore, this study will also reflect on how SVC might be measured for any system/network of interest. This is done by interacting with the network and exploring what aspects of sustainability are relevant (i.e., which ones might be influenced through altered business practice).

So, despite its potential, IS, and in extension EIPs, has not been very successful in the Netherlands (Sakr et al. 2011). Valladolid Calderón (2021) identified in their thesis a lack of knowledge when it comes to turning theory of IS into practice, which is seen as the primary cause for exchanges of material flows not happening in Dutch EIPs. This culminated in a cross-case study aiming to identify the factors that make successful EIPs in the Netherlands succeed. This study has brought valuable insights into these topics, but it still only scratches the surface when it comes to ensuring the future success of EIPs in the Netherlands. Another important factor for the failure of EIPs is the lack of robustness of industrial symbiosis networks (ISNs); ISNs are not robust in the sense that if one party leaves, it may cause the entire network to break apart (Lange et al. 2021a). The reason for leaving differs for each actor and situation. For example, it's possible one industry might decide to take its business elsewhere (for more profit or reorganization) and another is overtaken by another corporation which closed the site located in the network. This situation still persists in the Netherlands, which has undoubtably hampered progress towards a circular economy in the country. Therefore, more research into the inner working of these parks is needed to ensure their success.

Research problem

An important aspect of EIPs in the Netherlands, which is tied to the robustness issue, is the effective application of Circular Business Models (CBMs). CBMs help businesses and EIPs to plan ahead when it comes to their circular business practices and play an important role in the decision-making process. However, they are not widely used as there are inherent risks in trying out these mostly unproven business models (Lüdeke-Freund, Gold, and Bocken 2019; Schroeder, Anggraeni, and Weber 2019).

A recent publication by Lange et al. (2021b) sought to find a solution to this problem with CBMs through *ex-ante* experimentation. In their article they introduce a framework which applies agent-based modelling (ABM) together with the theory of planned behaviour (TPB) to model the outcome of various CBMs. For an illustrative example: urban ISN initiative for processing of organic waste. Agent based modelling is a computational method where a system or network of actors and stakeholders is modelled, and their actions simulated. Such systems are often considered 'Complex Adaptive Systems' (CAS), which are complex in the sense that they consist of many individual agents acting on their own and in doing so self-organize and show emergent behavioural patterns. The proposed case study can be considered a CAS because it entails multiple agents acting independently of each other, in addition to other numerous factors. The complexity of a CAS makes it exceedingly difficult to predict how a small change will impact the system as a whole. Important aspects of an ABM depicting a CAS include the relations and interactions between the various agents and the way these influence the network as a whole. By running many iterations of the ABM under different circumstances, the results it produces can be analysed for patterns. From these analyses recommendations/observations can be made to adapt the real network (Van Dam 2013). Using computer models for this purpose is faster, cheaper and easier than more conventional methods of testing such as real-life pilots, which require significant investment and time. The TPB is a psychological school of thought often used in conceptualizing and constructing these types of computer models, whereby the model attempts to simulate reality to a certain extent. Using the TPB when developing a computer model brings in the reality of human decision-making as a centerpiece, which makes the TPB highly relevant for these purposes.

The CBM experimentation framework allows for the testing of variables and scenarios in the model, which produces a likely survival rate for the network and economic gain for each input. These test results could be used by businesses to help in their decision-making whether or not to put a certain CBM into practice. Since they provide information on (1) the likeliness of the CBM to succeed and (2) the economic value created through the application of the CBM. Therefore, the computer model can potentially serve as a tool to promote the use and success rate of CBMs in ISNs.

Knowledge gap

As mentioned, the CBM experimentation framework is limited to the two dimensions of CBM likeliness to succeed and economic value creation. It does not consider the environmental, sustainability or circularity aspects of the system. While these aspects are some of the main reasons for establishing an ISN in the first place. This thesis will focus on the topic of sustainability in CBMs as it reflects both circularity and environmental aspects. Specifically, in the context of the CBM experimentation framework, the concept of sustainability value creation will be looked at in the context of CBMs. Some of the questions that come to mind are: How can one represent SVC in a CBM? How does it affect the choice for CBM? And its success rate?

When performing a literature search for the combination of terms "sustainability value creation" and "Circular Business Model" on Google Scholar (the largest database of scientific literature available), results in only eight hits. An even smaller number was found when looking for "CBM" instead. On closer inspection it was concluded that only one study gave insight into the relation between SVC and CBMs (Geissdoerfer et al. 2017). In the study the similarities and differences between circular economy/CBMs and sustainability is specified, which provides insight into how sustainability might be procured in a CBM. However, it does not give any indication as to how sustainability value could be explained/measured in a CBM and provides no insight into how SVC would influence or dictate a CBM. This thesis will attempt to fill this knowledge gap by defining how SVC can be represented in CBMs for ISNs.

This is where the CBM experimentation framework comes into play. Since the CBM experimentation framework was conceived in 2021, it has not been widely applied and it still needs refining. The framework has only been used for two CBMs to show the survivability rate and the economic value creation. It would benefit from the inclusion of SVC in its CBM experimentation. Certain ISNs, for example those with the primary objective of becoming sustainable, might be highly interested in the SVC potential of CBMs prior to implementation. The focal point of this study is the CBM experimentation framework, because it provides a steppingstone to include such dimensions in its methods. This study aims to supplement the CBM experimentation framework introduced in Lange et al. (2021b) by showing its potential to predict SVC in ISNs. To this end, this thesis will apply the framework to a case study of an Eco-Industrial Park in the Netherlands. This will add both credibility and scientific value to the framework by showing its applicability to other cases as well as demonstrate how it can be supplemented with the aforementioned aspects of CBMs.

2. Main research objective

This thesis' main research objective is to apply the CBM experimentation framework presented in Lange et al. (2021b) to a new ISN case, Merwe-Vierhavens in Rotterdam. The aim is to explore how sustainability value creation might be represented and determined for various CBMs using the same framework. However, as it is not clear from literature how sustainability value creation should be defined, this aspect has also been added to the present research.. For the specific case study this should be achieved and determined through close communication with participants of the network. Including another layer of insight to ISNs that aim to become more sustainable will add value to the existing framework. By showing the CBM experimentation framework can be applied to other cases both the credibility and scientific value of the experimentation framework are to be added upon. In addition, it shows how the anticipated sustainability 'value' gained or lost of experimental CBMs can be determined. This in turn may incentivise ISNs to adopt CBMs which have a higher predicted sustainability value than others may have in favour of having slightly higher economic value creation for example.

Research Question

To reach this objective, the following main research question for this study is posed:

How can the Ex-ante CBM experimentation framework presented in Lange et al. (2021b) be adapted to the case of an ISN of cattle-farmers and breweries and how can sustainability value creation be included as an additional dimension to aid in contract formation between these actors.

Sub-questions

To answer the main research question, several sub-questions are posed which coincide with intermediate objectives of the research approach:

1. *What parts of the existing CBM experimentation model are readily usable and what parts require adaptation for use?*
2. *How can sustainability value creation be included in an ISN and included within the CBM experimentation framework?*
3. *How can the results and insights gained in this study be used to develop generic design rules to supplement the CBM experimentation framework with sustainability value creation?*

Research Approach

This thesis' research takes a case-study modelling approach where an existing ISN in the Netherlands, the 'Merwe-Vierhavens' (M4H) in Rotterdam, will be subjected to study using the framework presented in Lange et al. (2021b). Merwe-Vierhavens is a development area located near Rotterdam's ports which has recently been the subject of a recent study by Thomas van den Dries (2021) on how circularity is perceived and is best facilitated. Ir. v.d. Dries has insider knowledge of the ISN and is still in close contact with the businesses located on site. He has indicated his willingness to facilitate communication between the author of this thesis and the businesses in Merwe-Vierhavens and provide additional insights. For this reason, the Merwe-Vierhavens was chosen as the case for this study.

It should be noted that M4H acts as a source of inspiration for this study and the goal is not to model the network as close to reality as possible. This is due to the nature of the framework and ABM in general, which would require extensive data collection over long periods of time which is not possible in this study as its running time is limited.

The CBM experimentation framework provides the steps necessary to construct an ABM of the actor network. After which the CBM experimentation design can be built and lastly analyse and use the data to suggest improvements in the tested CBMs. In the study two CBMs, which will have to be formulated in consultation with the case participants, will be tested for their sustainability value creation. Hence, the study's main methods consist of the framework.

This research approach has the advantage that it will showcase the proposed addition to the framework in a real-life example, which adds to its credibility that it will be more widely applicable to other ISNs as intended with the original CBM experimentation framework.

However, it should be noted that while this research focuses on a specific framework, this does not necessarily mean the chosen approach is ideal to fulfil the research objective. It might be more fruitful for example to focus on a type of modelling, other than ABM, which could provide other or even better insight into the value creation in an ISN.

3. Literature review

Sustainability Value Creation (SVC)

The concept of SVC is central to this thesis, as one of the main goals is to predict how different CBMs change the potential outcome for part of the M4H. The concept has its roots in the Brundtland Report (1987); which describes that current development (both economic and social) must meet both current and future generations' needs (Bilge et al. 2014). Over time however, the concept has been adapted and specified to include three main aspects of modern society: social, economic and environmental aspects (Kuhlman and Farrington 2010). Sustainability is very closely related to circularity and, by extension, to circular business models. There are many similarities and differences between circularity and sustainability (Geissdoerfer et al. 2017). Most importantly both concepts serve to the benefit of both the environment and the economy (i.e., businesses and their workers), which tightly binds them together. One aspect of sustainability is already covered by the CBM experimentation framework: Economic value gained and network survival rates represent the economic aspect (Lange et al. 2021b). However, out of these three, the environmental aspect is arguably the most pressing in regard of the current climate crisis (IPCC 2021). But it is currently not included in the framework of Lange, K. et al. Therefore, this thesis will explore how the environmental aspect of SVC can be represented in a multi-actor network, so the environmental performance of CBMs can be predicted prior to implementation.

The concept of assessing the environmental impact of a company's business model, be it circular or not, has grounds in literature in the form of various 'scorecard' systems (Hansen and Schaltegger 2016). The main goal of these scorecards was to indicate both the economic and sustainability performance of a company, as these two aspects of business are often not well-connected. In addition to promoting strategic sustainable development management (Hristov, Chirico, and Appolloni 2019). One of these stands out: the 'sustainability balance scorecard' (SBSC), a framework which considers all three major pillars of sustainability in its assessment (Hansen and Schaltegger 2016). In another review, the SBSC was improved to better reflect the three pillars in its framework. The newly 'adjusted' SBSC (ASBSC) gives clear goals and perspectives for a company or system to become both sustainable and economically profitable (Hristov, Chirico, and Appolloni 2019). This includes several indicators with which to assess the environmental sustainability performance of a company, along with economic and social indicators. For this thesis, the environmental aspect of sustainability is considered the most important. Hence, the indicators given in the ASBSC will serve as a guideline to determine suitable ways of measuring how well the modelled network performs in terms of SVC.

In the ASBSC, several aspects of a company's functioning are mentioned that should be monitored specifically when evaluating environmental performance and integrating sustainability in company strategy. These aspects are summed up in Table 1:

***Table 1**: Environmental aspects with indicators for companies according to the ASBSC framework from Hristov, Chirico, and Appolloni (2019)*

Environmental aspect	Indicator
Utility consumption	Energy, electricity, water, gas
Emissions	Air (GHG and other), water and soil
Disruptions	Radiation, noise, vibrations
Waste	Recycling rate for materials and water (% of waste separated),
Flow	Degree of circularity (rather similar to sources)
Sources	Energy mix, electricity mix, water origin, materials used (primary/secondary?)
Efficiency	Material and energy lost in production/processing

A number of environmental aspects with accompanied indicators were determined. From these, several will be selected for use in the model through careful consideration with the various agents involved, as not all aspects are relevant for every type of business or system. When chosen, a suitable unit of measurement will also be determined (e.g., air emissions might be measured in CO2-eq).

