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Agent-based modelling and simulation for circular business model experimentation

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A R T I C L E I N F O

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A B S T R A C T

The viability of novel network-level circular business models (CBMs) is debated heavily. Many companies are hesitant to implement CBMs in their daily practice, because of the various roles, stakes and opinions and the resulting uncertainties. Testing novel CBMs prior to implementation is needed. Some scholars have used digital simulation models to test elements of business models, but this this has not yet been done systematically for CBMs. To address this knowledge gap, this paper presents a systematic iterative method to explore and improve CBMs prior to actual implementation by means of agent-based modelling and simulation. An agent-based model (ABM) was co-created with case study participants in three Industrial Symbiosis networks. The ABM was used to simulate and explore the viability effects of two CBMs in different scenarios. The simulation results show which CBM in combination with which scenario led to the highest network survival rate and highest value captured. In addition, we were able to explore the influence of design options and establish a design that is correlated to the highest CBM viability. Based on these findings, concrete proposals were made to further improve the CBM design, from company level to network level. This study thus contributes to the development of systematic CBM experimentation methods. The novel approach provided in this work shows that agent-based modelling and simulation is a powerful method to study and improve circular business models prior to implementation.

1. Introduction

The Circular Economy (CE) is a regenerative economy in which resource inputs and outputs such as waste, energy and emission are minimised through slowing, closing and narrowing loops (Lüdeke-Freund et al., 2019). CE is being considered a promising sustainable and competitive alternative to the traditional linear economy, in which materials and energy are produced, sold, used and disposed of (Ghisellini et al., 2015). Therefore, it has gained wide attention among policy makers, businesses and scholars (Geissdoerfer et al., 2018). CE requires bottom-up efforts from companies, for example through actively encouraging closed loop value chains (Bressanelli et al., 2019). Although closed-loop value chains are a key part of the circular economy, the transition requires a broader approach than just establishing new supply chains (Schenkel et al., 2015): it requires rethinking the whole business logic, often transcending internal business functions across supply chains and even industries (Bocken et al., 2015). Hence, network-level business model innovation is seen as a key pathway for the transition towards a circular economy (De Angelis, 2016; Schenkel et al., 2015).

Up to date, the effect of novel circular business models (CBMs) on their intended future outcomes - to create sustainable value according to the principles of CE - remains unknown (Lüdeke-Freund et al., 2019). Many companies are reluctant to implement CBMs in their daily practice (Schroeder et al., 2019). Experimentation methods are required to support companies in the transition from traditional business models to CBMs. Iterative testing of new business models with stakeholders is crucial for gaining insight in the viability of CBMs (Bocken et al., 2019; Bocken and Antikainen, 2018; Weissbrod and Bocken, 2017).

Computer simulation models offer opportunities for CBM experimentation. If a simulation model is co-created with the stakeholders, it helps them to increase their knowledge about the system they operate in (Bas, 2017; Batten, 2009; Smetschka and Gaube, 2020). Co-creation with stakeholders has three main advantages: it improves the design of the models, it structures communication between the modellers and

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practitioners, and it helps in identifying impact potentials (Epstein, 2008; Smetschka and Gaube, 2020). Computer simulation models are particularly suitable for studying the effects of business model design and externalities *before* actual implementation, which is attractive for firms because it may avoid economic, social and/or environmental risks.

This study contributes to the development of CBM experimentation methods. It proposes a novel systematic method to explore CBM designs prior to implementation using agent-based modelling (ABM) and simulation.

2. Background

We first explore the literature on CBMs and discuss obstacles that hamper CBM implementation. Next, we show that agent-based models (ABMs) are particularly suitable for modelling and simulating CBMs.

2.1. Circular business models

There are many definitions of business models, but in general business models describe a firm's organisational and economic design, providing for insights in how companies create, deliver and capture value (Teece, 2010). Today's societal and environmental sustainability challenges undermine the viability of traditional business models, which are built upon an idea of competitive advantage in a linear production system of take-make-use-dispose (De Angelis, 2016). Business model innovation is considered to be crucial to implement changes in organisations (Geissdoerfer et al., 2018), and business model innovations have emerged to address the abovementioned sustainability challenges (Breuer et al., 2018; Schaltegger and Wagner, 2011; Stubbs and Cocklin, 2008). Traditional business models are generally built up of the following dimensions: value proposition, value creation and delivery, and value capture (Osterwalder and Pigneur, 2010; Richardson, 2008). Sustainable business models aim not only to create, deliver and capture economic value for the company involved, but also to contribute to environmental and social value creation among a broader span of stakeholders (e.g., Breuer et al., 2018; Stubbs and Cocklin, 2008). In line with this, business model innovation is regarded crucial to implement CE principles (De Angelis, 2016; Schenkel et al., 2015). Hence, circular business models (CBMs) are a specific type of sustainable business models (Bocken et al., 2014; Geissdoerfer et al., 2018). CBMs (sometimes named Circular Economy Business Models or CEBMs) are business models that create value according to the principles of CE, through reducing waste and consumption, and by closing, slowing and narrowing resource loops (e.g., Bocken et al., 2016; Lüdeke-Freund et al., 2019). Companies can do so by constructing a business model through combining a variety of design options, that affect the business model across all its dimensions (Lüdeke-Freund et al., 2019). Inspired by the work of D'Souza et al., 2015, Magretta (2002) and Osterwalder (2016), we thus consider a circular business model to be viable, when its design provides for a long term effective value proposition, value creation and delivery and value capture to foster closing, slowing and narrowing loops. Business model experimentation methods provide opportunities to understand the viability of CBMs (Bocken et al., 2019). However, the implementation of CBMs is currently slow and CBM experimentation studies are limited to a small number of cases.

2.2. Gaps in literature that hamper CBM implementation

Firms operate in a complex and evolving environment, caused by factors that are not manageable by them (D'Souza et al., 2015). Company representatives recognise the complexity and accompanying uncertainties that may affect the viability of CBMs, both on the firm level and the network level (Lindgren et al., 2010). Companies are therefore still reluctant to implement these CBMs (Circle Economy, 2020). Uncertainties are preferably recognised and dealt with before implementation of the business model to avoid financial risks. Since CBMs are rather novel, detailed information is lacking that could convince companies of their CBM viability (Breuer et al., 2018; Fichtner et al., 2005; Herczeg, 2016). In this article, we focus on the following gaps in literature that have been identified as obstacles for CBM implementation:

- **Effects of scale and time are hardly explicated and accounted for.** Although rarely mentioned in CBM literature, the performances of technical artefacts (e.g., production outputs of processing equipment) are depending on the scale and fluctuations in resource input quantity and quality (De Meyer et al., 2014), particularly when waste is used as inputs in circular initiatives (Paes et al., 2019). However, scale and time are barely addressed in literature regarding CBM viability (Lüdeke-Freund et al., 2019).
- **Effects of individual actor behaviour and social interactions among partners are hardly accounted for**. Actions of individual humans within firms influence the interaction between firms on the network level (Andrews, 2000), thereby affecting the captured value (Lüdeke-Freund et al., 2019). Thus, to keep all actors in a circular network involved, both explication of actor behaviour and incentivising collaborative interaction are important (Geissdoerfer et al., 2017). Although business models include a brief description of partnerships and customer relationships, literature that explicates actor behaviour and social interactions affecting the business model viability is still lacking (Lüdeke-Freund et al., 2019).
- **Effect of external environment on business model viability is hardly addressed.** The emerging studies on CBMs are mostly case-specific. Every case differs because of the variety of natural and societal contexts. Thus, case-specific outcomes have limitations with respect to their transferability to multiple contexts (Lewandowski, 2016).

In the light of circular business model experimentation, the gaps make clear that there is a need for a generic method to provide ex-ante insights in dynamic relationships between technical artefacts, social actors and environment. An understanding of complexity and dynamics of CBMs on both the firm level and the network level is crucial (Lewandowski, 2016; Ünal et al., 2019). Academic literature that provides for the required level-transcending methods and tools to systematically experiment with the CBM's key elements is lacking. Thus, ex ante CBM viability experimentation, addressing complexity and multi-stakeholder interdependencies, is required to contribute to the transition towards a circular economy.

2.3. Agent-based modelling and simulation

Agent-based models (ABMs) are exceptionally suitable for modelling and simulating complex adaptive socio-technical systems (Dam et al., 2013). Agent-based modelling serves as a tool to better understand a system, its components and the interaction among them (Janssen, 2005). It provides an opportunity to understand the functioning of the system "in-silico", by allowing us to consider a wide range of system properties and values which can prove to be (in)efficient and (in) expensive in the real-world (Holland, 1992). The modelled agents represent the social, autonomous actors that possess certain behaviours and technical artefacts with properties that enable certain processes to occur (Dam et al., 2013). Through the interaction among these agents with differing properties, patterns emerge which provide insights into the overall functioning of the system (Janssen, 2005). Thus, agent-based modelling and simulation offers opportunities for CBM experimentation to explore interactions between environment, actors and technologies on the micro- and meso-level that result in practices that are in line with the principles of the circular economy.

2.4. Existing agent-based modelling studies related to circular business models

In the fields of Industrial Ecology and Complexity Sciences, some agent-based models have already been used to study the complexity and dynamics of circular economy practices. Numerous studies focus on the creation of partnerships among agents to improve economic profitability and resource efficiency (e.g., Albino et al., 2016; Gang et al., 2014; Ghali et al., 2017; Mertens et al., 2016; Raimbault et al., 2020; Yazan et al., 2018). In these studies, some CBM elements have been modelled, for example products, partnerships, costs and revenues. Other studies also included environmental value creation (e.g., Batten, 2009; Camparotti, 2020; Cao et al., 2009; Romero and Ruiz, 2014). Moreover, social value creation was studied using an ABM, for example Chandra-Putra et al. (2015) modelled factors that affect the evolution of industry in liveable, well-balanced cities. Mantese and Amaral,@ (2017;2018) validated, evaluated and categorised indicators for capturing value. Some ABMs have been used to study customer acceptance (e.g., Lieder et al., 2017; Zheng and Jia, 2017). Zhu and Ruth (2013;2014) used ABMs to analyse the resilience of resource efficient collaborative networks in various contextual settings.