Circular Business Models (CBMs)

The other concept central to the thesis is Circular Business Models (CBMs). In a nutshell, CBMs are business plans with a focus on circularity of resources (Reduce, re-use and repurpose materials rather than recycle), while considering the socio-economic aspects as equally important. Lüdeke-Freund, Gold, and Bocken (2019) published a review of the current literature on CBMs. In it they sub-divided CBMs into the logistical part of 'Closed-Loop Supply-Chain'(CLSC) and economical part of 'Circular Economy Business Models' (CEBMs or CBMs for short). The major difference between the two parts is that CEBM focuses on the idea of value captured: a business model has to produce (monetary) value for the company. While CLSC focusses on the flow of resources and materials in their life cycles by looking for opportunities to move away from the traditional, linear product-life (produce → use → dispose) towards a more cyclical life-cycle. These 'reverse cycles' as they are called, are one of the most well-known and effective ways of implementing a circular based economy. The most important of these cycles are displayed in Figure 1:

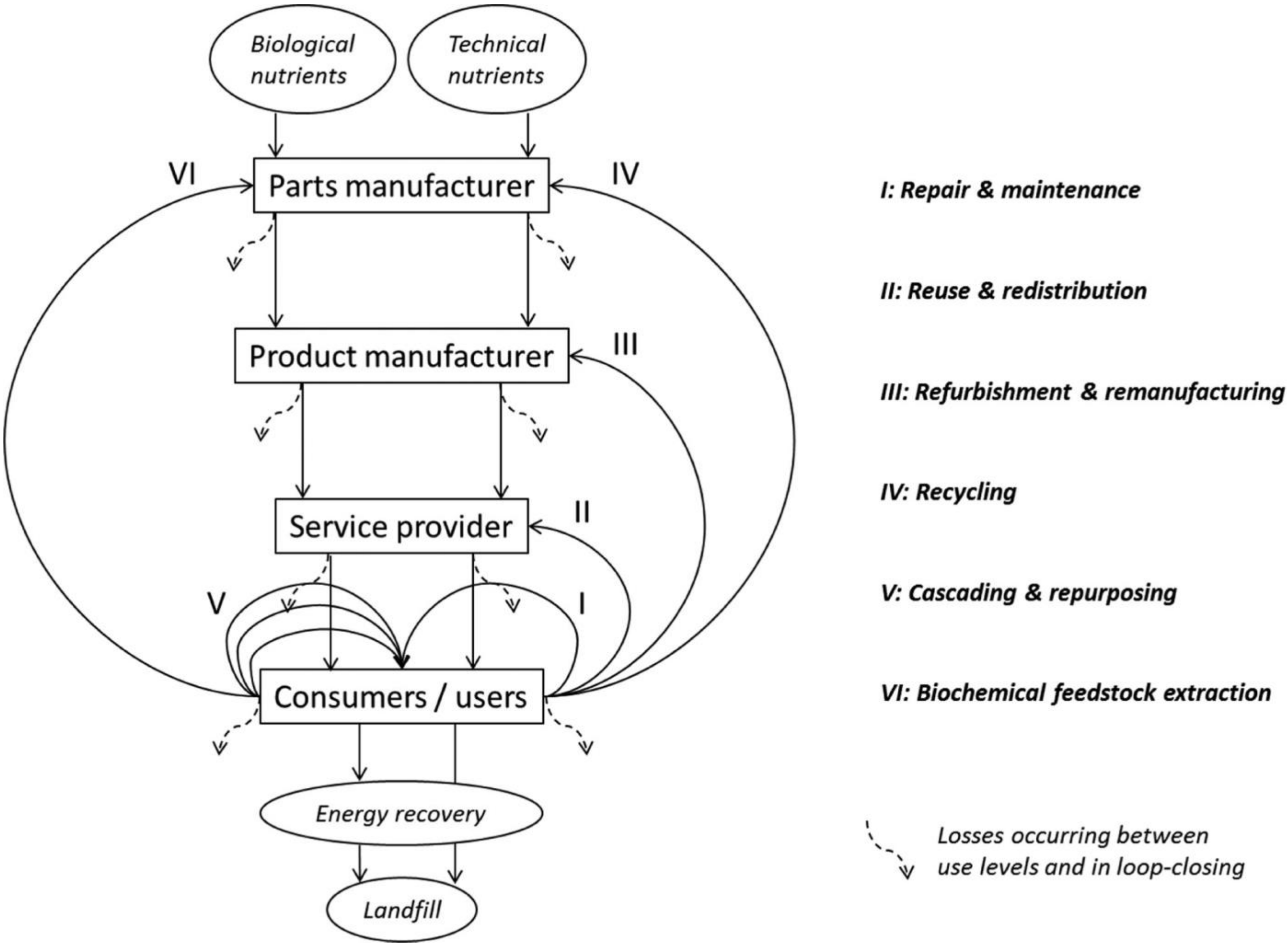

***Figure 1**: most important logistical reverse cycles in circular economy (taken from Lüdeke-Freund, Gold, and Bocken (2019))*

In this thesis, the main goal is to predict changes in environmental sustainability of a network prior to implementation. Given the conclusions from the review by Lüdeke-Freund, Gold, and Bocken (2019), it is logical to focus on the logistical part (CLSC) rather than the economical (CEBM). When conceptualizing the network and its actors, the examples provided in the review will give insight into possible alternative scenarios and what type of CLSC the network is working in right now.

The supporting information from Lüdeke-Freund et al (2019) lists examples of 26 CBM types, which can be used to identify the current (if any) CBM used in the network what might be a suitable one to use for experimentation.

Existing NetLogo model

The existing model presented in Lange et al. (2021b) describes the system of a biodigester processing local waste in the municipality of Amsterdam. This is very different to the network in M4H, which means it cannot simply be applied to the case of M4H. Some parts may be adapted or even copied over however, which could indicate that the model can act as a strong basis for future applications. To aid in the modelling of the M4H network, the existing NetLogo model was disseminated into parts which were categorized into functions, actor-affiliation and other relevant aspects of an ABM. For example, the process of contract formation or transport of goods from one actor to another might already be presented in the current version of the code and could thus be adapted without much change necessary.

The nature of the research means that it is highly dependent on the current situation of the ISN, if there is any meaningful cooperation between the agents at all. Therefore, many aspects of the original model will likely be left out or highly simplified. Depending on the state of the network, some of these aspects might be taken over and some might be disregarded. In any case, the code-modules from the original models will be considered.

4. Research Methods

In this thesis, an adaptation was made on existing work from Dr. Ir. Kasper Lange. This section specifies what steps were taken to obtain sufficient data in order to adapt the existing model and answer each sub-question posed. The CBM experimentation framework is applied to the case of M4H while also adhering to the general rules of ABM as described in Van Dam (2013). This was done to add clarity to the various steps performed, as the level of detail in describing them is higher in the latter work. The primary objective of this thesis is to introduce the concept of SVC into the CBM experimentation framework, which first requires a functional ABM of the current situation. Therefore, the application of the framework and adaptation of the model are the primary focus of this section.

Adapting the CBM experimentation framework

The CBM experimentation framework from Lange et al. (2021b) will be applied to the ISN of 'Merwe Vierhavens'. The framework consists of 5 iterative steps:

1. Case selection and description

This is the phase wherein the case-study should be described in the context of the study, i.e., how it will be represented through interactions, actors and stakeholders within the system. Other aspects include the processes, concepts and features of all elements within the system and how they will be used in the study. This section will use insights gained from the initial interviews as input.

2. Participatory and iterative model conceptualisation

This phase describes the conceptualization of the model through participation of the parties within the described system in further interviews. The goal of the model will be defined within the context of the given research question and based on that the relevant agents and features of the system will be targeted with further research (both interviews and literature study where relevant). The result will be a visual overview of the system and its interactions, which serves as an initial steppingstone for the next step in the process. Finally, at this stage the exact nature of sustainability value creation for this case will also be defined, as it is the central point of the next iterative step.

3. Software implementation

In this step, the model as it was conceptualised in the previous phase will be implemented in the NetLogo software. This includes extensive coding and visualization of the logic process through figures and schematics. This step accounts for a major part of the study, as modelling choices made in the previous steps stand to benefit from being revised and changed because of new insights or limitations. In addition, it is also the step which is most complex, as this is a complex adaptive system and benefits from a high level of detail in its modelling.

4. Experimental design

This phase includes the conception and application of the conceived model for the purpose of CBM experimentation; The model will be run multiple times with various parameterizations to provide data and insights to further answer the research questions. To determine what parameterizations are appropriate for the experimentation, a short literature review might be appropriate. Alternatively, the author of the paper introducing the CBM experimentation framework, Kasper Lange, could be consulted for additional insight.

5. Explorative and iterative CBM experimentation and analysis

Finally, this phase describes the analysis of data from the experimental design of the previous phase. Data will be subjected to statistical analysis in programming tools such as Python, R or a program such as excel, where the data can also be visualized. From this analysis the research (sub) questions are answered and recommendations are made for future changes.

In this thesis the CBM experimentation framework introduced in Lange et al. (2021b) is adapted to incorporate environmental aspects in addition to being applied on another case study. The structure of this research is identical to the framework, with the main differences being in how the software implementation is performed. The phases are a simplification of the steps conventionally followed in ABM (Van Dam 2013), the 'formal' steps as explained in that review are included underneath the phases used in Lange et al. (2021b):

1. Case selection and description
    a. Problem formulation and agent identification
    b. System identification and decomposition
2. Participatory and iterative model conceptualization
    a. Concept formalisation
    b. Model formalisation
3. Software implementation
    a. Software implementation
    b. Model verification
4. Experimental design
5. Explorative and iterative CBM experimentation and analysis
    a. Experimentation
    b. Data analysis
    c. Model validation
    d. Model use

For clarity, the framework will be applied using these headers and sub-headers.

5. Adapted framework application

In this section the adapted framework is applied to the hypothetical case of dairy-cow farmers of Floating Farm, trading with local breweries.

5.1 Case selection and description

Problem formulation and agent identification

For this study the Merwe-Vierhavens area of Rotterdam was considered as it is an area with known, small-scale ISNs and all companies there are motivated to work together towards a circular economy. The park has approximately 100 participants which range from small scale businesses that make products to logistical companies and collective organizations. In this study only a smaller part of the district will be considered since not all participants work interact directly with each other and it is reasonably impossible to model all of them in the time for this project. Therefore, advice was sought for any pre-existing cooperation between actors through contacts at both the Hogeschool Rotterdam and Rotterdam Maker's District Symbiosis.

As a centrepiece of this initial scoping phase, two businesses in the district were especially of interest: The Floating Farm and the Stadshaven Brouwerij. Floating Farm is of interest specifically, because they act as a sink for various organic waste streams in the M4H district as these can be added as a food supplement for the cows they own. The Stadshaven brewery (and other breweries) produce brewer's spent grain (BSG) as their main waste, which is rich in proteins. Therefore it is highly suitable as a supplement for the cows at Floating Farm (Belibasakis and Tsirgogianni 1996). Based on contact with the businesses and the information they provide on their websites, Floating Farm is already cooperating with various breweries in the area by taking on (part of) their BSG. This is in addition to other sources of organic waste from caterers and restaurants, but these will not be considered for this model as there is little data considering those flows. This provides us with the two main types of actors in the model: Floating Farm and local breweries.

After numerous attempts to secure the cooperation with businesses located in the M4H district, it was concluded that they were not willing to share the necessary date nor would they accept to be interviewed. This limited the study's capacity to model the network's level of detail and forced a different research approach; the case of breweries cooperating with Floating Farm was taken as an inspiration for a hypothetical model, where it provided the inspiration for many of the aspects included in the model. Therefore, this should not be considered a case-study in the same sense as the original application of the framework was, as the amount of data available was very limited comparatively. Due to this lack of information, the network dynamics and interactions were estimated from public data available on the companies' websites as well as literature and logical deduction. From this data, a model depicting the current situation (i.e., one Floating Farm collecting BSG from multiple breweries) was constructed.

The main goal of this model is to provide insight into both the contracting dynamics and the environmental impacts related to the cooperation between Floating Farm and local breweries. Specifically, by experimenting with two CBMs which dictate the amount of BSG going from breweries to the Floating Farm. This will showcase the framework's ability to predict not only economical results, but also environmental impacts of different CBMs.

System identification and decomposition

In this phase, data would be gathered using participatory iterative methods such as interviews and brainstorm sessions with the subjects of study to identify all aspects of the network. However, both the Floating Farm and breweries were either unresponsive or did not wish to cooperate with the researcher. Due to this limitation, it was decided to model a hypothetical state of the network instead of the current state of affairs. Data was collected on agents, their (inter)actions, the boundaries of the system and the role of the environment. The basis for assumptions made later in modelling is also explained here.

Actors and their properties and (inter)actions are summarized below.

Floating Farms:

- Properties/states
  - Has a static number of cows in each single run, which have a static demand for feed.
  - BSG demand, dependent on the number of cows which the Floating Farm will always aim to fulfil.
  - BSG storage capacity in which they aim to have at least 1 weeks' worth of consumption in storage at all times.
  - Participating in the network or not, which is determined by whether they get their BSG from breweries (participating) or the market (not participating).
- Actions
  - Determine whether they need more BSG for feeding their cows
  - Check for breweries with available BSG until they satisfy BSG demand.
  - Initiate contract formation with breweries.
  - Repeat until BSG requirement is met or there are no available contracts. In which case additional fodder is bought from the market/environment. This influences the environmental flows coming out of the actor.
  - Produce methane per time-unit dependent on number of cows
  - Produce manure per time-unit dependent on number of cows
  - Repeat

Based on the article of Belibasakis and Tsirgogianni (1996) it was determined that 25% of cow feed could be made up of BSG to allow for optimal milk production, which is the value that will be used in this review. The article also argues that BSG can be consumed in its wet state by cattle, as long as it is done so in short time-period. Since the Floating Farm has a capacity for overstocking on BSG, it is assumed for simplicity that BSG does not deteriorate in the timespan of 12 weeks; old BSG is consumed first and it is stored in a cool, dark place which ensures continued viability for use as feed. To prevent spoiling of older BSG, Floating Farm will empty stocks first before signing a new contract. Since higher milk production logically equals more profit, it was also concluded that Floating Farms will always aim for complete fulfilment of this demand. The other 75% of feed is considered fodder in this review, as that is what cows would normally receive on grazing fields. The costs associated with fodder, both economic and environmental, are not considered in this review.