The abovementioned ABMs have proven their capability of experimenting with scale, time, actor interactions, individual behaviour and context. Network-level dynamics that emerge as result of the modelled individual-level actions and interactions were explored under varying circumstances, such as different market prices and behaviour profiles. Although not directly linked to CBM literature, these models implicitly included some elements within the business model dimensions (value proposition, value creation and delivery, and value capture). However, to our knowledge an agent-based modelling approach has not yet been used to *systematically* test business model viability from the CBM perspective. This article aims to fill this gap, by proposing and testing a systematic method for ex ante CBM experimentation, explicitly including value proposition, value creation and delivery and value capture.

3. Proposed iterative CBM experimentation method and application to an illustrative case

In this section we illustrate how we contribute to explorative CBM experimentation by presenting the proposed method and applying it to a case study.

We created and used an agent-based model (ABM) by means of an iterative and participatory design science approach (Lange et al., 2017). Design science research is a methodological approach that combines finding practical solutions with scientific knowledge development (Hevner, 2007). Design science research is considered a suitable research approach when working in close collaboration with practitioners; to test new designs in a realistic context, while solving a domain problem through the construction of an artefact (Dresch et al., 2015). In this study, our ABM is exactly that artefact: allowing to iteratively find new knowledge and solutions, by researchers and practitioners, aimed at collaboratively and incrementally improving the CBM viability. This also means that our ABM is not intended to provide the answer to a question of what the best or optimal settings for high CBM viability would be by a straightforward quantitative analysis of a multidimensional design space. Instead, the ABM describes how a combination of multiple design options in two CBMs in different contexts affect single agents. Furthermore, from the interactions among these modelled agents, mechanisms and outcomes emerge on the network level.

To explore the efficacy of the studied CBMs and design options, this article proposes a methodological approach for CBM experimentation, by following and applying these modelling and simulation steps in an illustrative case:

1 Case selection and description (section 3.1);
2 Participatory and iterative model conceptualisation (section 3.2);
3 Software implementation (section 3.3);
4 Experimental design (sections 3.4);
5 Explorative and iterative CBM experimentation and analysis (section 4).

During the modelling and simulation steps, we conducted 11 semi-structured interviews, five roundtable discussions and 17 individual feedback sessions with case practitioners and experts. Furthermore, we used written feedback from the case participants to iteratively construct, improve and calibrate the model assumptions, mechanisms and outcomes. Extensive background information on the process and results can be found in a repository (Lange et al., 2021a): https://www.comses.net/codebase-release/1f328ca2-653e-4f9c-98e6-d6a11752f1a6/https://doi.org/10.25937/3ewr-yt59. This includes information on empirical data collection methods, a model description according to the ODD protocol by Grimm et al. (2020), source codes, flowcharts, input data, and simulation results.

3.1. Case selection and description: industrial symbiosis network around anaerobic digestion

For case selection and model conceptualisation we used the method of Lange et al. (2017). We used three case studies to be able to model a realistic narrative of real-world industrial symbiosis networks (ISNs) as described in Mulder et al. (2020, 2018). Rooted in the field of Industrial Ecology, ISNs are defined as collaborative webs of actors that aim for value creation through resource efficiency and information sharing (Cecchin et al., 2020; Doménech and Davies, 2010). Although it is not the only archetype of business models within CE practice, scholars consider ISNs to be crucial in the transition towards a circular society (Baldassarre et al., 2019). ISNs can be vulnerable to unexpected events, causing the collaborations to end and the network to collapse (e.g., Chertow and Ehrenfeld, 2012; Chopra and Khanna, 2014). For example, ISNs collapse when (residual) resource suppliers stop exchanging their streams with the users (or processors), or when the users stop utilizing these local residuals. Hence, in this article ISNs are considered a fair representative of the CBM viability challenges.

For conciseness, only the case used for this study's simulation is described here. This concerns the case of an urban ISN initiative in which anaerobic digestion is used to process local organic waste. Biodigestion is considered one of the key technologies to close biobased materials loops in the circular economy (EMF and McKinsey, 2014). In developed countries, at least 58% of the food waste occurs in firms, such as food manufacturing, service, retail, and distribution (Mirabella et al., 2014). In Amsterdam, the Netherlands, there are several ISN initiatives that attempt to address this problem by collecting, processing and reusing organic and food waste from companies locally (Mulder et al., 2020, 2018).

One of those initiatives emerged at a former shipyard area called NDSM wharf, which was one of the largest of its age between the 20s and 80s of the twentieth century. Today the area is a commercial area and a hotspot for creative activities, such as festivals, markets and fairs. Two organisations are actively involved in the management of the area, a cooperative that aims to foster the renewable energy transition (approximately 60 members), and a foundation that aims to serve the interests of around 400 companies. Both organisations are aware that the companies they represent have to comply with the municipality's Circular Economy agenda, which follows the EU regulations that in 2023 organic waste and kitchen waste has to be collected and processed separately (Municipality of Amsterdam, 2020). In 2017, the renewable energy cooperative tried to set up a symbiotic network for small-scale biodigestion of organic waste to produce energy for local use. This idea did not yet take off, mainly because the proposed business model did not provide for assurance that the network would survive with regards to waste supply, and product demand (i.e., gas and digestate).

The case participants required insights in the effect of reshaping the business model, offering an opportunity to use this case for business model experimentation.

3.2. Model conceptualization

We iteratively conceptualised and calibrated a model in collaboration with our case participants (Fig. 1). Furthermore, the model builds upon recently published work of the authors (Lange et al., 2021b). Within the modelled ISN, firms act either from the role of waste supplier or from the role of local waste processor. Traditionally, waste suppliers in our case study have their waste brought to an incinerator. In the new ISN, suppliers negotiate with the local processor to establish a synergy that leads to local waste exchange and treatment. As shown in the process overview (Fig. 2), the model represents the production of biogas and digestate from local waste. Based on interviews with case participants, it is assumed that these products are fully reused within the area. Selling gas and digestate are therefore modelled as an infinite sink. Many decisions that determine the interaction among waste suppliers, processor and incinerator depend upon the CBM design.

In consultation with our case participants, we test two CBMs: Circular waste management (CBM 1) and Waste as by-product (CBM 2). Using the CBM morphology by Lüdeke-Freund et al. (2019), Table 1 shows how CBM design options come about in our case study, forming a so called 'patterns'. Our case study shows high similarities with the three generic patterns that Lüdeke-Freund et al. (2019) propose for organic feedstock: recycling, the cascading or repurposing.

The value proposition of CBM 1 focuses on two aspects: offering a waste removal service and producing an energy carrier for business-to-business (B2B) customers. Value creation and delivery is mostly performed and directed by the waste processor and facilitated by the waste suppliers. The waste processor creates revenues from selling energy and collecting waste. In CBM 2 the value proposition focuses on the value of waste as a resource for the production of the biogas as an energy carrier. The waste processor creates revenues from selling energy and digestate as fertiliser. The supplier sells waste as a valuable resource to the processor. Value creation and delivery are performed and directed by the waste processor as well as the waste suppliers, who now put more effort in the increase of the quality of their valuable by-product.

3.3. Software implementation

This section provides a generic model description, which is parameterized and used in the case study. We implemented the model in NetLogo (Wilensky, 1999). The model code including an extensive description and flowcharts can be found in the repository (Lange et al., 2021a).

3.3.1. General model

We modelled three types of agents: the waste processor, the waste supplier and the waste incinerator. Each simulation step represents 1 month to be able to model changes in waste quantity and quality over the year. The waste processor and supplier go through all process stages for local exchange and treatment of organic waste to product as shown in Fig. 2. For the sake of conciseness, we explain these steps briefly:

1 Waste suppliers produce waste. Suppliers that already have a contract with the local processor make transactions, determined by the CBM design and context.
2 The waste processor checks its available production capacity. If necessary, it asks all waste suppliers in the network to reveal their waste quantity and quality.
3 The processor selects and prioritizes potential supplying partners, from highest to lowest waste value. The waste value is determined by the waste quantity and quality, thus modelling the fitness to process the waste in the biodigester.
4 Bilateral negotiations take place between the processor and processor's most preferred supplier. For this, both agents determine

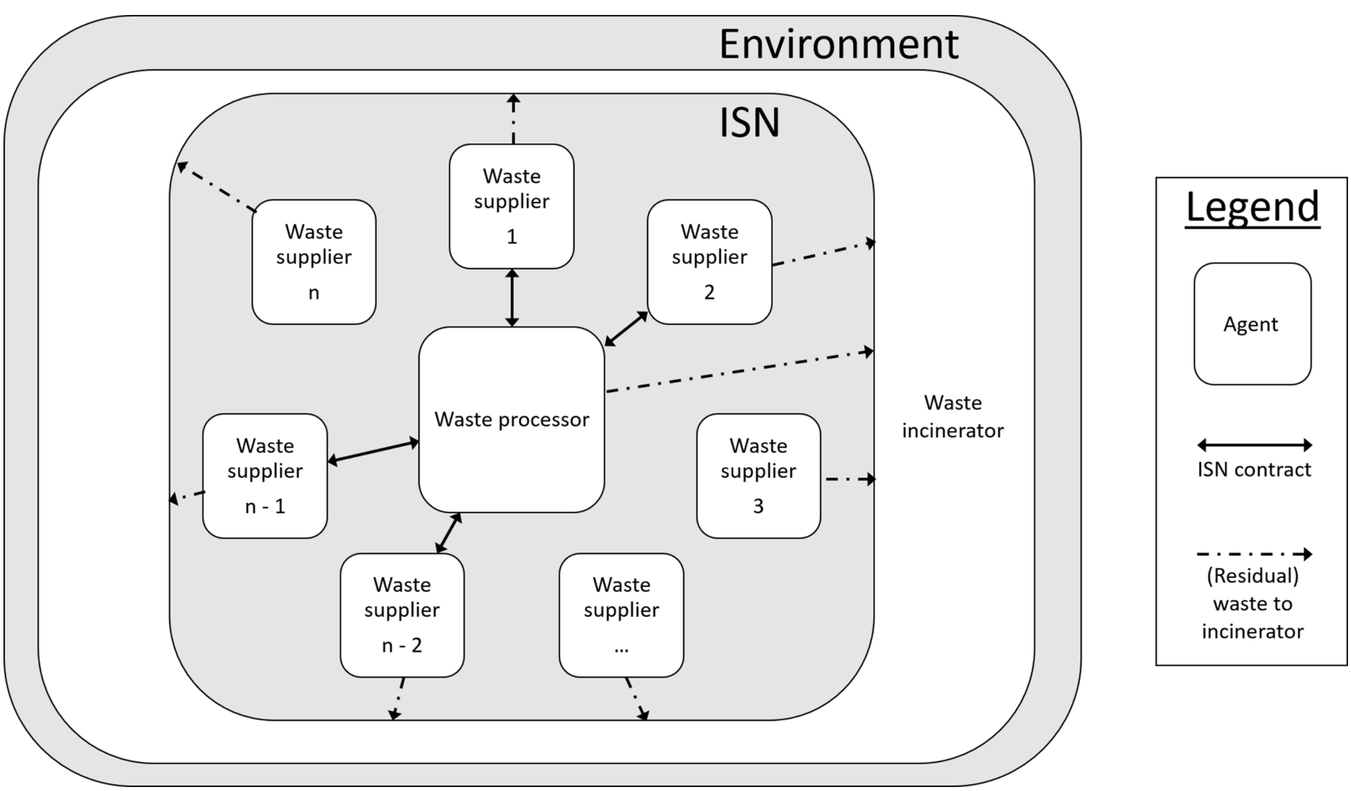

Fig. 1. The modelled Industrial Symbiosis Network (ISN). Waste suppliers and processor exchange waste and money if a contract is established. Residual waste is brought to the incinerator (Lange et al., 2021a).

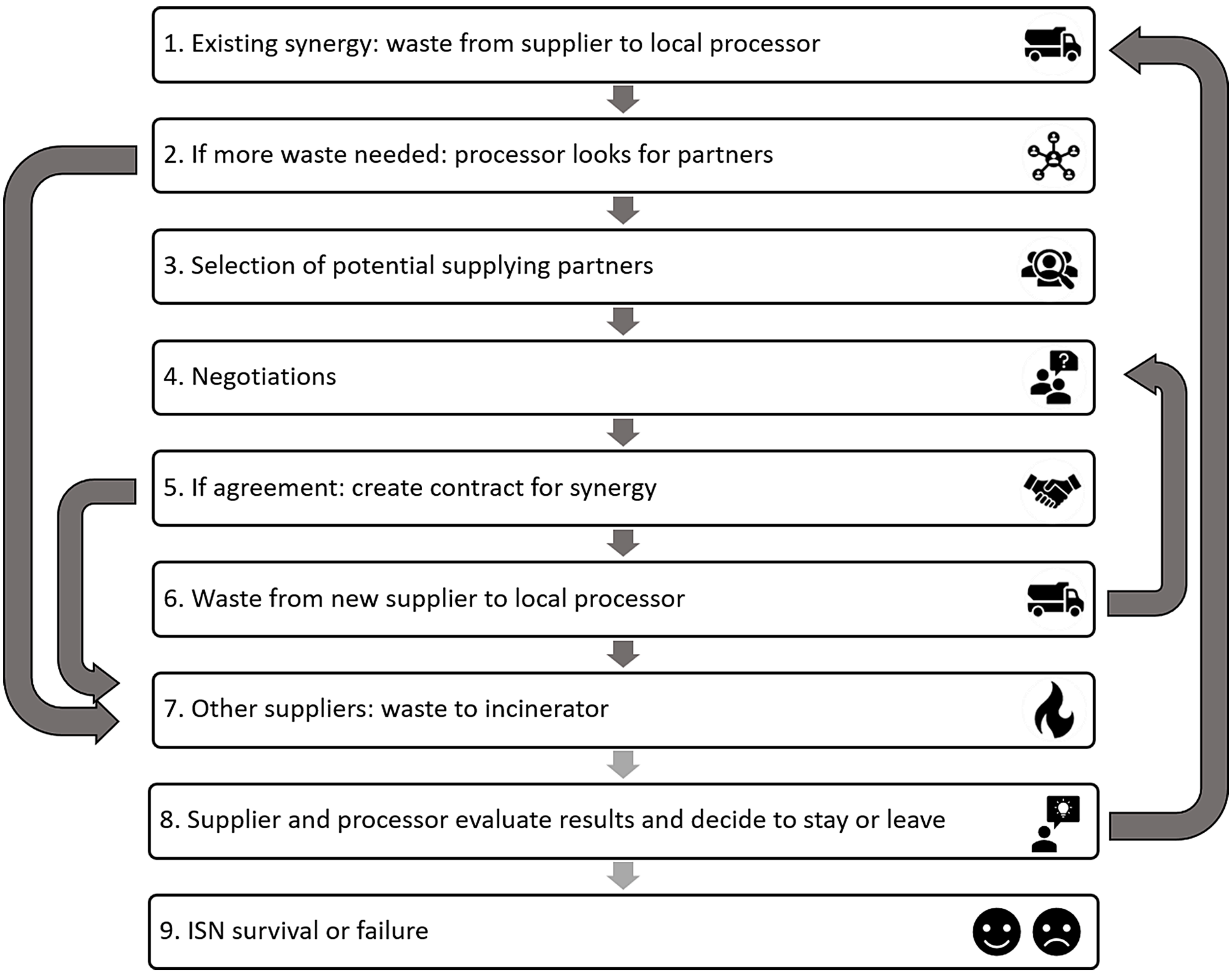

Fig. 2. Schematic of the process of exchange and treatment from waste to product. Adapted from Lange et al. (2021a).

target and limit prices of the waste. These prices are formed based on waste quantity and quality, market prices, and the actor's intention to form a synergy. The model of behavioural intention was based on the Theory of Planned Behaviour (Ajzen, 1991), since this is a suitable theory to use in modelling synergies among companies (Ghali et al., 2017).

5 If an agreement is made, a contract is established. The contract specifies the maximum amount of waste to be transacted each month, the agreed price and the contract duration.
6 The new supplier delivers the waste to the processor and monetary transactions are made. If the processor capacity is not reached, steps 3 to 6 are repeated with the next potential supplying partner. Otherwise, the model goes to step 7.
7 The incinerator takes up all the waste that is left.
8 Waste supplier and processor agents evaluate their cash flow outcomes and the extent of biodigester usage. If the waste supplier loses too much money, the agent decides to leave the network.
9 If the processor leaves the network, for example because of insufficient waste input or because cashflow results are below a threshold, the whole network fails. The simulation either ends after the network fails, or after running a set time span.

3.3.2. Modelling of CBMs and design options

Business models are the complete set of elements that create a story (Magretta, 2002), and therefore CBMs determine the model narrative. To experiment with the two CBMs as described in Table 1, we modelled these as exogenous variables, i.e., as input parameters set to our model. By using a switch, the course of events during model start-up is determined, which sets the agents' roles, aims and actions, see Table 2.

Design options are the instantiations of the set of *design variables* within our model, that affect the course of events made within the CBM narratives. We quantitatively modelled 20 CBM design variables, which are related to the CBM dimensions, see Table 3.

To increase the model's validity, we iteratively developed the model input variables according to the case study and assessed the outcomes. This process was repeated until the model outcomes met the expectations of the case study participants.

3.4. Experimental design

3.4.1. Aim and setup

According to Magretta (2002), a viable organisation is built on a viable business model. In addition, stakeholders should be motivated to be part of the business model by capturing value (D'Souza et al., 2015). In our model, the value captured is calculated as the relative cash flow compared to the initial state, i.e., using incineration costs as a benchmark. The simulated ISN fails to capture value, if the waste processor leaves before the given time span of 5 years. Therefore, our main performance indicators for viability of CBMs are [1] the ISN survival rate (percentage of runs with surviving ISNs) and [2] the value captured,

Table 1
Both modelled and tested CBMs including design options (inspired by Lüdeke-Freund et al., 2019).

	CBM Dimensions		Design options	Explanation
CBM 1	Value proposition	Products	Products based on recycled waste	Production of energy (heat, electricity from biogas).
		Products	Waste as recyclable production inputs	Organic waste is input for biodigestion process.
		Services	Take-back management	Offering a safe deposit system for separated organic waste.
		Services	Waste handling, processing	Service of handling and processing organic waste.
	Value delivery and creation	Target customers	Business-to-business (B2B) Customers	Waste removal from firms, and energy delivery to firms.
		Target customers	'Green' customers	Customers with a 'green interest' (Bocken et al., 2016): using biogas as energy source instead of fossil resources fits with these interests.
		Value delivery processes	Taking back waste	Waste removal.
		Value delivery processes	Sharing waste	Sharing waste to gather a stable amount of input for the production of energy.
		Partners and stakeholders	Collectors of waste	Proprietor of the biodigester.
		Partners and stakeholders	Suppliers of waste	All firms that separate organic waste for supply to the biodigestion facility.
		Value creation processes	Taking back waste	Safe and agile removal of the waste to prevent plague or biological hazard.
		Value creation processes	Using waste as input	Traditionally waste was seen as sunk costs, in this CBM it is seen as an input for energy production.
	Value capture	Revenues	Additional product revenues	Selling biogas.
		Costs	Waste handling, processing	Opportunity to save on waste disposal costs.
		Costs	Resource inputs	Saving on energy costs by not paying to 'traditional' external energy suppliers.
		Costs	Transportation, logistics	Opportunity to save on waste disposal costs.
CBM 2	Value proposition	Products	Products based on resources	Production of energy (heat, electricity from biogas).
		Products	Waste as recyclable production inputs	Organic waste is input for biodigestion process.
		Services	Delivery of by-products (organic residuals)	Offering a safe deposit system for separated organic waste.
		Services	Waste handling, processing	Service of handling and processing organic waste.
	Value delivery and creation	Target customers	B2B Customers	Waste selling to and buying from firms, and energy delivery to firms.
		Target customers	'Green' customers	Customers with a 'green interest' (Bocken et al., 2016): using biogas as energy source instead of fossil resources fits with these interests.
		Value delivery processes	Taking back waste	Purchasing waste as by-product.
		Value delivery processes	Sharing waste	Selling waste as a valuable by-product (resource) to gather a stable amount of input for the production of energy.
		Partners and stakeholders	Collectors of waste	Proprietor of the biodigester.
		Partners and stakeholders	Suppliers of waste	All firms that separate organic waste for supply to the biodigestion facility.
		Value creation processes	Taking back waste	Safe and agile removal of the waste to prevent plague or biological hazard.
		Value creation processes	Using waste as input	Traditionally waste was seen as sunk costs, in this CBM it is seen as a valuable resource for energy production.
	Value capture	Revenues	Additional product revenues	Selling biogas.
		Revenues	Additional product revenues	Selling waste as a valuable by-product.
		Costs	Waste handling, processing	Opportunity to save on waste disposal costs.
		Costs	Resource inputs	Saving on energy costs by not paying to traditional external energy suppliers.
		Costs	Transportation, logistics	Opportunity to save on waste disposal costs.

expressed as the average cash flow each actor generates per tonne waste (Euro/tonne waste/actor).