High production dairy cows require approximately 175 kg of dry feed per week (albertamilk.com). Considering the BSG is in a wet state when consumed, it was assumed that cows require a total of 200 kg of feed per week in the Floating Farm.

Breweries:

- Properties
  - Distance to Floating Farm in meters
  - Produces BSG every time-unit/tick which can be traded to Floating Farm or the market
  - Has beer-brewing facilities with a static capacity in a single run, can vary between runs to show potential differences in behaviour space
  - Random price per kg BSG; base price with slight variance + modifier/addition related to the distance to the centre (transport related costs)
- Actions
  - Produce X kg BSG per week, which has to be sold off to Floating Farm or the market.
  - Announce their distance and price to Floating Farm
  - Receive offers for contracts from Floating Farm
  - Fulfil contract requirements by delivering BSG to contractors
  - IF there is still an excess of BSG, it is transported to the market
  - Repeat

Breweries present in the vicinity of the Floating Farm are more than likely willing to cooperate by trading BSG, as can be seen by the actual cooperation present in M4H.

Distance between breweries and the Floating Farm would likely translate to slight differences in price for BSG, since transport over longer distances would logically increase. This model does not consider the possible different methods of transportation and considers a simplified situation where price increases linearly with distance.

Since there is no data on the means of transportation of BSG, the action of transport itself was not included. This includes any potential environmental impacts associated with it.

Environment:

1. Sets a global base price for BSG.
2. Acts as a sink (market) for excess BSG from breweries.

The global market price of BSG directly influences the agreed sums for traded BSG in contracts between breweries and the Floating Farm. Since the model depicts a symbiotic network, it is assumed that businesses inside it are willing to drop prices for the sake of reduced environmental impact. Prices for BSG traded within the network are therefore lower than if it were bought from the market because transport would logically be less (normally BSG would have to go to farms outside of the city).

These agent/environment states, interactions and the system's boundaries were all estimated without the participation of the companies and may include concepts which either are irrelevant or too complex to model. Many of these concepts were refined, excluded or otherwise changed in the model formalization to finally produce a functioning model.

5.2 Participatory and iterative model conceptualization

Concept formalization

This stage aims to contextualise the agents, their relations/interactions with each other and the environment for formalization into an actual model. Contextualise in this sense means translating real-world concepts in such a way they can be understood and processed by a computer (a computer does not understand the concept of a written contract for example).

Normally formalization would be done through participatory interviews with the agents in question, due to limitations it was however not possible to do so. To simulate the way these interviews would influence the application of the framework, this chapter contains sections where interviews would have been a major influence in deciding certain aspects of the (conceptual) model.

The network in its current state only contains one Floating Farm and a number of breweries which provide part of their BSG to the farm. In this review the primary goal is to describe the network in its current state; one Floating Farm collecting BSG from multiple breweries.

In this network, the Floating Farm acts as the centrepiece, wherein they serve the role of BSG sink. I.e., it takes up as much BSG from any breweries in the area as possible and uses it to supplement cow feed. Through discussion in interviews and conferences it would likely be concluded this has at least two foreseeable benefits for the participants:

1. The cows will receive more protein-rich feed which increases their milk production and thus profit for the Floating Farm, possibly allowing them to expand their facilities. Floating Farm assumably also has to spend less on buying fodder.
2. The breweries can safely and conveniently get rid of their waste through local means rather than having to pay for transport and handling to another location outside of Rotterdam.

The economic benefits are apparent for both parties, but underneath the surface there could be unanticipated environmental impacts that are exacerbated if this cooperation would increase in the future. For example, if the percentage of proteins in the cow's feed increases it will lead to them producing more methane, a highly potent greenhouse gas. This is in addition to the increased water use and manure produced by the Floating Farms, should they expand and their productivity increase. Also, contracts might become highly competitive which drives prices down to the point they might cost the breweries more money than they save.

Transport

Another aspect that would likely be mentioned in interviews is the distance between Floating Farms and breweries; an important question asked would likely be "Who pays for transport? How much will it cost? And is it more sustainable than transporting to the national market?". Therefore, the conceptual model considers distance an important factor, as transport of goods such as BSG (i.e., high weight but low value) will inevitably influence the price. Breweries that are further away from the Floating Farms might ask a higher price for their BSG as its transport will account for a larger part of the associated costs. Alternatively, they might lower the price of their BSG because they want to deliver to local consumers rather than far-off farms (either due to transport costs or because they desire to facilitate the companies within M4H). It is assumed that a longer distance to the Floating Farm will increase BSG price to a minor extent, as transport will logically be more expensive.

SVC indicators

The major goal of this study is to show that the experimentation framework can be used to include environmental aspects through SVC. Therefore, another important aspect of the model conceptualization which would be discussed in interviews and conferences with the participants, is the SVC and how it should be included.

Through interviews the SVC categories which were mentioned in chapter 3 would be discussed with the participants (mainly Floating Farm). Through an iterative process the selection of categories to be included would be refined to include one or several which could act as SVC indicators in the model. In the context of this network, the likely candidates for selection would be emissions (methane and manure) and utility consumption (gas and water). These categories are closely associated with dairy production using cows. Therefore, these categories will be included in the model as indicators for SVC as if they were selected through iterative participation with the agent.

Theory of planned behaviour

A highly important aspect of the original CBM experimentation framework and ABM is the Theory of Planned Behaviour which was applied through values set for associated variables in the model. These variables are highly complex and directly influence the way in which agents act when forming a contract. The variables are conventionally determined by extensive interviewing and reviewing of data, which was not possible in this instance. Because of the lack of data and the similarities between the original case of Amsterdam and M4H, it was therefore decided to leave the values exactly the same as in the original.

Contracts

Contracts between Floating Farms and breweries are not considered agents, but they have a set of rules associated with them:

Contracts:

- Have a set length which is negotiated/determined at the formation.
- Have a set price for the duration of the agreement
- Have a set amount of BSG which the brewery agrees to deliver to the Floating Farm that initiated the contract each time-step.

The aforementioned concepts will be represented in the model through various means, the initial ideas for which are described in the tables below:

Table 2*: Floating Farm and cows' concepts and their variables*

Concept	Representation	Possible values
Number of Cows	Integer	> = X and < = Y
BSG demand	Integer	Cows * initBSG_per_cow_required
Methane produced per time unit	Integer	Literature number
Manure produced per time unit	Integer	Literature number
Gas demand per time unit	Integer	Literature
Water demand per time unit	Integer	Literature

Table 3*: Brewery concepts and their variables*

Concept	Representation	Possible values
BSG production per year	Integer	> = X and < = Y
Distance to Floating Farm hub	Integer	> = 1 and < = 20
Price per kg BSG	Integer	Random value (between two values) * distance modifier OR Random value + distance dependent integer

Table 4*: Contract concepts and their variables*

Concept	Representation	Possible values
Duration	Integer	> = X and < = Y
Amount of BSG delivered	Integer	> 0
Price per kg BSG	Integer	Random value (between two values) * distance modifier OR Random value + distance dependent integer

Before the model can be formalized, many simplifications must be made in the form of assumptions. Most assumptions are made primarily to account for the fact this study was not able to obtain any data through interviews from the businesses described in the model. Using these assumptions, it becomes possible to show the proof of concept of the new model. Assumptions were made using auxiliary sources of information, comparison to other networks and logic.

Main Assumptions:

1. BSG makes up 25% of feed for cows, the rest of which is made up of fodder acquired from the market which is outside of the scope of this review.
2. All Floating Farms will pursue to fulfil the complete demand for BSG by establishing contracts with breweries.
3. The BSG can be consumed directly after production in the brewery (in its wet state) and does not need any treatment, only transport.
4. Transport of BSG only affects cost and does not have an emission attached to it.
5. Cows require 200 kg of food every week (per cow).
6. Food which is not BSG consists entirely of fodder which comes from outside the system and is not considered in the model.
7. There are multiple breweries in the vicinity of the Floating Farm willing to trade BSG, the base number of which can be altered in the model.
8. Distance between the Floating Farm and breweries does not include the type of terrain in between and is assumed equal for all breweries (i.e., there is no distinction between water or land distance).
9. All types of transport between agents are exactly the same. The only difference between them is the distance travelled which directly influences emissions (not included in the model) and cost of BSG.
10. The price of BSG is determined by a base value that represents the overall market value of BSG from the environment (i.e., what a company would pay if they were to buy BSG on the national market). Since this review focuses on the environmental aspects of symbiosis in the M4H network, it is assumed the base market price for BSG is twice as high as BSG traded within the network due to lower transport cost and a general willingness to contribute to lower environmental impacts by the participants.
    a. It is also assumed that the price of BSG differs between breweries based on the distance to the Floating Farm hub: The larger the distance, the larger the effect on price. Which is calculated as follows:
    Base_BSG_price_brewery = (BSG_marketprice * 0.5) * (1 + distance_to_hub / 4000)
    This means that every 100m of distance between the brewery and the hub causes a 2.5% base price increase.
11. Floating Farms will continue to seek contracts for BSG until they have more than the required weekly amount of BSG. Any leftover BSG will trickle over into the next tick, which builds up a stock for use. It is assumed that BSG can be stored for at least 3 months (12 weeks) and older BSG is fed to cows first, this means in practice that the BSG stock never deteriorates in value over time.
    a. When a BSG-contract ends, Floating Farms will first empty their stocks of BSG they have built up (which can take several ticks) before trying to find a new contract to balance their BSG-consumption/import. The new contract will be established in the tick prior to the storage emptying, to ensure the BSG supply never runs out.
12. Assumed contracts always run their full course before being terminated.
13. When there is a deficit in BSG-stock for the Floating Farm in a tick and there are no more contracts available (or they are too undesirable), the Floating Farm will acquire BSG from the market and the ISN is assumed to have failed.
14. At the start of each run, all Floating Farms have a week’s worth of BSG in their stores as leftover.

Model formalization

In this phase normally the conceptual model would be rewritten and formalized in the form of pseudocode, which is akin to a code narrative from which the actual model is written. This narrative describes the interactions that agents within the model will perform with each other, in a logical order. However, since the new model is an adaptation of an already existing one, there was no pseudocode involved. Rather, the existing code was directly adapted and added upon segment by segment while a code log file was continuously updated to keep track of changes.

Specific details on all changes made to the code are excluded as it would be too extensive to cover here. Instead, all changes to the code are depicted in appendix A, the code log. Please note the code log is not intended as a reference on how to change the code itself, as it was written with the sole intent for use by the researcher. It was merely included to provide additional insight to modellers interested in how the adapted model was established.

Instead, a simplified overview of the model's functionality is shown in Figure 2.