Aiming to test and improve CBM viability, our study thus searches for CBM designs with highest network survival rates and captured value by the ISN. To do so, we simulated the two CBMs of section 3.3, including the range of design variables, environment and behaviour values

Table 2
Two modelled CBMs.

	Model variables	Input value	Description
CBM 1: Circular waste management	Waste-as-by-product?	FALSE	The target customer is the waste supplier, and the waste processor offers the service of removing and treating waste. This implies that the supplier pays the processor to remove the waste. In the model, during the negotiation stage, the supplier acts as a buyer, and the processor as a seller.
	WSQualPenalty?	FALSE	Waste of too low quality cannot be processed locally. However, since the supplier pays for the waste collection and processing service, no additional costs are charged if the quality of the waste delivered does not meet the minimum quality threshold.
CBM 2: Waste as by-product	Waste-as-by-product?	TRUE	This CBM is focused on production of energy (biogas) and/or fertiliser (digestate). The waste supplier is the seller and the local waste processor is the buyer of local resources.
	WSQualPenalty?	TRUE	Waste of too low quality cannot be processed locally. If the waste supplied is of poor quality, the supplier pays a compensation for the processor's production losses.

(Fig. 3).

The environment and agent behaviour moderate the mechanisms and outcomes during the simulations. Billing by the incinerator occurs outside the ISN. Based on the cases, two incinerator billing scenarios were included in our experiments. In scenario A, waste suppliers pay the incinerator per month. In scenario B, waste suppliers pay the incinerator per mass unit waste. This may occur when a collection system is equipped with sensors to measure the amount of waste. This implies that in scenario B, the waste supplier avoids costs by bringing waste to the ISN (see design variable 16, Table 3).

3.4.2. Input parameters and simulation runs

To experiment with the CBM design, we ran multiple simulations with our model. We thus explored random combinations of CBMs and design options by means of 50 input parameters: 20 parameters related to design variables, and an additional 30 inputs for environment settings and agent behaviour. The parameter settings for the design variables and environment variables were calibrated by means of interactive discussions with case study participants and experts. The behaviour parameter settings were set in such a way that all kinds of actor behaviour were represented in the simulation. A complete parameter setup table can be found in the repository (Lange et al., 2021a).

We used a Latin-hypercube sampling (LHS) algorithm to decrease simulation runtime while still exploring the full simulation space. Based on the requirements of the case study, we simulated both CBMs over 5 years, a maximum of 60 simulation steps. Each simulation was repeated 100 times in order to create data with enough statistical significance, thus creating 10000 runs for each CBM including design options.

The simulation results comprise data regarding local synergy participation, waste exchanges, whether or not the ISN survived, cash flow outcomes per agent, and average value captured by the ISN. Following the scope of this study, this data was then used to analyse the CBM viability on the network level. In the next sections, the results, the contributions and limitations with regard to this CBM experimentation

Table 3
Modelled design variables the relation to CBMs.

Design variables in the model Nr.	Design variables	Explanation	Relation to CBM Dimension
CBM Partners			
1	ISNSize	Amount of potential ISN participants (number of firms)	Value creation and delivery.
CBM Quantity control parameters			
2	MaxQuantityAllowed	Maximum biodigester capacity (kg/month).	Value creation and delivery.
3	WPMinProcThresholdPerc	Minimum required amount of waste (kg/month) to keep the biodigestion process running.	Value creation and delivery.
4	WPProcThresholdPerc	Acceptable amount of waste (kg/month) for the processor.	Value creation and delivery.
5	I/Oratio	Mass of digestate out: mass of waste in (kg/kg).	Value creation and delivery.
6	GasProdRatio	Volume of biogas out: mass of waste in (Nm^3/kg).	Value creation and delivery.
CBM Quality control parameters			
7	WPQualThresholdPerc	Quality is defined as: "the extent to which the residual can is suitable as an input for production at the waste processor." The waste processor strives for the highest input stream quality and can determine whether to accept residuals based on quality observations. The minimum allowed quality is determined by using this minimum quality threshold, which can be increased or decreased. All waste below that quality is discarded by the waste processor and send to the incinerator.	Value proposition, value creation and delivery, value capture.
8	WSWQualControl	Increase of waste quality by the supplier by means of active separation at the source.	Value proposition, value creation and delivery, value capture.
9	WSWQualRNorm	Decrease of waste quality variance by means of active separation at the source.	Value proposition, value creation and delivery, value capture.
CBM Revenue and costs			
10	initCPrice	Different market values for digestate. 0 euro per tonne, if it is not sold, but pumped to the sewer. Approx. 3 euro/tonne if it is sold to a farmer (Akkerwijzer.nl, 2011).	Value capture.
11	initGasPrice	Different market values for digestate. Approximately 0,07 to 0,01 euro per produced kWh, based on Mulder et al. (2020).	Value capture.
12	initBPPrice	By-product price (used when Waste-as-by-product? = TRUE).	Value capture.

(*continued on next page*)

Table 3 (*continued*)

Design variables in the model Nr.	Design variables	Explanation	Relation to CBM Dimension
13	initWPrice	Costs for waste handling (used when Waste-as-by-product? = FALSE), based on Mulder et al. (2020).	Value capture.
14	ProcCostsPerUnit	Processing costs for waste treatment.	Value creation and delivery, value capture.
15	PercProductYield2WP	Sharing of revenues. When 0 all revenues are allocated to the supplier, when 1 the processor takes all revenues.	Value creation and delivery, value capture.
16	PercAvoidedWasteCosts2WS	Sharing of costs. When 0 all avoided costs are allocated to the processor, when 1 all avoided costs are assigned to the supplier. (Works in scenario B only, see sec. 3.4.1.)	Value creation and delivery, value capture.
CBM Other contractual requirements			
17	Contract_Length	Duration of a contract between the waste supplier and waste processor.	Value creation and delivery.
18	WSStepOutMoney	Premature contract cancellation by the waste supplier, due to losses.	Value creation and delivery, value capture.
19	WPStepOutMoney	Premature contract cancellation by the local waste processor, due to losses.	Value creation and delivery, value capture.
20	WPStepOutEmpty	Premature contract cancellation by the local waste processor, due to lack of resources.	Value creation and delivery, value capture.

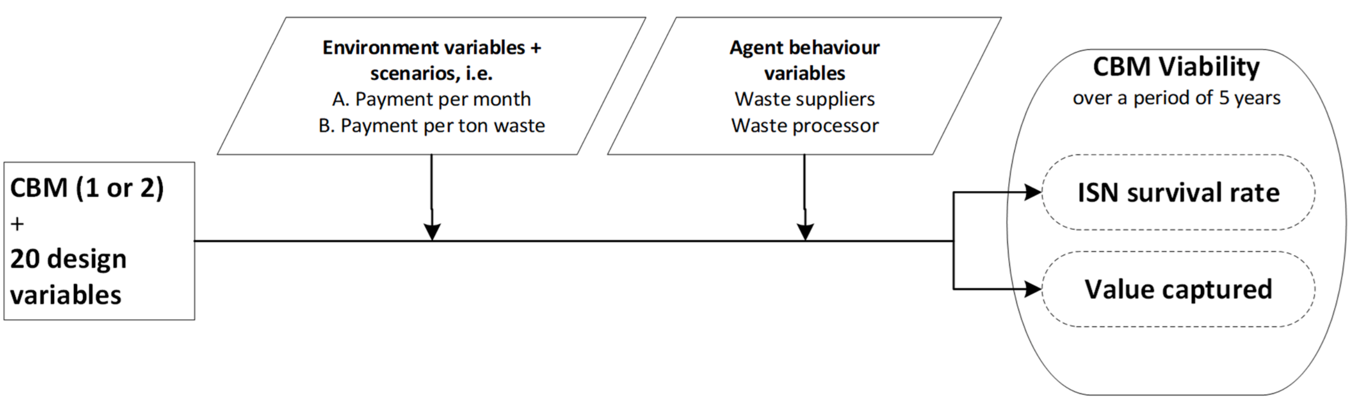

Fig. 3. Application of conceptual framework to the case study.

approach are shown and discussed.

4. Explorative and iterative CBM experimentation and analysis

This section describes how the data was analysed and used to improve CBM viability in accordance with the iterative design science method as described in section 3. Four steps were followed:

- Step 1: we compared the two CBMs as described in Table 1 and 2 (section 4.1);
- Step 2: we explored the efficacy of CBM design variables of Table 3 with the highest survival rate (section 4.2);
- Step 3: we improved the CBM viability by optimising design variable ranges based on the results of step 2 (section 4.3);
- Step 4: we explored directions for further viability improvement, by studying the role of context and behaviour variables (section 4.4).

4.1. Comparing the efficacy of the two CBMs

The simulation results for comparing the CBMs are shown in Fig. 4. It shows the survival rates of both CBMs in the bar charts on the left. The average value captured or lost per actor in the ISN (expressed in Euro/ tonne waste/actor) is shown in the box plots on the right.

CBM 1 clearly shows higher survival rates than CBM 2 in both scenarios. In addition, it shows that scenario B - in which waste suppliers pay the incinerator per mass unit waste - is clearly more in favour of local biodigestion initiatives, regardless of the chosen CBM. When actors collaborate and the network survives, it generally correlates to positive cash flows, compared to not joining the ISN. The captured value per actor is generally higher for CBM 2 in comparison with CBM 1. We would like to stress that the value captured in the box plots does not represent individual profits and losses. Following the scope of this study, it indicates whether the ISN as a whole is capturing or losing value.

Continuity of the ISN is evidently preferred to support the circular economy. We therefore decided to explore the CBM with the highest survival rate - CBM 1 - in the next steps. Yet, it is still evidently desirable to find ways for companies to increase its viability. Therefore, the next step describes how to explore the effect of the design variables.