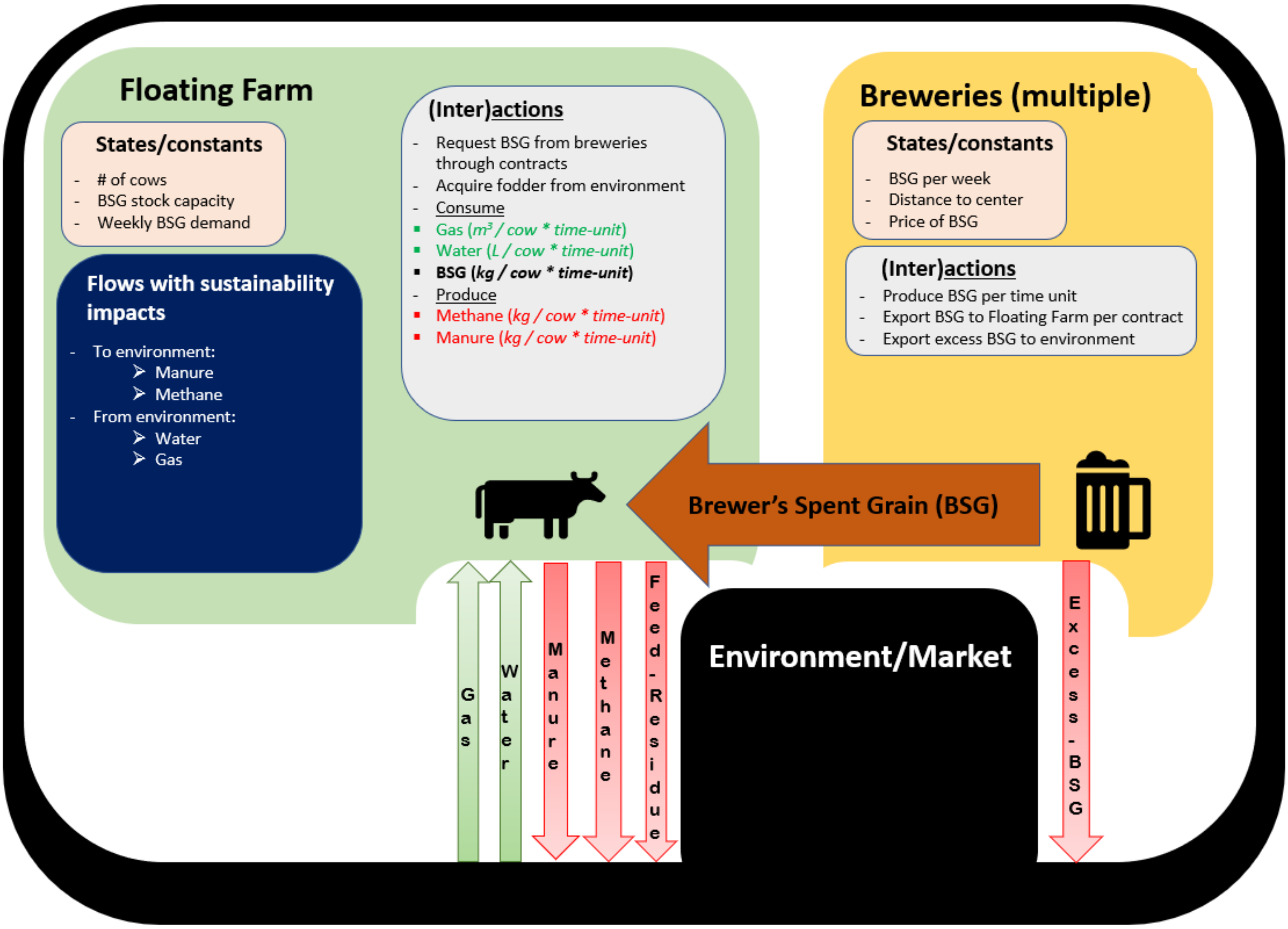

***Figure 2**: Simplified conceptual model prior to software implementation. Floating Farm and brewery agents are shown with their initial states and constants, their interactions and their potential sustainability impact flows. Interaction with the environment or market is shown as arrows, red meaning outgoing (i.e., selling or emitting) and green meaning incoming (i.e., buying). Contract formation is not included in this figure.*

5.3 Software implementation

Software implementation

Extensive reworks of the old model were made to accommodate the newly described situation, while there were also a large number of similarities:

- Waste processors (WPs) and Waste Suppliers (WSs) act in almost the exact same way, which is why most references to them has been left unchanged. For clarity they have been renamed to ‘Floating Farm’ and ‘Breweries’ respectively in the overlay, while leaving most of the underlying code still referring to WP and WS.
- Contracting was also assumed to be highly similar (since no real data could be referred to), which is why code pertaining to the way contracts are presented, negotiated and established is highly similar.
- Anything related to the Theory of Planned Behaviour (TPB) has been left exactly as before, including initial values for runs which are set by the ‘Default_settings’ command.

Many aspects of the model had to be changed in order to make sense in the context of the new situation however, most importantly what states and variables the agents in the model have and how these are altered:

- Originally, the states and variables of WSs were imported from a datasheet which were dependent on Latin Hypercube Sampling. This form of sampling has been omitted from the model to retain simplicity and agents (both WPs and WSs) were given pseudo-random values at the start of each run (small discrepancies to a base value). This means that each run will be slightly different due to changes in both BSG availability/price and its demand.
- Contracts can have a fixed or variable length in a run, wherein variable contract length is determined at random for each individual contract (up to a limit of 2 x Contract_length variable)
- Contract volumes (i.e., the amount of BSG traded per tick) are now allowed to be lower than the previous model, which required either all of a supplier’s waste or up until enough to meet demand for processor. When set to variable, contract volumes will end up between a global minimum (250 kg) and the maximum which is the weekly production of supplier. This was done to better reflect equal opportunity in the network for suppliers to deliver their BSG as well as diversifying of risk for the processor (with more suppliers there is a lower chance of failure of delivery). Additionally, the minimum volume ensures that no contracts are made for a negligible amount of BSG (which would be too inefficient to transport).

Model verification

To verify the conceptual model was translated correctly, it was run numerous times and its reporters (shown as graphs) and agents were observed under several possible setups. In addition, the general behaviour of agents with each other and the environment (i.e., do they interact as expected and update their variables correctly) was monitored. Several model variables were tested individually as well as together for their influence on the model, their evaluations are shown in Table 5 below.

***Table 5**: variables checked during model verification*

Variable	Functions as intended?	Notes
Fixed_contract_length?	YES	When turned on, contracts have a fixed duration of exactly the number of ticks chosen on the 'Contract_length' slider. When turned off the duration of contracts is determined at random for each individual contract established.
Amount_of_FF	YES	Correctly creates the number of Floating Farms on set-up.
Amount_of_breweries	YES	Correctly creates the number of breweries on set-up.
minimum_contract_volume?	YES	Allows contract volumes smaller than WSWWeek of breweries while remaining higher than the set minimum contract volume.
Minimum_contract_volume	YES	No contracts established are of a lower volume than the minimum set value.
Initmethane_per_cow_produced	YES	Methane produced by cows shows correct values in the graph depending on setting.
Initmanure_per_cow_produced	YES	Manure produced by cows shows correct values in the graph depending on setting.
initBSG_per_cow_required	YES	BSG required translates into a BSG demand which is in turn met through contracting. Fodder demand is only shown through a number which updates correctly.
initfodder_per_cow_required	YES	Fodder requirement updates correctly throughout model runs
Initwater_per_cow_requirement	YES	water requirement updates correctly throughout model runs
Initgas_per_cow_requirement	YES	gas requirement updates correctly throughout model runs

In addition to the variables, the behaviour of specific agents was also tested. It was concluded that floating-farms (FFs) establish contract with the most lucrative breweries (i.e., the best prices for BSG) up to the point that weekly BSG demand is met for most runs. Problems arise, however, once there is more than one floating-farm in the network; the process of contract establishment does not function properly and causes extreme volumes of BSG to be traded, causing a major surplus in floating-farms whenever two FFs attempt to contract a new brewery at the same time. Most of the times one of the FFs' BSG stock then plummets and the run ends, indicating an SN-failure (Symbiotic Network-failure). The code provided from the original model did not provide a sufficient way to model multiple waste processors bidding for waste at the same time, the code for which is highly complex. It was therefore decided to stick to a simplified state of the network with only one Floating-Farm. There are instances where the model also stops with only 1 Floating Farm, indicating an SN-failure as well. This is comparable to the possible outcomes of the original model, in which there was always the possibility a waste processor would not be satisfied with the contract options presented and would opt out of the network.

Breweries who have excess BSG (either contracted or un-contracted ones) correctly establish 'contracts' with the environment/market to sell off any excess. The environment in turn tracks the amount of BSG it receives through a global variable correctly. Prices for BSG alter with each run as expected (due to a difference in distance from the FF, which influences the price), which in turn causes the FF to establish different contract every run.

5.4 Experimental design

The adapted model includes aspects which were not present in the original model; the two most influential are the variables 'fixed_contract_length?' and 'minimum_contract_volume?'. Both variables represent an important aspect of contract formation which were simplified in the original, where contracts always had a fixed length and were highly flexible when it came to determining volume (either max BSG or the remaining deficit of BSG would be the agreed volume of a contract). This would sometimes lead to contracts with relatively low volumes, which is unrealistic in the case of BSG trading (it would be too much effort for little gain). By including a minimum volume requirement, more realistic contract formation can be simulated. Since there is no data or information on existing CBMs within the network, experimentation will be conducted on the effect these two variables have on BSG trading contracts within the system. The main reporter for this experimentation will be the amount of BSG present in the Floating Farm each week.

Experiments will be run on the effect of two variables which were added to the model in this review: 'contract_fixed_length?' and 'minimum_contract_volume?'. Because they both change BSG contracts in a significant way. These experiments are organized numbered 1-4 as shown in Table 6.

Table 6*: experiments performed using the new model and their configurations*

	minimum contract volume OFF	minimum contract volume ON
Contract fixed length OFF	Experiment 1	Experiment 2
Contract fixed length ON	Experiment 3	Experiment 4

Other model variables were kept constant at predetermined values, all of which are explained in Table 7.

Table 7*: default values for variables used in the model during experimentation*

Variable	Value	Reasoning
Minimum contract volume	250 kg	Approximately half of a brewery's BSG produced per week
Amount of Floating Farms	1	As stated prior, the model only works for a single FF
Amount of breweries	30	A surplus of breweries ensures the Floating Farm can find ample contract opportunities since there is an overabundance of BSG in the system. If there were less it would lead to more frequent SNFailure
Initmethane per cow produced	2 kg	Chosen arbitrarily since it was only used to provide proof of concept for SVC inclusion
Initmanure per cow produced	5 kg	Chosen arbitrarily since it was only used to provide proof of concept for SVC inclusion
Initwater_per_cow_requirement	20 m3	Chosen arbitrarily since it was only used to provide proof of concept for SVC inclusion
Initgas_per_cow_requirement	10 m3	Chosen arbitrarily since it was only used to provide proof of concept for SVC inclusion
initBSG requirement per cow	50 kg	25% of 200 kg per week of feed required
initBSG price	10	Chosen arbitrarily since price did not influence success of Floating Farm or breweries directly; economic failure is no longer possible.
Contract_length	12 weeks	Assumed time BSG can be stored before degrading

5.5 Explorative and iterative CBM experimentation and analysis

The final section of the experimentation framework consists of 4 parts: experimentation, data analysis, validation and model use. The experimentation section is included in this chapter as it is closely related to the application of the model, while the latter three are included as the main results of this study in the next chapter.

Experimentation

As described in the experimentation chapter, 4 experiments were conducted using the new model:

Experiment 1 depicts a situation wherein there is no fixed contract duration and the volume of each contract is determined the same way as in the original model: either all waste produced by the supplier or the amount still required by the processor to meet demand that week. It is expected that this model configuration will lead to stable BSG stocks in the Floating Farm, as there is a high degree of flexibility in contracts; both volumes and duration are almost completely flexible which means that any time BSG is needed a contract for the exact amount needed can be established.

Experiment 2 describes a situation wherein contracts have no fixed length but have a minimum volume requirement. This reflects a more realistic business model where contracts will only be established if the Floating Farm is willing to take on a worthwhile volume from the brewery. It is expected that this minimum volume requirement will lead to a larger stock of BSG in Floating Farm overall, since the model takes a step-wise approach; the Floating Farm will first establish contracts for a large volume (max production of a brewery), after which it will require one contract to reach a balance in BSG. However, what could happen is that the amount of BSG required is lower than the minimum contract volume, which will lead to a stock building over time until a contract ends. The Floating Farm will then start emptying stocks until more BSG is required to meet demand. The BSG stock might therefore show an increase-decrease-increase pattern.

Experiment 3 resembles the original iteration of the model the most; contracts have a fixed length (determined with a variable slider, default = 12) and do not have a minimum volume requirement. This is the ‘base’ situation which the other experiments will be compared to, since it can be used to showcase the changes introduced by new variables. It is expected that the model will behave similarly to experiment 1, but in a more regular pattern since the contract duration is fixed and rounds of contract formation may be visible as regular pattern repetitions of BSG stock.

Experiment 4 resembles a situation in which contracts are agreed for a set length but with a minimum volume requirement, which is more realistic than the case of contracts without a minimum volume. The behaviour of this setup is expected to be similar to that of experiment 2, but with more regular intervals of the same patterns due to the fixed contract length.

6. Results

In this section, the completed model was used to generate data using the experimental setups as explained in chapter 5.4. The data generated consists of the environmental indicators such as methane, manure, gas and water. In addition to the BSG stocks of the Floating Farm for each tick and the BSG going to the market each tick. While the environmental indicators function properly, they do not generate data which is of any particular use nor interest to this study; they were included to provide proof of concept and not to show the actual behaviour of the model. Their values and graphs are not included in this review but can be viewed in the model. Instead, BSG stocks in the Floating Farm will function as the primary means of assessing the model's behaviour for each experiment. BSG stocks were chosen because they are the direct, most obvious result of contract formation between Floating Farm and breweries within the network. Analysing the way these stocks behave under various experimental setups can provide insight into what a certain choice of contract formation style might result in for the BSG stock in Floating Farm.