4.2. Exploring the efficacy of CBM design variables

The results of two variables are shown in Fig. 5a, since these represent two types of outcomes, which we call Type I and Type II variables[1].

1 Type I variables show either a clear positive or negative correlation with both ISN survival and value captured. For example, increasing the gas production ratio (design variable 6: *GasProdRatio*), results in higher CBM viability;
2 Type II variables do not show a clear positive or negative correlation with both viability indicators, for example the distribution of revenues between processor and supplier (design variable 15: *PercProductYield2WP*).

[1] The results of the other 18 design variables can be found in the repository (Lange et al., 2021a).

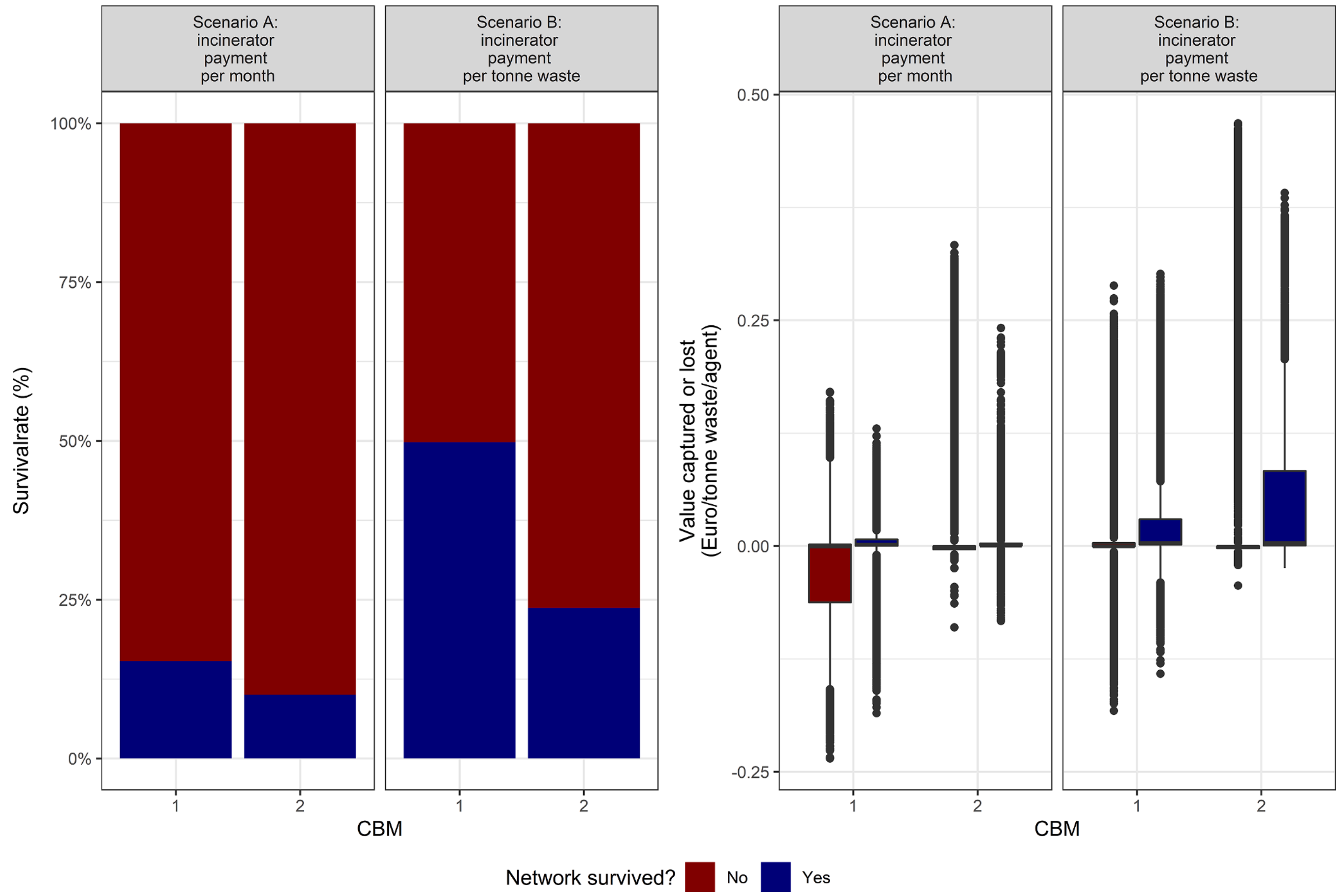

Fig. 4. Survival rate (left) and economic benefits or losses (right) of both CBMs in two scenarios. The box plots follow standard Tukey representations, showing the mean value (line), the interquartile range (IQR, box), the values no further or lower than 1.5*IQR (whiskers) and outliers (dots).

Increasing or decreasing Type I variables is clearly correlated to a higher CBM viability. However, improvement of CBM viability through Type II variables is less obvious: stakeholders have to decide which of the two indicators (ISN survival or value captured) should be given priority. As we decided to prioritize avoiding the risk of network failure, we now can find a range optimum to primarily maximize ISN survival rates and secondarily optimise the value captured. This is shown in the next step.

4.3. Improving CBM viability

To improve CBM viability, we listed the results of steps 1 and 2 and ordered these results according to the highest survival rates. Based on this list, it was decided which survival rates were both feasible and acceptable. In our example, four simulation runs had resulted in a survival rate higher than 75%. Moreover, all these runs resulted in captured value (no loss), and therefore no results needed to be discarded. We then chose a new range of input values, determined by the minimum and maximum values of each design variable in this top four list.

After running simulations within the new range of design variables, the survival rate had increased to approximately 65%, as can be seen for the examples in Fig. 5b. This means that even within a favourable design variable range, one third of the simulation runs leads to ISN failure. The average cash flow per actor is slightly positive with negative outliers.

4.4. Exploring new directions for CBM viability improvement

The previous results show that possibilities to make the modelled local biodigestion initiative robust with the 20 chosen design variables are limited. In addition, the current design generally leads to limited value captured, and often value lost. Adding extra design variables to the model may improve the CBM viability. The current model already provides for new ideas, since context and behaviour variables were included. As shown in Fig. 6, the context and actor behaviour parameters may also affect the CBM viability outcomes.

In this case, modifying the contract duration between the supplier and incinerator (context variable *WSWIMaxfixedContractLength*) may improve the survival rate. Moreover, changing leaving behaviour (variable *WPStepOutB*) or collaborative behaviour (variable *initWPB*) improves ISN survival rates and value captured. Thus, adding design variables that respond to - or even shape contextual and behavioural factors - may offer opportunities for improvement of CBM viability.

5. Discussion

In this section we discuss the simulation results, reflect on the proposed CBM experimentation method, and discuss the study limitations and implications for practitioners.

5.1. Validation

Since the purpose of the model is to explore multiple possible futures, traditional validation by real-world comparison is not feasible. Echoing Dam et al. (2013), we therefore validated whether the model is useful and convincing for understanding the mechanisms and outcomes of this study and for improving the CBM. Throughout the modelling and simulation process, multiple interactive sessions with experts and case participants were conducted to iteratively validate and calibrate the

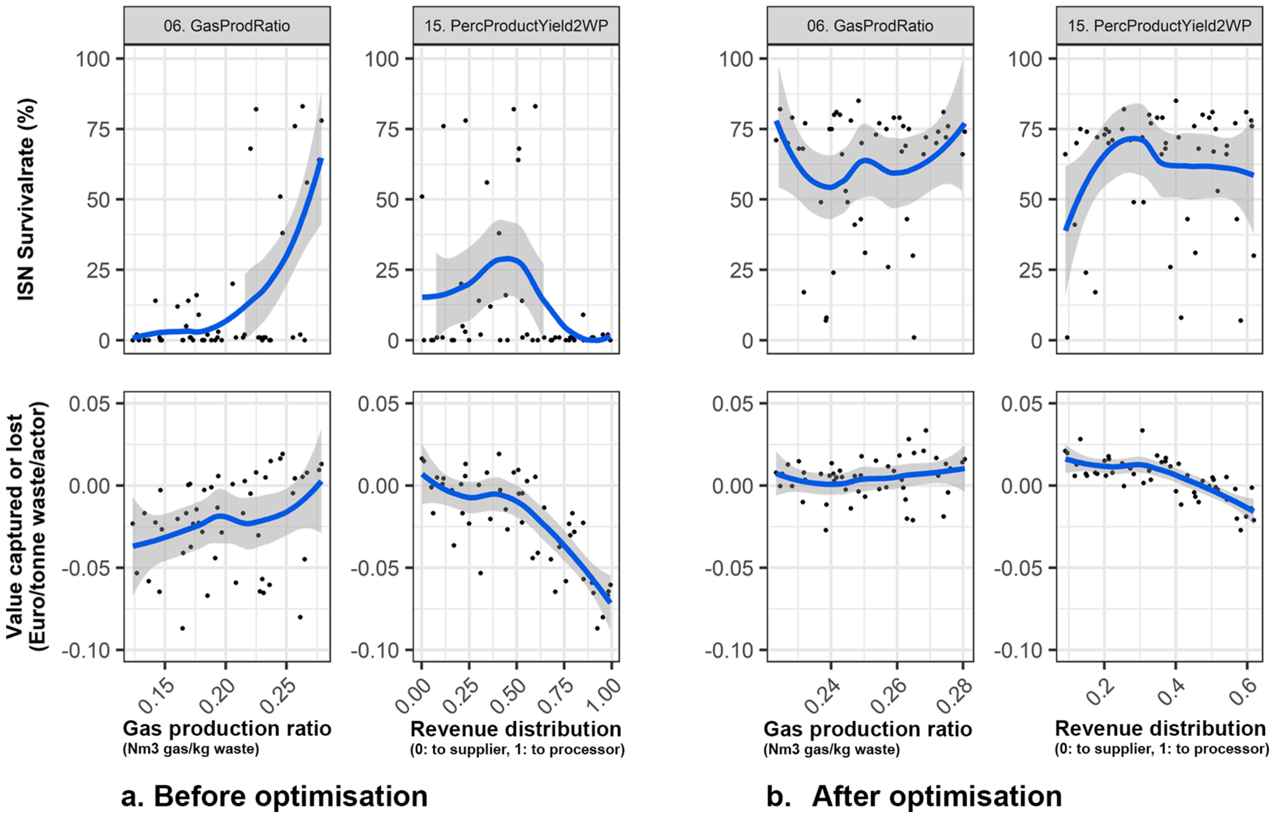

Fig. 5. Correlation between two design variables and CBM viability indicators (a.) before optimisation (section 4.2) and (b.) after optimisation (section 4.3). The lines and shaded areas respectively represent the polynomial regression of the average and standard deviation.

model assumptions, simulation mechanisms and outcomes. In addition, we compared the results with academic literature, and business reports. After close examination of the agent behaviour in the model, it showed that the low survival rates in small sized ISNs were often a result of waste processors leaving due to an insufficient waste supply, which is in line with the expectations of the case participants. In addition, the modelled ISNs that failed, were not able to create new synergies after the first were established, which corresponds to observations by Chertow and Ehrenfeld (2012). Cash flows ranges were confirmed by experts and compared to data from a Life Cycle Costing study by Mulder et al. (2020).

5.2. Discussion of the simulation results

The results of the case study simulations offer four perspectives on the effect of CBMs and underlying design options on CBM viability, providing insights into opportunities for improvement of both the CBM and the model itself.

First, by comparing survival rates and value captured over the complete range of design variables, the simulations increase insight into CBM viability under different circumstances. These insights help stakeholders in deciding which type of CBM to explore further. In our example, the decision to select '*Circular waste management*' (CBM 1) in favour of '*Waste as by-product*' (CBM 2) was based on the highest survival rate. The effect of the two incinerator billing scenarios showed that incinerator payment per tonne waste increases the network robustness. Thus, the CBM viability improves if the incinerator is convinced to switch to a payment-per-tonne scenario. This may be achieved by involving the incinerator as a network partner. Or by convincing public policy makers to redesign policies that encourage payment per mass unit.

The second perspective was the exploration of design options, expressed as a set of design variables. The study showed to what extent and how the different design variables affect the viability. Some variables (i.e., Type I) both reinforce the survival rate and value captured, whilst other variables (Type II) may be conflicting. Decisions regarding CBM viability optimisation are therefore dependent on stakeholder preferences for either survival or value capture.

The third perspective was to explore a range of inputs for each design variable, which is correlated to high ISN survival rates and positive captured value for the ISN as a whole. By doing so, the network survival rate increased from less than 25% to approximately 65%. Still, the relative value captured (i.e., compared to not implementing the CBM) remains close to zero. A value proposition could be added to the CBM to create extra revenues. For example, this could be done by creating revenue from visitors who are willing to pay for education on the process of biodigestion. Another way to improve CBM viability could be to capitalize environmental and social benefits that are related to the CBM.

Fourth, by exploring the effects of context and actor behaviour variables on CBM viability, directions for future business model improvement and policy interventions were provided. The CBM could be improved by adding CBM design interventions that test or increase the behavioural intention of the processor to create synergies (Lange et al., 2021b).

5.3. Reflection on the proposed CBM experimentation approach and contribution to research

An extensive literature review of CBM approaches by Pieroni et al. (2019) shows that systematically designing and testing new business models and design options is hardly being studied in a quantitative way. The proposed iterative methodological approach contributes to filling this gap. The simulation results show that the approach and its outcomes are of value to experiment with CBMs and design options that are yet to be implemented. The agent-based modelling and simulation approach helps to gain insights on complexity and dynamics on both the firm level and the network level, which is required for CBM innovation (Ünal et al.,

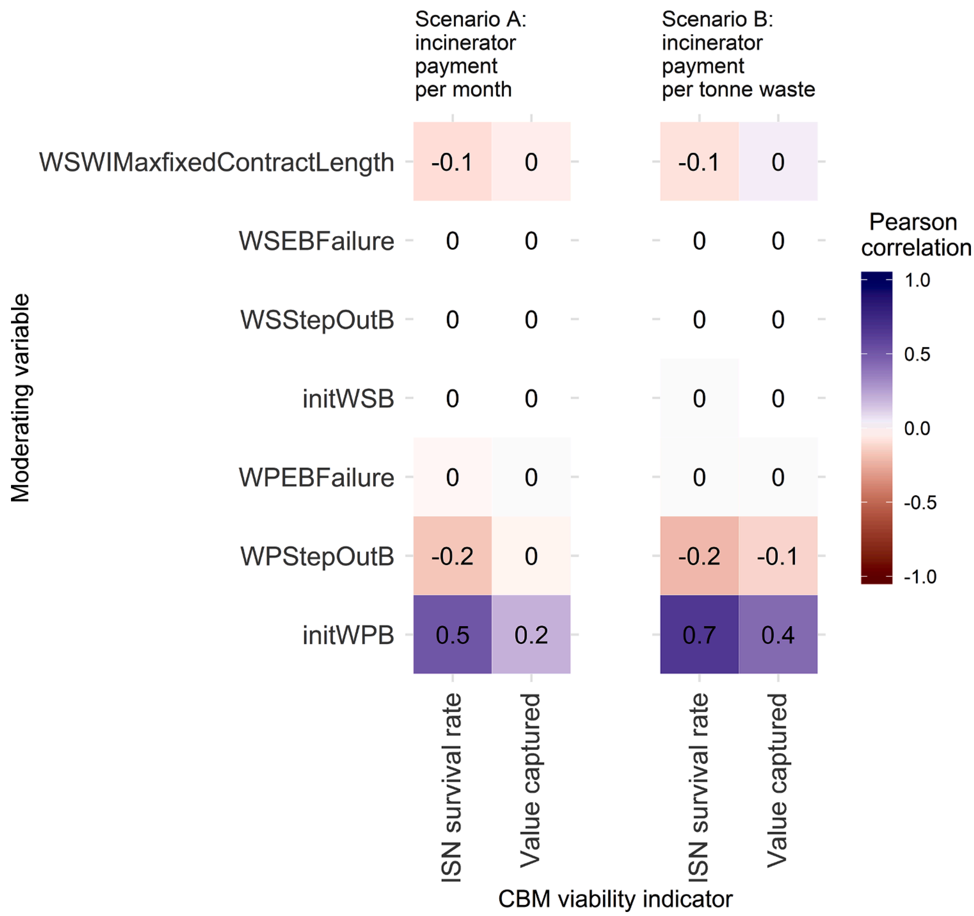

Fig. 6. Correlation between moderating context and behaviour variables and CBM viability in both scenarios.

2019).

This work illustrates how agent-based modelling and simulation offer ways to improve *"the lack of clearly defined variables"* in CBMs (Ünal et al., 2019, p. 296). The method forces the modellers and participating stakeholders to explicate scale, time and actor interactions during the modelling process. The use of agent-based modelling and simulation is a powerful method to experiment with CBMs and a variety of design options. Where ISNs are rooted in Industrial Ecology and focussed on resource efficiency, other types of CBM archetypes have different purposes that also foster the principles of CE. Based on the sociotechnical nature of CBMs, and the fact that the proposed approach encompasses the generic business model dimensions, we expect a similar approach can be applied to other CBM archetypes. Some examples already show evidence in this direction. The work of Lieder et al. (2017) shows that ABMs can be used to test various social business model archetypes, such as pay-per-use or buy-back strategies. Another example is the ABM approach of Kawa & Golinska (2010) to study Closed Loop Supply Chains, originating from the field of Supply Chain Management. More research is needed to include all business model dimensions in ABMs of these other CBM archetypes.

Due to the aforementioned systematic approach to test generic business model dimensions, we expect that the proposed experimentation method can also contribute to collaborative business models from a broader perspective than that of the circular economy. For example, it can be used to systematically test business model designs with respect to demand and supply dynamics in traditional supply chains, also known as industrial dynamics (Forrester, 1997) or the bullwhip effect (Lee et al., 1997).

5.4. Limitations and avenues for future research

In this section, we discuss several study limitations and opportunities for future research regarding the model, the modelling process and the modelling and simulation strategy.

5.4.1. Model

The modelled interfirm collaborations are bound to free market waste exchanges, based on the organisational and legal context. Other ways to settle agreements in ISNs, for example by joining an ISN cooperative in which fees are determined during a general meeting of members, were not modelled. Thus, the simulation results cannot be applied to other cases, without modifying the model and input values. Furthermore, this model is limited to a specific type of industrial synergies. To incorporate multi-material exchanges and processes, the model should be extended. Furthermore, future research should also entail the extension of our model with other business model designs. By means of the proposed participatory approach, CBMs that include newly introduced agents may also be tested on CBM viability, for example to experiment with the role of an external facilitator or a cooperative manager.

CBMs and contexts can also be modelled differently, e.g., by using other theories. In our example, we modelled negotiation as time-dependent. It is also possible to use other models such as behaviour- or resource-dependent negotiation models, which may lead to different outcomes. Furthermore, the model does not include behaviour with respect to agent learning, habitual routine or mutual trust. Thus, we recommend comparing the ABM of this study to other models using different theories (e.g., behavioural theories other than the Theory of Planned Behaviour), similar cases and other business model experimentation methods, to increase its explorative power. Adding agent learning to address company's adaptive nature is another recommendation for future research.

Although not yet included in this version of the model, social and environmental revenues and avoided costs are essential parts of CBMs (Geissdoerfer et al., 2018). Consequently, agent-based models for CBM experimentation must be developed further, incorporating social and environmental benefits and multi-material exchanges as well.

5.4.2. Modelling and simulation approach

The approach to participatory modelling and simulation is part of a complex sociotechnical system: the provided insights affect the ongoing process of business model innovation. Therefore, the model contributes to exploration of possible mechanisms and outcomes, rather than to predicting the future. Yet, it allows companies to explore potential risks in the future before these actually occur, which makes the contribution of this modelling approach to the business experimentation literature even more powerful. Moreover, the approach allows companies to add and test various new design options to improve their own individual benefits, as well as the benefits for the network as a whole, which is an important condition for network-level business models (Lindgren et al., 2010).

Whereas we improved CBM viability through targeted iterative simulation steps between researchers and case participants, another way to use ABMs that have matured in such processes, could be to subject them to a deep computational analysis, and simultaneously explore multiple CBMs in combination with multiple parameter sets. The Exploratory Modelling and Analysis methodology (Bankes, 1993) enables modellers to support such robust decision making under deep uncertainty (Kwakkel, 2018). It could identify combinations of parameters and variable settings for improving CBM resilience. It helps in uncovering factors that dampen the negative effect of extreme externalities or in finding ways to deal with extreme events by changing the configuration of the CBM design according to the environment.