Data analysis

Each experimental setup had varying effects on the behaviour and outcome of model runs. Several repeating patterns in the change of BSG stocks present in the Floating Farm were noted. In this section these patterns will be shown and explained for each experiment, including whether they were as predicted.

The model was run 10 times for each experiment and it became apparent that there were no additional patterns to be observed. The BSG in Floating Farm graphs were exported as images, including runs in which the network failed (i.e., the BSG stock went into the negative and no new contracts were being formed).

Results that are not in line with expectations are discussed in the next chapter.

Experiment 1: No fixed length and no minimum volume

Experiment 1 describes a situation with no fixed contract lengths and no minimum volume requirement for contracts. The resulting BSG stocks for 10 runs are displayed in Figure 3.

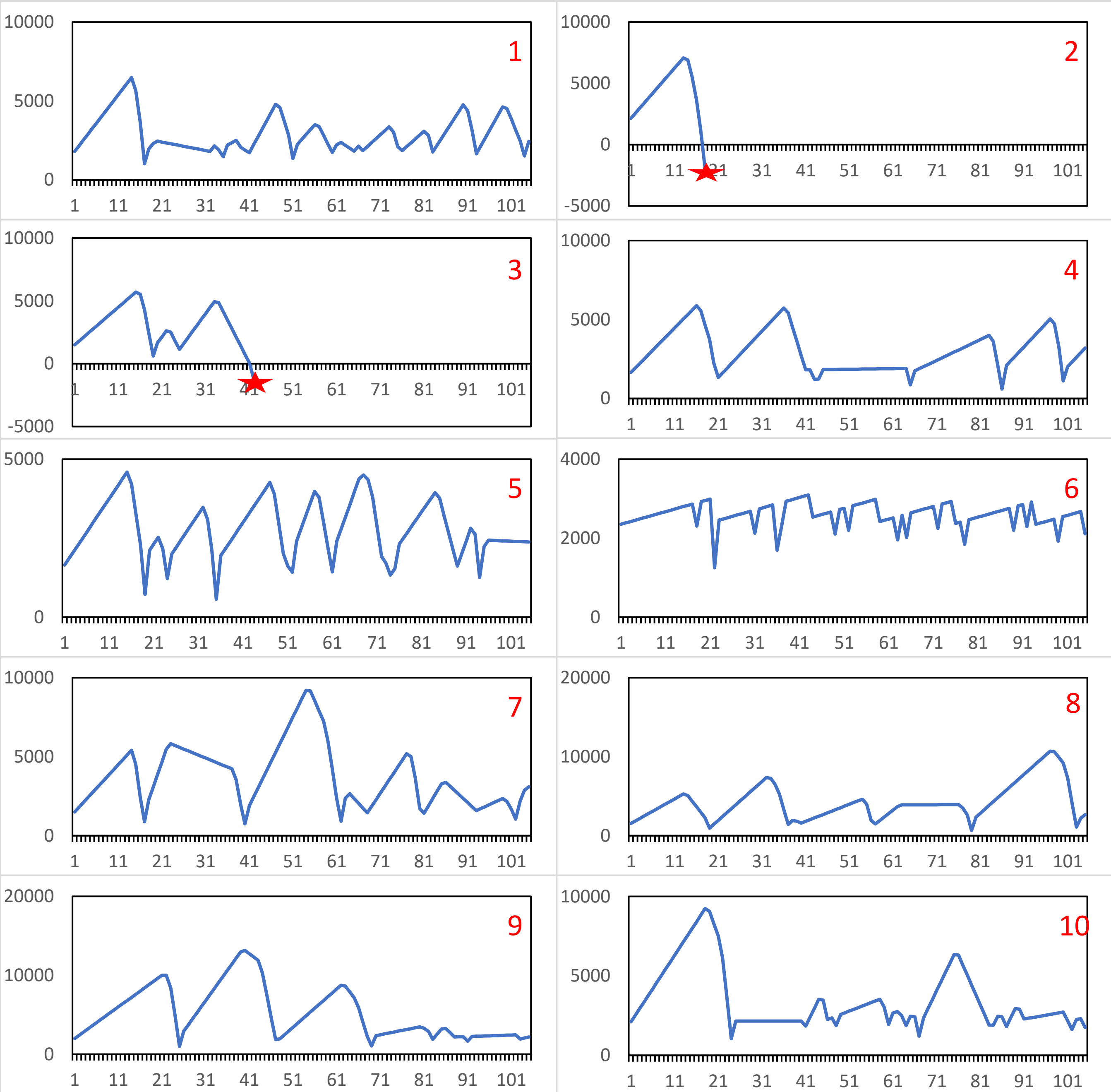

Figure 3*: BSG stock in Floating Farm graphs from 10 different runs using experiment 1 configuration. X-axis shows runtime of model in weeks, Y-axis shows the current BSG stock in Floating Farm in kg. Runs are labelled 1-10 from the top left to the bottom right. Red stars depict an ISN failure.*

Each run depicts a clear pattern of 'hills' where the stock of BSG increases from the onset of contracts and then decreases when these contracts have ended. The stock then decreases up to the point 1 week's worth of BSG is left and then it increases again when new contracts are established. Some hills have steeper slopes than others, indicating a difference in the BSG balance during that time. These hills represent a systematic overstocking of BSG.

An outlier in this regard is run 6, which shows a different pattern entirely of relatively stable BSG stocks at lower levels. The likely cause is that in that particular run a few of the same contracts were repeated after each other, which resulted in a more stable BSG stock.

The runs also ended twice in ISN failure, where the BSG inflow was insufficient to keep BSG stock at acceptable levels. Run 2 and 3 show that the model stops after a series of successful contracts were completed and no new contracts were established.

For comparison, all runs were plotted on the same graph as shown in Figure 4.

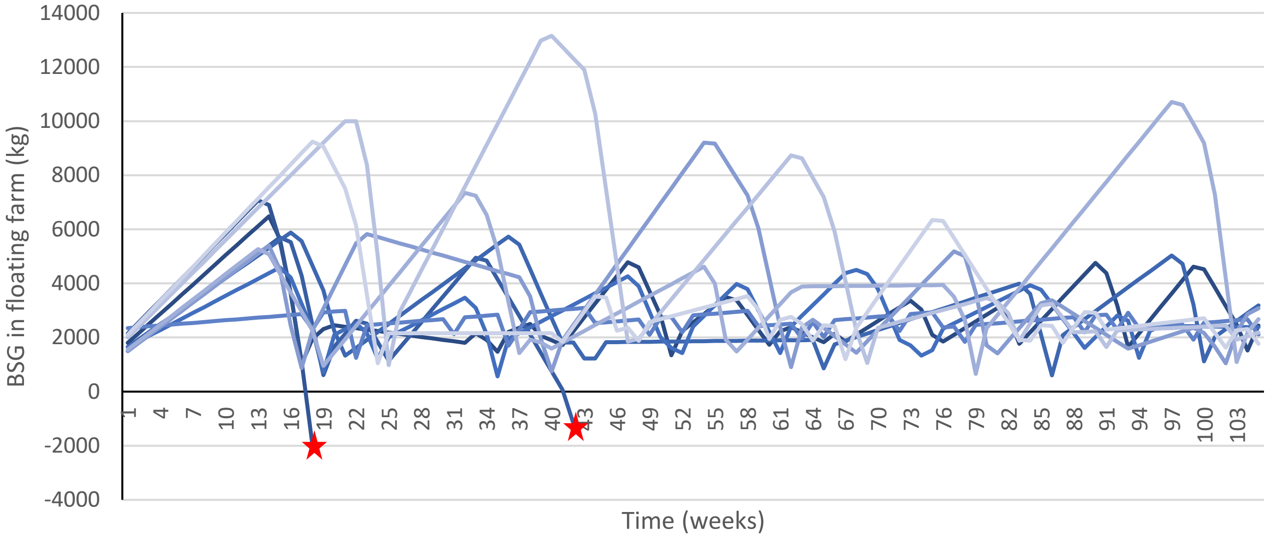

Figure 4*: Resulting BSG stock in Floating Farm for 10 runs of experiment 1 together. Darkest colour is run 1, lightest is run 10. Red stars depict runs which ended in ISN failure.*

Figure 4 shows the approximate behaviourspace (i.e., the possible results which the model can produce) of the model for experiment 1. There are several outliers where BSG was stocked in large quantities and there were also runs that ended in ISN failure. The experiment causes the BSG stock to fluctuate around 2000-3000 kgs, which is approximately 1-2 weeks' worth of BSG.

These patterns are not in line with expectations, which stated that the BSG stock would be stable due to the flexibility in determining the contracts' volume. Possible causes are explained in chapter 7.

Experiment 2: no fixed length but with minimum contract volume

Experiment 2 describes a situation wherein contracts do not have a fixed length but do have a minimum volume of 250 kg per week. The resulting BSG stocks for 10 runs are displayed in Figure 5.

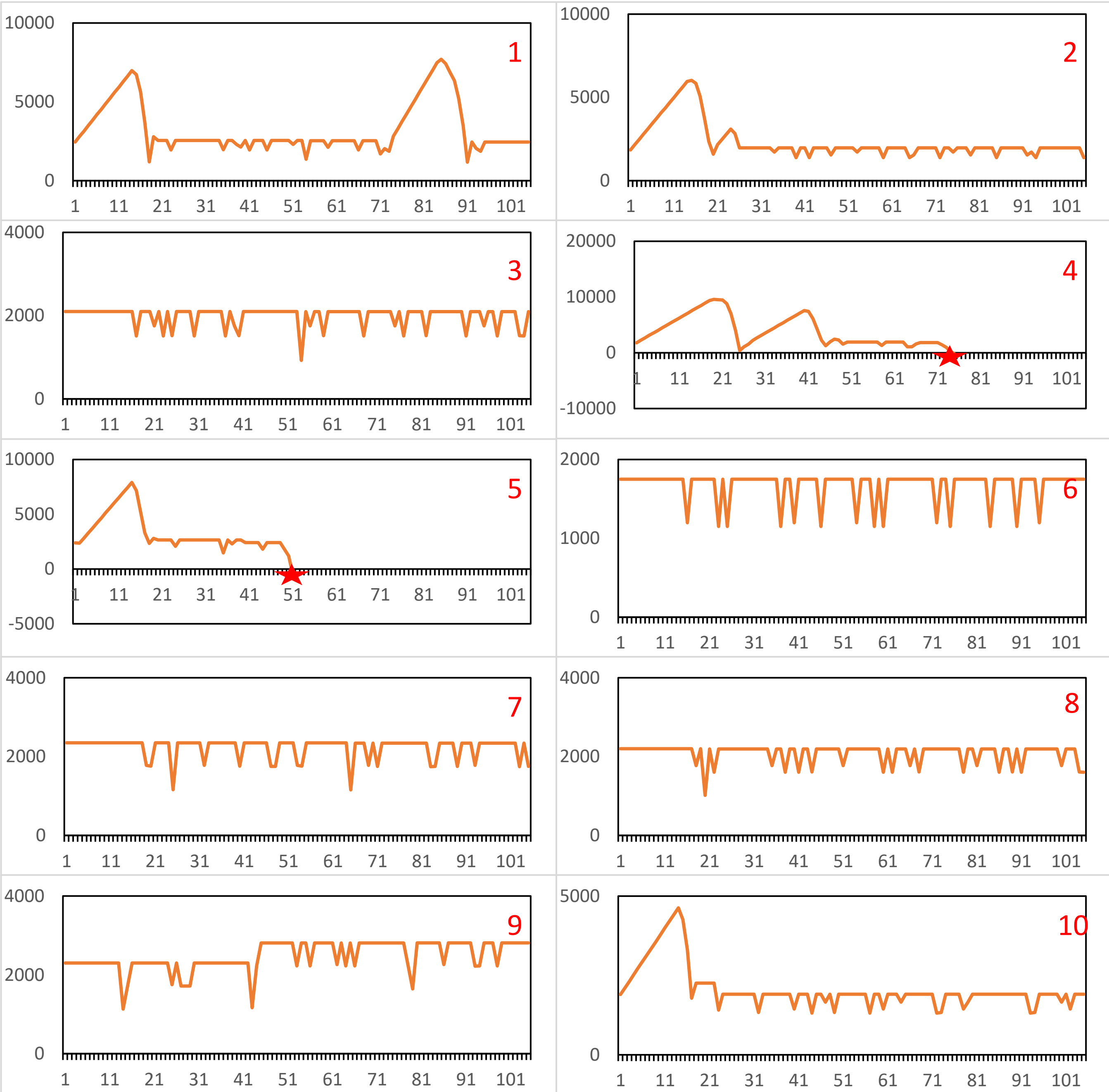

Figure 5*: BSG stock in Floating Farm graphs from 10 different runs using experiment 2 configuration. X-axis shows runtime of model in weeks, Y-axis shows the current BSG stock in Floating Farm in kg. Runs are labelled 1-10 from the top left to the bottom right. Red stars depict an ISN failure.*

Two major patterns can be observed in the runs of experiment 2 as depicted in Figure 5: the 'hills' as seen in experiment 1 and a flat line interrupted by small decreases and subsequent increases of BSG stock which returns to the Floating Farm's weekly BSG requirement. In line with expectations the hills are likely caused by a contract round in which the BSG balance of the Floating Farm was smaller than the minimum contract volume. By entering a contract with the minimum requirement, a stock would increase over time which then decreased as contracts ended. In the new contract formation round, sometimes better contract combinations were found which is why the stock would remain stable afterwards. This pattern shows how a BSG balance of 0 is maintained until a contract ends, at which point the stock dips for one tick and then, upon formation of a new contract, returns to the value of the flat line. This is not as expected since the initial dip in BSG caused by the lack of a contract, cannot be supplemented if the BSG balance returns to 0 with the new contract. This implies the BSG stock calculation in the model is not correct, as it would be expected that the BSG stock remain constant at the value after a dip.

Using this setup, the model also shows ISN failures on multiple occasions as can be seen in Figure 5 graph 4 and 5.

For comparison, all 10 runs are shown together in one graph in Figure 6.

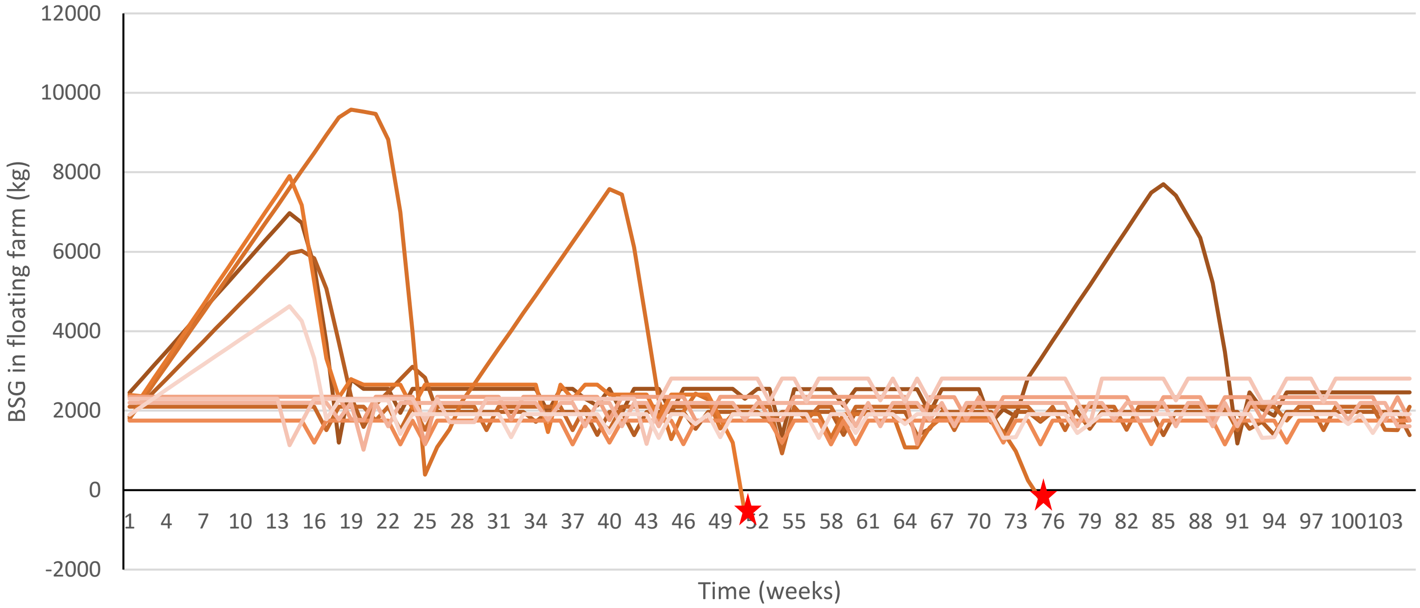

Figure 6*: Resulting BSG stock in Floating Farm for 10 runs of experiment 2 together. Darkest colour is run 1, lightest is run 10. Red stars depict runs which ended in ISN failure.*

When compared, it becomes apparent the behaviourspace for experiment 2 is more concentrated than experiment 1. Some major BSG stock build-ups can be seen but these are relatively rare. The BSG stock stagnates approximately at 1 week's worth of BSG for the Floating Farm.

Experiment 3: fixed contract length of 12 weeks, no minimum contract volume

Experiment 3 describes a situation wherein contracts do have a fixed length of 12 weeks but do not have a minimum volume per week. The resulting BSG stocks for 10 runs are displayed in Figure 7.

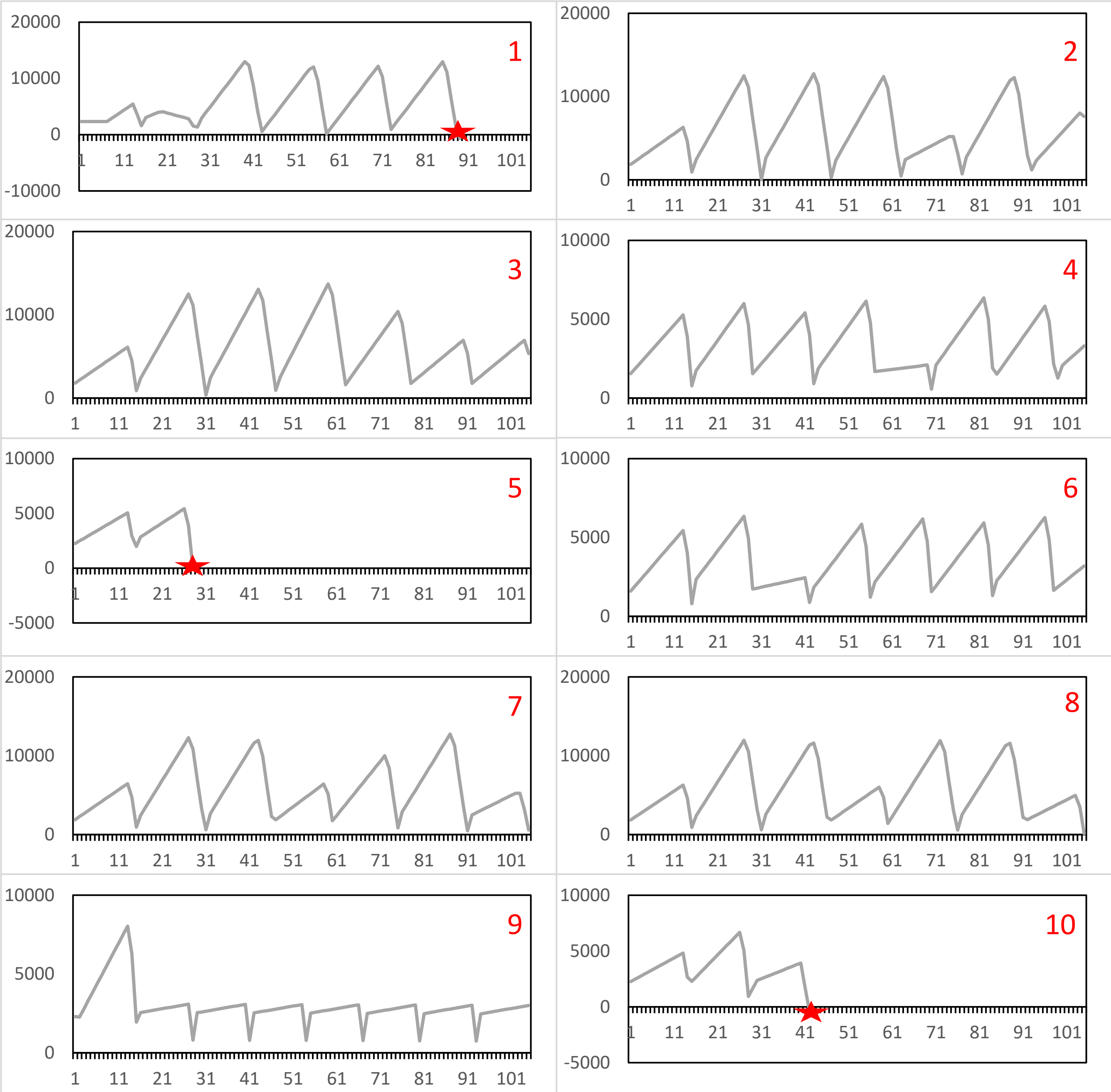

***Figure 7**: BSG stock in Floating Farm graphs from 10 different runs using experiment 3 configuration. X-axis shows runtime of model in weeks, Y-axis shows the current BSG stock in Floating Farm in kg. Runs are labelled 1-10 from the top left to the bottom right. Red stars depict an ISN failure.*

Experiment 3's configuration shows the same major pattern of hills as identified in experiment 1, but at regular intervals due to the fact contract lengths are now fixed. Interesting to note is that some runs (4, 6 and 9) show a smaller maximum BSG in storage than others, which indicates that in some runs the contract volumes are more 'ideal' in the sense that they lead to a BSG balance closer to 0. This then caused a smaller BSG build-up over time, hence the lower peak values. It can also be noted that the peaks of hills are often at the approximate same height. This is likely because the same contracts are repeated after the old ones expire, this is possible in this setup since all contracts will always end at the same time.

The results are partly in line with expectations, as it was expected to behave similarly to experiment 1 but at more regular intervals due to the introduction of the mandatory contract length. Again, however, the BSG stock behaviour was not as expected with the exception of run 9. Run 9 shows a distinct pattern of slight overstocking and then emptying as was expected. This implies the Floating Farm in that run had an ideal set of contracts that it could repeat, which resulted in only a minor overstocking of BSG.

Finally, all runs were layered over each other for comparison in Figure 8.

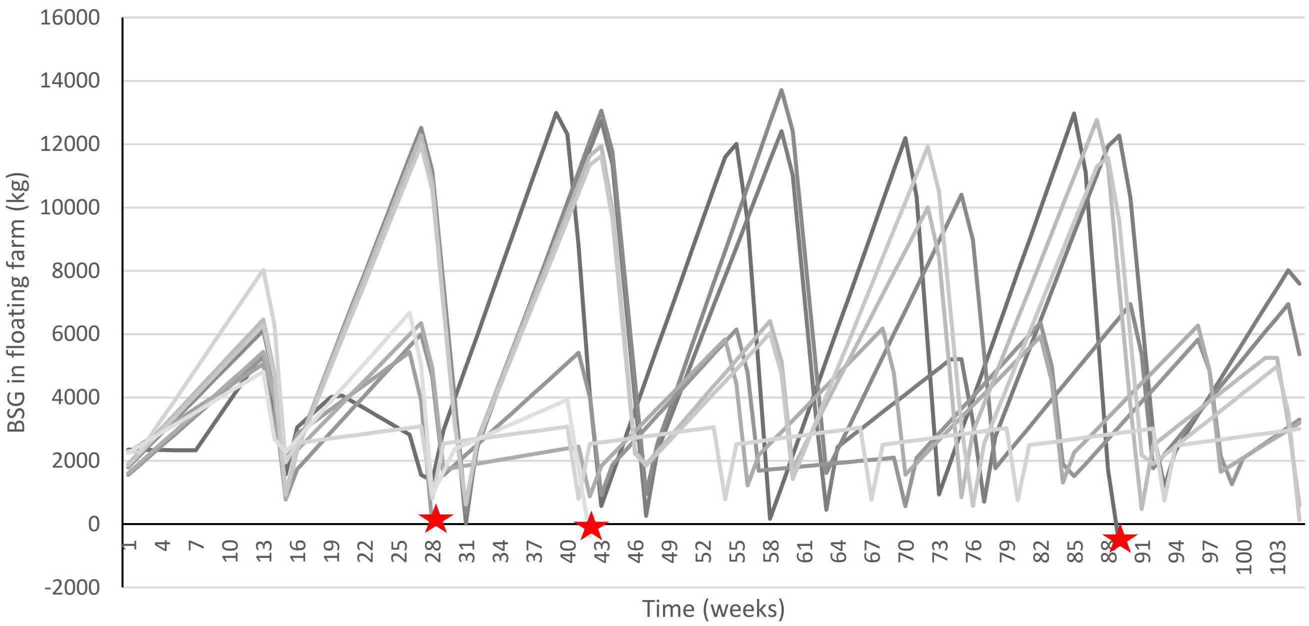

Figure 8*: Resulting BSG stock in Floating Farm for 10 runs of experiment 3 together. Darkest colour is run 1, lightest is run 10. Red stars depict runs which ended in ISN failure.*

Figure 8 shows that the overall behaviour of the model in this setup is comparable for each run. There are many high peaks that are interrupted by smaller peaks at a regular interval. The only big difference is the height of the peaks.