As this work also allows for providing new perspectives on business model experimentation in the broader context of supply chain management, we advise researchers from that field of interest to consider the proposed modelling and simulation approach as well. It may provide opportunities to integrate business model experimentation literature and studies on the dynamics of supply chain management, e.g., Zarandi et al. (2008), Costas et al. (2015), Trkman et al. (2015) or Zimon et al. (2019).

5.5. Implications for practitioners

Agent-based approaches help stakeholders to understand the system in which they operate and what role they play. This provides insights to avoid missing dynamics in their environment that may lead to individual decisions that eventually harm their business (Bas, 2017, p. 181). Referring to Epstein (2008, sec. 1.9), we mainly used this model to *"explain the system, guide data collection, illuminate core dynamics and uncertainties, bound outcomes to plausible ranges, demonstrate trade-offs, and raise new questions"*. The explorative nature of the study may also contribute to prescriptive knowledge by training (future) stakeholders. Examples of beneficiaries are collectives of firms that engage in circular practices, but also individual companies, searching for ways to improve individual value creation within the collective. For public institutions the agent-based approach helps in designing policies to support CBM innovations. During the process of modelling, practitioners were encouraged to concretise their goals, ideas, definitions, actions and doubts. This approach enables potential industrial and commercial partners to cooperate through coevolutionary social learning (Batten, 2009; Edmonds et al., 2019). Yet, we also observed that it is necessary to have companies involved that are willing to invest time and effort in this approach, which is in line with similar findings by Bas (2017, p. 181). We recommend starting with simple and small models, which are easy to create, communicate, understand and improve. Through multiple iteration steps, larger and more complex models can be built, while expanding the knowledge and network of stakeholders. In the end this may result in a complex, yet realistic model, which can be used for more long term and high-risk decision making. Moreover, the model can be used to add or adjust design options, once the CBM is implemented.

6. Conclusion

This study contributes to the development of *ex ante* circular business model experimentation methods by proposing a quantitative method to simultaneously explore and improve CBM design options. The proposed method is the first to systematically explore all dimensions of CBMs with a dynamic agent-based simulation model, which comprehensively describes the influence of external factors and individual actor behaviour. It thus provides for knowledge and design solutions that are related to obstacles that currently hamper CBM implementation. Participatory agent-based modelling allows us to simulate the day-to-day activities and interactions of actors and technologies as a result of CBM design and its context. The network-level CBM viability outcomes are a result of the modelled micro-level processes. The results provide insights that can be used for the benefit of the collaborative initiative, as well as for the individual stakeholder. Although the case showed an example of CBM experimentation within the context of ISNs, the proposed experimentation method bridges the gap between generic key elements of CBMs and agent-based modelling. We infer that this method can be applied to all types of CBMs which involve stakeholder collaborations. This study shows that participatory agent-based modelling and simulation is a powerful method for circular business model experimentation. Hence, we invite the research community to adopt it as a standard approach to study and improve circular business models.

Author contributions

Kasper Lange contributed to conception of the work, data collection, analysis and interpretation, model development, drafting and writing the article. Gijsbert Korevaar contributed to model development, data interpretation, critical revisions of the article, and final approval. Inge Oskam contributed to critical revisions of the article, and final approval. Igor Nikolic contributed to software implementation, data analysis and interpretation. Paulien Herder contributed to model development, data interpretation, critical revisions and final approval.

Declaration of Competing Interest

The authors declare no conflict of interest. The funding sponsors had no role in the design of the study, nor in any activities regarding modelling, simulation or analysis.

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References

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process. 50, 179–211. https://doi.org/10.1016/0749-5978(91)90020-T.
Akkerwijzer.nl, 2011. Gebruik digestaat drukt kosten van kunstmest [WWW Document]. URL https://www.akkerwijzer.nl/artikel/86195-gebruik-digestaat-drukt-kosten-van-kunstmest/(accessed 7.13.20).
Albino, V., Fraccascia, L., Giannoccaro, I., 2016. Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study. J. Clean. Prod. 112, 4353–4366. https://doi.org/10.1016/j.jclepro.2015.06.070.
Andrews, C.J., 2000. Building a micro foundation for industrial ecology. J. Ind. Ecol. https://doi.org/10.1162/108819800300106375.
Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., Calabretta, G., 2019. Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating Circular Economy and Industrial Ecology perspectives. J. Clean. Prod. 216, 446–460. https://doi.org/10.1016/j.jclepro.2019.01.091.
Bankes, S., 1993. Exploratory Modeling for Policy Analysis. Oper. Res. https://doi.org/10.1287/opre.41.3.435.
Bas, G., 2017. Resilient Industrial Systems : A Complex System Perspective to Support Business Decisions. https://doi.org/10.4233/UUID:4341F2E2-232A-4361-A4EE-D21D91476E1B.
Batten, D.F., 2009. Fostering industrial symbiosis with agent-based simulation and participatory modeling. J. Ind. Ecol. 13, 197–213. https://doi.org/10.1111/j.1530-9290.2009.00115.x.
Bocken, N., Antikainen, M., 2018. Circular business model experimentation: Concept and approaches. In: Smart Innovation, Systems and Technologies, pp. 239–250. https://doi.org/10.1007/978-3-030-04290-5_25.
Bocken, N., Boons, F., Baldassarre, B., 2019. Sustainable business model experimentation by understanding ecologies of business models. J. Clean. Prod. 208, 1498–1512. https://doi.org/10.1016/j.jclepro.2018.10.159.
Bocken, N., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.
Bocken, N., Rana, P., Short, S.W., 2015. Value mapping for sustainable business thinking. J. Ind. Prod. Eng. 32, 67–81. https://doi.org/10.1080/21681015.2014.1000399.
Bocken, N., Short, S., Rana, P., Evans, S., 2014. A literature and practice review to develop sustainable business model archetypes. J. Clean. Prod. 65, 42–56. https://doi.org/10.1016/J.JCLEPRO.2013.11.039.
Bressanelli, G., Perona, M., Saccani, N., 2019. Challenges in supply chain redesign for the Circular Economy: a literature review and a multiple case study. Int. J. Prod. Res. 57, 7395–7422. https://doi.org/10.1080/00207543.2018.1542176.
Breuer, H., Fichter, K., Lüdeke-Freund, F., Tiemann, I., 2018. Sustainability-oriented business model development: Principles, criteria and tools. Int. J. Entrep. Ventur. 10, 256–286. https://doi.org/10.1504/IJEV.2018.092715.
Camparotti, E., 2020. Camparotti, Eduardo. Diss. Mestr. UFSCAR. Universidade Federal de Sào Carlos.
Cao, K., Feng, X., Wan, H., 2009. Applying agent-based modeling to the evolution of eco-industrial systems. Ecol. Econ. 68, 2868–2876. https://doi.org/10.1016/j.ecolecon.2009.06.009.
Cecchin, A., Salomone, R., Deutz, P., Raggi, A., Cutaia, L., 2020. Relating industrial symbiosis and circular economy to the sustainable development debate. in: Salomone, R., Cecchin, A., Deutz, P., Raggi, A., Cutaia, L. (Eds.). Industrial Symbiosis for the Circular Economy, Strategies for Sustainability. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-36660-5.
Chandra-Putra, H., Chen, J., Andrews, C.J., 2015. Eco-evolutionary pathways toward industrial cities. J. Ind. Ecol. 19, 274–284. https://doi.org/10.1111/jiec.12234.
Chertow, M., Ehrenfeld, J., 2012. Organizing self-organizing systems: toward a theory of industrial symbiosis. J. Ind. Ecol. 16, 13–27. https://doi.org/10.1111/j.1530-9290.2011.00450.x.
Chopra, S.S., Khanna, V., 2014. Understanding resilience in industrial symbiosis networks: Insights from network analysis. J. Environ. Manage. 141, 86–94. https://doi.org/10.1016/j.jenvman.2013.12.038.
Circle Economy, 2020. Circularity Gap Report, 2020.
Costas, J., Ponte, B., De La Fuente, D., Pino, R., Puche, J., 2015. Applying Goldratt's theory of constraints to reduce the bullwhip effect through agent-based modeling. Expert Syst. Appl. 42, 2049–2060. https://doi.org/10.1016/j.eswa.2014.10.022.
D'Souza, A., Wortmann, H., Huitema, G., Velthuijsen, H., 2015. A business model design framework for viability; a business ecosystem approach. J. Bus. Model. https://doi.org/10.5278/ojs.jbm.v3i2.1216.
Dam, K.H.van, Nikolic, I., Lukszo, Z., 2013. Agent-based modelling of socio-technical systems. in: Dam, K.H. van, Nikolic, I., Lukszo, Z. (Eds.). Agent-Based Modelling of Socio-Technical Systems. Springer Science+Business Media, Dordrecht. https://doi.org/10.1007/978-94-007-4933-7, pp. 52, 53.
De Angelis, R., 2016. A Conceptualisation of Circular Business Models and Explanation of Their Adoption: Evidence From Four In-Depth Case Studies Submitted. Univ. Exet. https://doi.org/10.1017/CBO9781107415324.004.
De Meyer, A., Cattrysse, D., Rasinmäki, J., Van Orshoven, J., 2014. Methods to optimise the design and management of biomass-for-bioenergy supply chains: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.12.036.
Doménech, T., Davies, M., 2010. The role of Embeddedness in Industrial Symbiosis Networks: Phases in the Evolution of Industrial Symbiosis Networks. Bus. Strateg. Environ. 20, 281–296. https://doi.org/10.1002/bse.695.
Dresch, A., Lacerda, D.P., Antunes, J.A.V., 2015. Design science research: a method for science and technology advancement. Design Science Research: A Method for Science and Technology Advancement. https://doi.org/10.1007/978-3-319-07374-3.
Edmonds, B., Le Page, C., Bithell, M., Chattoe-Brown, E., Grimm, V., Meyer, R., Montañola-Sales, C., Ormerod, P., Root, H., Squazzoni, F., 2019. Different modelling purposes. JASSS 22. https://doi.org/10.18564/jasss.3993.
EMF, McKinsey, 2014. Towards the Circular Economy: Accelerating the scale-up across global supply chain [WWW Document] Rep. world Econ. forum. URL http://www3.weforum.org/docs/WEF_ENV_TowardsCircularEconomy_Report_2014.pdf (accessed 1.4.16).
Epstein, J.M., 2008. Why Model? Journa Artif. Soc. Soc. Simul. 11, 12.
Forrester, J.W., 1997. Industrial dynamics. J. Oper. Res. Soc. 48, 1037–1041. https://doi.org/10.1057/palgrave.jors.2600946.
Gang, W., Xiao, F., Chu, K.H., WANG, G., FENG, X., Khim Hoong, C., 2014. Symbiosis analysis on industrial ecological system. CHINESE J. Chem. Eng. 22, 690–698. https://doi.org/10.1016/S1004-9541(14)60084-7.
Geissdoerfer, M., Morioka, S.N., de Carvalho, M.M., Evans, S., 2018. Business models and supply chains for the circular economy. J. Clean. Prod. 190, 712–721. https://doi.org/10.1016/j.jclepro.2018.04.159.
Geissdoerfer, M., Savaget, P., Bocken, N., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.12.048.
Ghali, M.R., Frayret, J.-M.M., Ahabchane, C., 2017. Agent-based model of self-organized industrial symbiosis. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.05.128.
Ghisellini, P., Cialani, C., Ulgiati, S., 2015. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.
Grimm, V., Railsback, S.F., Vincenot, C.E., Berger, U., Gallagher, C., Deangelis, D.L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A.S.A., Milles, A., Nabe-Nielsen, J., Polhill, J.G., Radchuk, V., Rohwäder, M.S., Stillman, R.A., Thiele, J.C., Ayllón, D., 2020. The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. JASSS 23, 7. https://doi.org/10.18564/jasss.4259.
Hevner, A.R., 2007. A Three Cycle View of Design Science Research. Scand. J. Inf. Syst. 19, 87–92.
Holland, J.H., 1992. Complex Adaptive Systems [WWW Document]. URL. http://www-personal.umich.edu/~samoore/bit885w2012/ComplexAdaptiveSystemsHolland.pdf (accessed 1.12.16).
Janssen, M.A., 2005. Agent-Based Modelling. Soc. Change 1–9.
Kawa, A., Golinska, P., 2010. Supply chain arrangements in recovery network. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics. Springer, Berlin, Heidelberg, pp. 292–301. https://doi.org/10.1007/978-3-642-13541-5_30.
Kwakkel, J.H., 2018. EMA Workbench documentation — Exploratory Modeling Workbench [WWW Document]. URL. https://emaworkbench.readthedocs.io/en/latest/ (accessed 12.3.20).
Lange, K.P.H., Korevaar, G., Nikolic, I., Herder, P.M., 2021a. Circular Business Model experimentation: local biodigestion network (Version 1.1.0). CoMSES Comput. Model Libr. https://doi.org/10.25937/3ewr-yt59 (accessed 7.6.21). https://www.comses.net/codebases/2168a12b-654d-478a-931b-761b3719818b/releases/1.1.0/ (accessed 3.22.21).
Lange, K.P.H., Korevaar, G., Nikolic, I., Herder, P.M., 2021b. Actor Behaviour and Robustness of Industrial Symbiosis Networks: An Agent-Based Modelling Approach. J. Artif. Soc. Soc. Simul. 24. https://doi.org/10.18564/jasss.4635.
Lange, K.P.H., Korevaar, G., Oskam, I.F., Herder, P.M., 2017. Developing and understanding design interventions in relation to industrial symbiosis dynamics. Sustain 9. https://doi.org/10.3390/su9050826.
Lee, H.L., Padmanabhan, V., Whang, S., 1997. The Bullwhip Effect in Supply Chains.
Lewandowski, M., 2016. Designing the Business Models for Circular Economy—Towards the Conceptual Framework. Sustainability 8, 43. https://doi.org/10.3390/su8010043.
Lieder, M., Asif, F.M.A., Rashid, A., 2017. Towards Circular Economy implementation: an agent-based simulation approach for business model changes. Auton. Agent. Multi. Agent. Syst. 31, 1377–1402. https://doi.org/10.1007/s10458-017-9365-9.
Lindgren, P., Taran, Y., Boer, H., 2010. From single firm to network-based business model innovation. Int. J. Entrep. Innov. Manag. 12, 122–137. https://doi.org/10.1504/IJEIM.2010.034417.
Lüdeke-Freund, F., Gold, S., Bocken, N., 2019. A Review and Typology of Circular Economy Business Model Patterns. J. Ind. Ecol. https://doi.org/10.1111/jiec.12763.
Magretta, J., 2002. Why business models matter. Harv. Bus. Rev. 86–92. https://hbr-org.tudelft.idm.oclc.org/2002/05/why-business-models-matter.
Mantese, G.C., Amaral, D.C., 2018. Agent-based simulation to evaluate and categorize industrial symbiosis indicators. J. Clean. Prod. 186, 450–464. https://doi.org/10.1016/j.jclepro.2018.03.142.
Mantese, G.C., Amaral, D.C., 2017. Comparison of industrial symbiosis indicators through agent-based modeling. J. Clean. Prod. 140, 1652–1671. https://doi.org/10.1016/j.jclepro.2016.09.142.
Mertens, A., Van Meensel, J., Mondelaers, K., Lauwers, L., Buysse, J., 2016. Context Matters—Using an Agent-Based Model to Investigate the Influence of Market Context