Experiment 4: fixed contract length of 12 weeks and minimum volume requirement of 250 kg

Experiment 4 describes a situation wherein contracts do have a fixed length of 12 weeks and also have a minimum volume of 250 kg per week. The resulting BSG stocks for 10 runs are displayed in Figure 9.

Figure 9*: BSG stock in Floating Farm graphs from 10 different runs using experiment 4 configuration. X-axis shows runtime of model in weeks, Y-axis shows the current BSG stock in Floating Farm in kg. Runs are labelled 1-10 from the top left to the bottom-right. Red stars depict an ISN failure.*

Similar to experiment 2's results, experiment 4's main difference is that patterns are more regular, as expected with fixed contract lengths enabled. BSG stocks show the same pattern of returning to a flat line with new contracts, while sometimes hills are present which indicate stocks building and emptying. It was expected that once a pattern establishes it will repeat until the end of the run (best contracts are found and kept for the duration of the run). But there are instances where the regular stable pattern suddenly emerges after several high peaks of BSG stock build-up and emptying. The BSG stock also plummets to almost negative quite often compared to the other experiments. After plummeting it immediately springs back to the plateau level around 2000 kg. This is not in line with expectations; contracts should be established to provide a steady build-up of BSG to around 2000 kg, after which new contracts would have to be made. An immediate increase in stock to the plateau is therefore unexpected.

Finally, the runs for this experiment were layered together on a single graph for comparison in Figure 10.

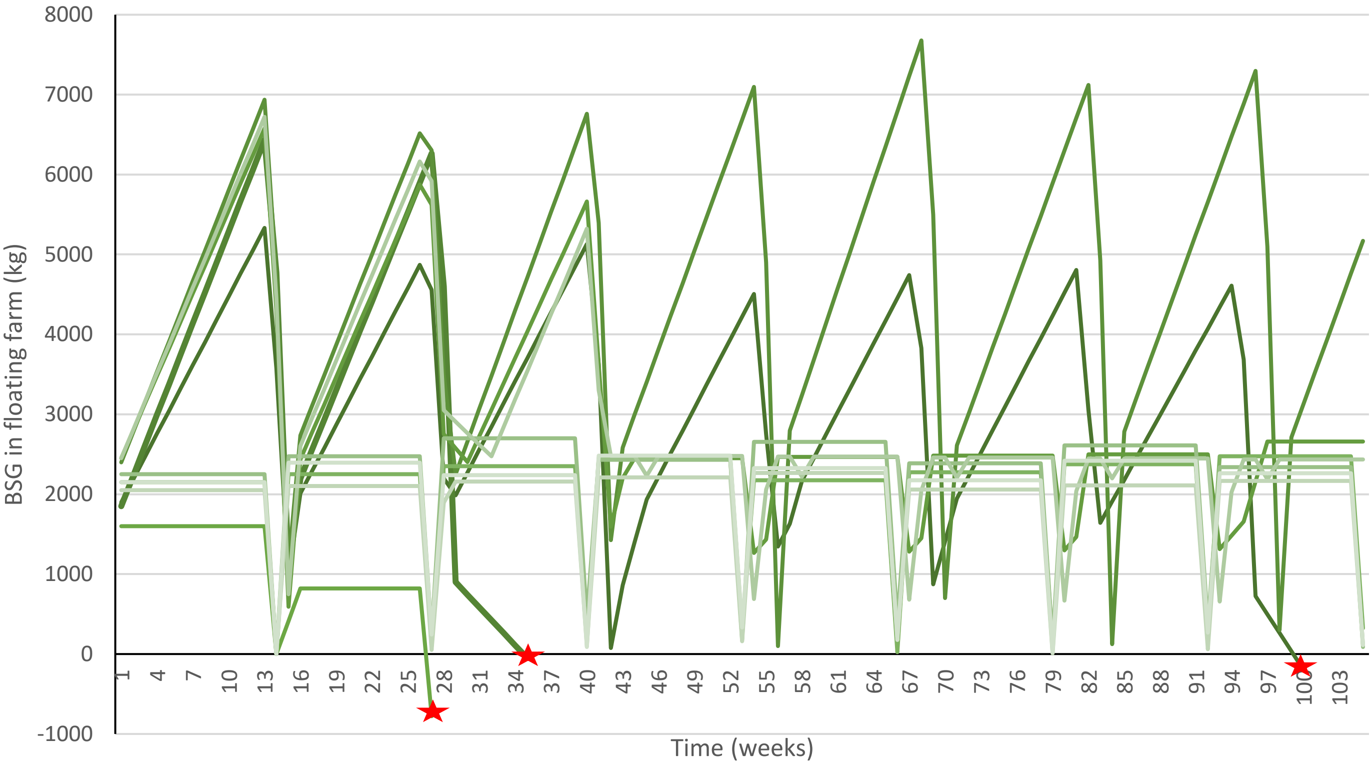

Figure 10**: Resulting BSG stock in Floating Farm for 10 runs of experiment 4 together. Darkest colour is run 1, lightest is run 10. Red stars depict runs which ended in ISN failure.

Similar to experiment 3, a regular pattern of hills and in this case, plateaus can be observed. However, this experiment shows a lower number of hills overall and seems to be focused around the 2000 kg BSG line as can be seen in the plateaus.

Comparison between experiments

The data on BSG stocks generated for each experiment was combined into a singular scatter plot graph as seen in Figure 11. Showing the data points on a single graph makes the differences in stock size and tendency to overstock more apparent. Several observations can be made from this graph:

- All experiments show a tendency to cause overstocking in the first round of contracts. As can be seen on the left side, all colours are included in the initial overstocking area.
- Experiment 2 and 4 (orange and green) are located densely at around 2000 kg BSG in stock, which is approximately 1 weeks' worth of BSG. There are some outliers in the middle of the graph where stocks grow in size, but these are relatively rare compared to the other two experiments.
- Experiment 3 (light blue) shows a larger presence above the 2000 kg BSG line, including many steep increases and decreases in BSG stock. In addition, its peaks are relatively higher than the others at first glance which implies it overstocks BSG at a higher rate than the other experiments.
- Experiment 1 (dark blue) shows little presence around the 2000 kg BSG line, but its peaks are not as high as those of experiment 3.

From these observations it can be concluded that experiment 2 and 4 provided the most stable BSG stocks relative to the other 2 experiments. These experiments had one thing in common: the minimum required contract volume was set at 250 kg. In addition, experiment 2 had no fixed contract length and experiment 4 had a contract length requirement of 12 weeks. Apart from a lower number of peaks, there seems to be no discernible difference between both experiments, where experiment 2 had fewer overstock events (i.e., peaks). It is unclear whether this is the cause of the unfixed contract length.

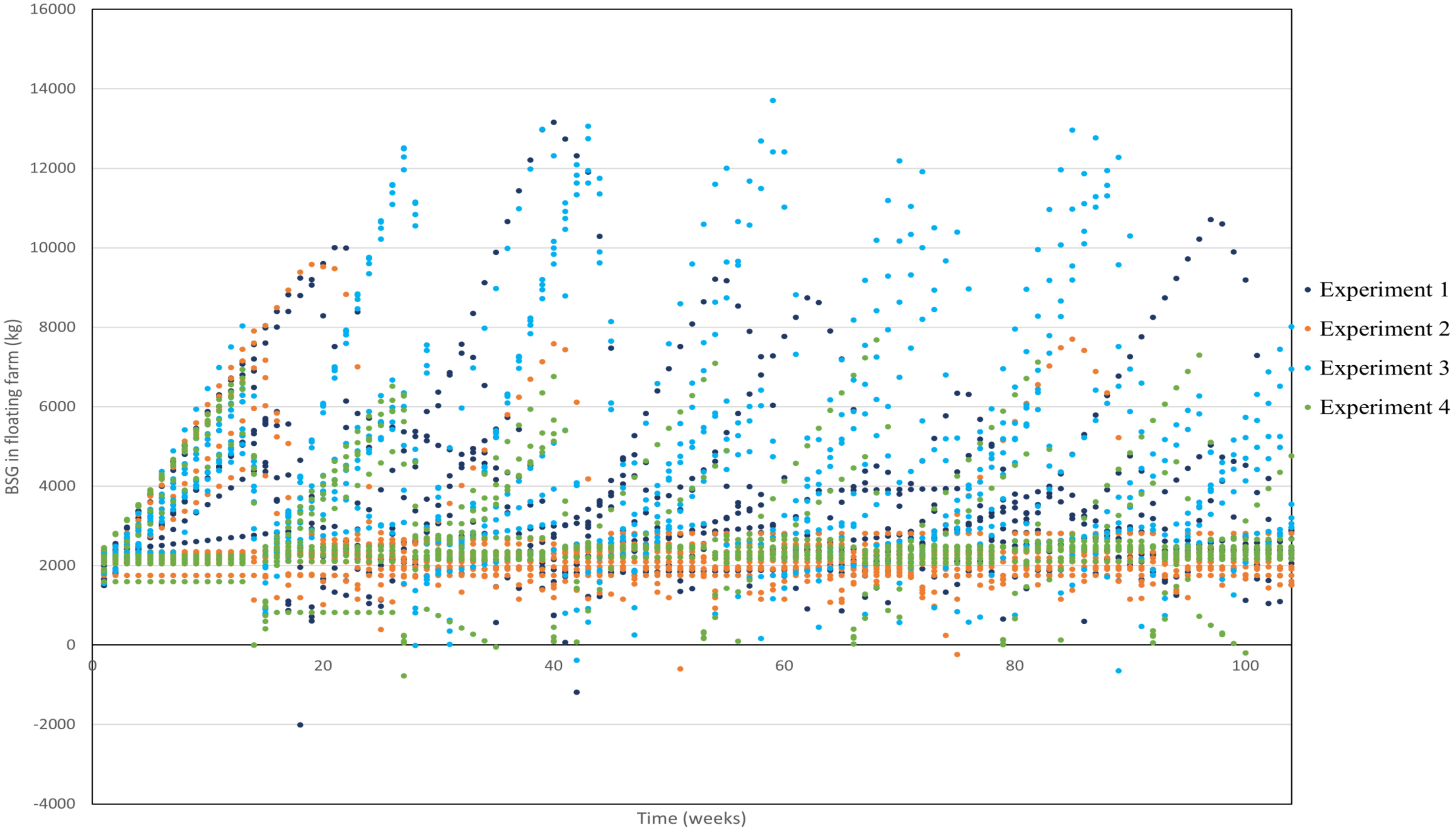

***Figure 11**: Scatter plot containing all data from experiment 1, 2, 3 and 4 on BSG stocks in Floating Farm. Experiment 1 is displayed in dark blue, Experiment 2 in orange, Experiment 3 in light blue and Experiment 4 in green.*

Validation

Normally the results generated from the experiments would be compared to actual data from its real-life counterpart (or a comparable network). Validation of this model is not possible however due to lack of such data and thus outside of the scope of this study.

Model use

This study was conducted without the direct involvement of the stakeholders. In addition, the adapted model and its results were not shown or discussed with them. Since the main research problem and knowledge gap posed did not include the stakeholders directly, this section will instead focus on how the model works and what its main limitations are.

Every tick of the model represents a week of time. All variables added in this study are shown on the left side and can be freely altered to see their effects. Two variables which are especially of interest are the boolean sliders for fixed_contract_length? and minimum_contract_volume? As these change the way contract formation is done as opposed to, for example, initBSG_per_cow_required which only changes the BSG demand for the Floating Farm by increasing the amount required per cow. By altering the sliders for amount_of_breweries and amount_of_floating_farms the number of breweries and Floating Farms respectively can be altered. It should be noted however that adding additional Floating Farms to the model will almost always lead to the model showing a symbiotic network failure (which happens when BSG stock of a Floating Farm goes negative). BSG stocks and contracts are not determined as intended in the case of more than 1 Floating Farm, which is why runs should be made with only one Floating Farm.

In the middle section the outputs of the model are shown as both graphs and the ‘environment’, which shows the agents as objects (breweries as houses, Floating Farm as cows and markets as factories with smokestacks) and contracts as lines between them. If a brewery shows a number > 0 it means that amount of BSG is currently being transported to the Floating Farm. If the number is 0, it adds its stock to the market, this is also represented as a line between the brewery and the closest market. Numbers on lines represent the current age of a contract and the number on top of each market (located in the corners) represents the amount of BSG currently going to that market.

The graphs above show the amount of BSG going to market each tick (kg/week), the amount of BSG currently stocked by the Floating Farm (kg) and the total amount of methane/manure emitted and gas/water consumed by the farm over the course of a run. The graphs for methane, manure, gas and water are not based on real values, as there was no data available. They only serve to show the potential for including them in future models as a means to determine sustainability value creation.

Finally at the right side of the model are the TPB variables which were introduced in the original model. Nothing was changed in this section, including the values for each variable. This is a major limitation in itself, as ideally these values should be based on interviews conducted with the stakeholders. However, as mentioned early in this review, this model is purely hypothetic and does not intend to reflect reality as closely as possible.

Using the buttons on the left side the model can be set-up, either using default settings to reset all values to those which were used to conduct the experiments (with the exception of the two Boolean sliders) or using custom settings. The model will run for 104 ticks (2 years) or until the Floating Farm’s BSG stock goes negative, at which point the model will stop and indicate a ‘Symbiotic Network Failure’.

Underneath the model’s controls is a command monitor which monitors certain information depending on what monitor control booleans have been enabled. These are directly copied from the original model and were not used to test the model. Many parts of the code which were changed also influenced the way these monitors functioned. They were not removebecause they did not influence the outcome of the model and could potentially be adapted to monitor the new model as well, but it was deemed unnecessary in this case as it would require more time than was available.

When a behaviourspace experiment is attempted in this model, the program will issue an error saying that ‘nothing named WASTESUPPLIERS has been defined. At position 55 in ….etc.’. It is unclear what exactly causes this error since the term ‘wastesuppliers’ never occurs in any of the code at position 55. This error prevents the use of the behaviourspace programming which is why no statistical analysis of data was performed. Besides this error however, no other errors have been noticed while testing and running the model.

7. Discussion

This section serves to discuss irregularities, problems with the model and other points of interest that were noted during the research.

Generalisability

One of the main goals of this review was to show the potential of the CBM experimentation framework to be adapted for use in different cases and with added dimensions of complexity and interest. The original model described a system which was highly specific but used very versatile names for its agents: waste suppliers, waste processors, waste incinerators and contracts. These agent types were readily adapted for use in the new network, with changes to their internal variables and states being the primary difference (both names and values). The interactions between agents, as well as contract formation and the logic behind it were mostly kept the same, indicating a high degree of generalizability to similar waste processing networks. A challenging aspect to adapt was the transformation of incinerator to markets and how waste processors actually processed their waste. Contracts to the market were made more flexible as the new network was modelled on a weekly basis, which required extensive rewriting of code. The waste processor’s function was also altered to a significant degree, since the original processor would compost waste in batches which sat idly for long times. The new processor acted as a similar sink but would instead consume the waste (BSG) instantly and produce instant outputs instead of delayed ones. Deleting the batches was not difficult, but there were some interdependencies within the TPB code which also had to be disabled. The TPB code was not altered in a major way because it was outside of the scope of this review. Finally, economics were mostly excluded because the situation described is a hypothetical one, which means there was not enough information to show the economic success of the network in a meaningful way. Several sections of economics related code were disabled to prevent the model from crashing. In future reviews, which include interviews and have more data on these matters, the economic dimension can be added with little effort; networks of businesses which trade waste have a high degree of similarity, which means they can likely be adapted to the original code.

SVC as a new dimension

In this review, an environmental dimension was added to the framework through the inclusion of SVC indicators. The indicators would normally be selected through iterative participatory interviews with the involved parties, but since these were not willing to cooperate the indicators were chosen by the researcher. The results of the model show that such SVC indicators can be tracked throughout experiments and can provide valuable information on the environmental performance of various CBMs to the user. The current model does not include any code which influences the SVC indicators, as there was not enough information to do so. If a more thorough study were to be performed, including proper interviews, these indicators could be made much more realistic by adding outside influences which could alter it. This in turn would provide a more in-depth perspective on the outcome. As a point of interest: the model could be set-up in such a way that the resulting indicator data could be used in a full Life-Cycle-Assessment (LCA), which would be very difficult to perform within the confines of ABM. The data could be used as direct input for an LCA model of the same case-study, which could then in turn provide in-depth information on where environmental impacts originate from in the entire production chain.

Oversimplifications and limitations

Initially, it was the intention of the researcher to conduct a case study focused on the symbiotic network of a Floating Farm and local breweries in the Merwe-Vierhaven district of Rotterdam. However, it soon became apparent that the businesses were not willing to share data relevant to the case nor participate in interviews, which severely limited the amount of information to work into the model. To account for these data-gaps, many simplifications of the system were made as described earlier in the review. Eventually, it was decided to only use M4H as an inspiration for a hypothetical network to model, which would reduce the dependency on such data. In addition, this allowed the researcher to focus on the generalizability of the original model and provide proof of concept for the SVC dimension. It should be noted, however, that some of these simplifications (may) have impacted the way the model functions in a major way.

For example, there was no detailed information on the nature of the CBM currently present in the network, which limited the possibility for designing CBM experiments. Transport was also simplified to the point that its only impact was on the price of good; currently, breweries ask for a higher initial price for their BSG when they're farther away from the hub (to compensate for transport costs). In reality breweries who are in close proximity to the Floating Farm hub would likely capitalize on the opportunity to make extra money off of the sustainable Floating Farms, it as they would be willing to pay more if it meant that their BSG had a lower environmental impact. It is more likely the base price would be higher which in turn would likely cause the auctions to turn out very different.

Contracts are also limited in the sense that Floating Farms can only have 1 contract with a brewery at a time, which prevents them from establishing additional contracts with a brewery that might have more BSG to give.

Values for the TPB were imported from the original model, which impacts contract formation in the new network. While the networks share similarities, it is highly likely that these values would be different if a proper participatory study was conducted. Different values for the TPB would have led to vastly different outcomes of the model, as is shown in Lange et al. (2021b).

While money is present in the new model and it influences contract formation, agents do not have their own value for it as in the old model. This simplification was made because of a lack of data and has likely had substantial influence on the outcome of runs. One of the most important aspects of the original model was that SNfailure was determined based on economic success.

Values for BSG/fodder requirement per cow are not taken from literature, primarily because they serve to provide proof of concept and not reflect actual reality. In addition, fodder was intended to have its own environmental effects, but these were not included. In a more complete model, these values should be properly determined and have associated environmental impacts and economic requirements.

No statistical- or complete behaviourspace-analysis was conducted due to an error in the code. Especially the SNFailure rate would have been an interesting reporter to examine, as that is the primary result relevant to stakeholders (in the original model).

Finally, numerous assumptions made during modelling can be seen as oversimplifications. An example is the assumption that all waste is of equal quality and has the exact same composition; this is useful for modelling, as it prevents having to keep track of extra variables and their effects down the line, but it severely limits the model's capacity to reflect reality.

These simplifications and limitations make the model highly hypothetical and not of much use as it could have been for the network it describes. In future adaptations of the model, it is the researcher's hope that such oversimplifications can be avoided by extensive cooperation with the stakeholders.

Interpretations of results

Influence of variables

Given the researcher's experience with the new model, it was expected to behave in certain ways upon experimentation. While the effects of fixed contract lengths were as expected (regular intervals of patterns on fixed, irregular on non-fixed), the way contract volumes were determined in the code caused unexpected results for all experiments.

Minimum_contract_volume OFF:

It was expected that BSG stocks would be relatively stable in this configuration. However, the way contract volumes were determined in the original model is based on the BSG-stock deficit of the waste processor in that particular tick. The value of which could be different from the actual BSG-balance (the change in BSG). This is likely what caused the patterns of consistent overstocking (and then emptying) of BSG in the Floating Farm. The BSG-balance was more often than not higher than 0.

Minimum_contract_volume ON:

Encountered an error in the way BSG stock is calculated since the BSG stock increases where it should not (after a dip, while BSG balance = 0). Logically what should happen is that the offset to the desired BSG stock would have to be supplemented through a BSG balance slightly larger than 0, so that the BSG stock would be at the desired number again at the end of the contract. This was not included in this instance of the model and should be considered for future work. The overall implication is that the BSG stock calculation is erroneous in some way, which leads to the pattern of pseudo-stable BSG stocks.

ISN failure

The results also showed the model's tendency to end in ISN failure; a situation wherein the Floating Farm decides to buy BSG from the market instead of local breweries, which is interpreted as a failure of industrial symbiosis. Whether the Floating Farm agrees to contracts it is offered or not is entirely dependent on the TPB variables' settings and the prices offered by breweries in each run. If the prices offered by breweries in a single run are considered too unattractive (i.e., too expensive) by the Floating Farm, it will stop attempting to get BSG within the network. If the variables for the TPB were determined correctly through iterative participatory interviews, the tendency for ISN failure could also be different. In addition, this iteration of the CBM experimentation framework does not go in-depth into the economical side of the ISN. Considering revenue, expenses and shifting market prices for BSG would greatly influence the way contracts are negotiated within the network.

Finally, there are no results on the likelihood the model will end in ISN failure for the various experimental set-ups. This is due to an unknown error preventing the use of the behaviourspace software within the NetLogo program. Normally, this would allow generating data for a statistically relevant amount of runs for each experiment. In future iterations of this model this should be fixed.

8. Conclusions and future research recommendations

In this final section, the research questions posed at the beginning of this review will be answered, an overall conclusion will be drawn and general recommendations on how to further improve the CBM experimentation framework will be provided.

Research questions

Sub question 1

What parts of the existing CBM experimentation model are readily usable and what parts require adaptation for use?

After disseminating the original model into its component parts to understand how each part functioned individually, it was concluded that many aspects of the original could be used readily or only required minor adaptation for use in the new model. Specifically, the code which pertains to contract formation and the TPB were almost completely re-usable. This is because the new network had many similarities compared to the old one as mentioned in the discussion. Specific agent states and variables had to be added/deleted or renamed to make sense in the new network, but these aspects were trivial in comparison to the complexity of contract formation and the TPB. Overall, many aspects of the model were highly useable, while many details required adaptation.

Sub question 2

How can sustainability value creation be included in an ISN and included within the CBM experimentation framework?

A literature study was conducted on the subject of what sustainability value creation means in a broad sense. It was concluded that there were multiple categories, each equally valid, which could be considered relevant for the CBM experimentation framework. Normally speaking, the most relevant categories should be decided in deliberation with the stakeholders involved, after which a more specific definition could be made for the case of cattle-farmers and breweries. In this review no such deliberation was done, which meant that relevant categories had to be selected based on literature and logic. It was concluded that the most obvious environmental impact of the network was the excrements of cows in the Floating Farm: methane and manure. However, since there was no discussion with the stakeholder it was not possible to assign a 'value' to these environmental impacts, which would have to be measured against something other of value such as economic gain.

The answer to the sub question is therefore: it depends on the network, but it is likely to at least be part of the categories mentioned in the literature study section.

Sub question 3

How can the results and insights gained in this study be used to develop generic design rules to supplement the CBM experimentation framework with sustainability value creation?

Through the results of the literature study and observations made on the results and work performed on the model, several generic design rules were considered. In order to include sustainability value creation into the CBM experimentation framework, generic design rules should focus on providing a widely applicable and highly flexible framework which can be adapted to various types of networks and situations. To this end, the framework at its base (i.e., prior to actual implementation) should include at least the SVC aspects as described in Table 1. Potentially expanding into more detailed aspects which have not been covered in this review. These will provide a strong basis to select more relevant aspects from for each specific case the framework is applied to using the described participatory process.

Main research question

How can the Ex-ante CBM experimentation framework presented in Lange et al. (2021b) be adapted to the case of an ISN of cattle-farmers and breweries and how can sustainability value creation be included as an additional dimension to aid in contract formation between these actors.

This question is answered by the completed model which describes the hypothetical ISN of a Floating Farm surrounded by several breweries. The CBM experimentation framework was successfully adapted and applied to build the model which includes aspects relevant to the concept of sustainability value creation for a network of breweries and cattle-farmers.

Conclusion

In conclusion, the CBM experimentation framework in its current form provides a strong basis to build upon and include additional aspects relevant to industrial symbiosis networks. As shown in this review it is possible to apply the framework to networks similar to the original one while also including a new dimension, sustainability value creation. Since the ‘value creation’ aspects of SVC are highly dependent on the stakeholders’ perspective, it was not explored in depth in this review. Instead, a proof of concept that such aspects could be included was provided by showing that relevant environmental flows could be tracked and made dependent on actor’s behaviour in the network.

Future research recommendations

The concept of Sustainability Value Creation was explored in the context of the Circular Business Model Experimentation Framework in this review. By supplementing the existing framework with SVC aspects and applying it to a new case-study, it was shown that the framework acts as a strong basis to build upon in future research. Specifically, it is the researcher’s belief that future research should focus on adding detail to the SVC indicators within the context of the framework. In addition, future reviews using this framework should try to capture the economical side in equal measure to the environmental side; in this review, the economic aspects of the model were left out almost entirely and based upon previous work and assumptions. Ideally, future iterations of the framework should put equal attention to the economic and environmental applications by combining the SVC aspects from this review with the economic considerations in the original work (Lange et al. 2021b).

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