on the Supply of Local Biomass for Anaerobic Digestion. BioEnergy Res 9, 132–145. https://doi.org/10.1007/s12155-015-9668-0.
Mirabella, N., Castellani, V., Sala, S., 2014. Current options for the valorization of food manufacturing waste: A review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2013.10.051.
Mulder, M., Akker, J.van den, Lange, K.P.H., Hees, M.van, Verloop, J.W., Schrik, Y., Oskam, I.F., 2018. Re-organise - Sluiten van stedelijke kringlopen door decentrale verwerking van organisch bedrijfsafval. Amsterdam.
Mulder, M., Lange, K.P.H., Schrik, Y., Faddegon, K., Rijke, S.J.de, Oskam, I.F., 2020. Re-Store: Duurzaamheidsimpact bepalen en vergroten voor stedelijke initiatieven die voedselresten verwerken. Amsterdam.
Municipality of Amsterdam, 2020. Strategie Amsterdam Circulair 2020 - 2025. Amsterdam.
Osterwalder, A., 2016. Why Companies Fail & How To Prevent It [WWW Document]. Strategyzer. URL. https://www.strategyzer.com/blog/posts/2016/6/20/why-companies-fail-how-to-prevent-it (accessed 8.31.20).
Osterwalder, A., Pigneur, Y., 2010. Business model generation: a handbook for visionaries, game changers, and challengers. http://www.consulteam.be/media/5985/businessmodelgenerationpreview.pdf.
Paes, L.A.B., Bezerra, B.S., Deus, R.M., Jugend, D., Battistelle, R.A.G., 2019. Organic solid waste management in a circular economy perspective – A systematic review and SWOT analysis. J. Clean. Prod. 239, 118086 https://doi.org/10.1016/j.jclepro.2019.118086.
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2019. Business model innovation for circular economy and sustainability: A review of approaches. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.01.036.
Raimbault, J., Broere, J., Somveille, M., Serna, J.M., Strombom, E., Moore, C., Zhu, B., Sugar, L., 2020. A spatial agent based model for simulating and optimizing networked eco-industrial systems. Resour. Conserv. Recycl. 155, 104538 https://doi.org/10.1016/j.resconrec.2019.104538.
Richardson, J., 2008. The business model: an integrative framework for strategy execution. Strateg. Chang. 17, 133–144. https://doi.org/10.1002/jsc.821.
Romero, E., Ruiz, M.C., 2014. Proposal of an agent-based analytical model to convert industrial areas in industrial eco-systems. Sci. Total Environ. 468–469, 394–405. https://doi.org/10.1016/j.scitotenv.2013.08.049.
Schaltegger, S., Wagner, M., 2011. Sustainable entrepreneurship and sustainability innovation: categories and interactions. Bus. Strateg. Environ. 20, 222–237. https://doi.org/10.1002/bse.682.
Schenkel, M., Caniëls, M.C.J., Krikke, H., van der Laan, E., 2015. Understanding value creation in closed loop supply chains - Past findings and future directions. J. Manuf. Syst. 37, 729–745. https://doi.org/10.1016/j.jmsy.2015.04.009.
Schroeder, P., Anggraeni, K., Weber, U., 2019. The Relevance of Circular Economy Practices to the Sustainable Development Goals. J. Ind. Ecol. 23, 77–95. https://doi.org/10.1111/jiec.12732.
Smetschka, B., Gaube, V., 2020. Co-creating formalized models: Participatory modelling as method and process in transdisciplinary research and its impact potentials. Environ. Sci. Policy 103, 41–49. https://doi.org/10.1016/j.envsci.2019.10.005.
Stubbs, W., Cocklin, C., 2008. Conceptualizing a 'sustainability business model. Organ. Environ. 21, 103–127. https://doi.org/10.1177/1086026608318042.
Teece, D.J., 2010. Business Models, Business Strategy and Innovation. Long Range Plann 43, 172–194. https://doi.org/10.1016/j.lrp.2009.07.003.
Trkman, P., Budler, M., Groznik, A., 2015. A business model approach to supply chain management. Supply Chain Manag 20, 587–602. https://doi.org/10.1108/SCM-06-2015-0219.
Ünal, E., Urbinati, A., Chiaroni, D., Manzini, R., 2019. Value Creation in Circular Business Models: The case of a US small medium enterprise in the building sector. Resour. Conserv. Recycl. 146, 291–307. https://doi.org/10.1016/j.resconrec.2018.12.034.
Weissbrod, I., Bocken, N., 2017. Developing sustainable business experimentation capability – A case study. J. Clean. Prod. 142, 2663–2676. https://doi.org/10.1016/j.jclepro.2016.11.009.
Wilensky, U., 1999. NetLogo. https://ccl.northwestern.edu/netlogo/.
Yazan, D.M., Fraccascia, L., Mes, M., Zijm, H., 2018. Cooperation in manure-based biogas production networks: An agent-based modeling approach. Appl. Energy 212, 820–833. https://doi.org/10.1016/j.apenergy.2017.12.074.
Zarandi, M.H.F., Pourakbar, M., Turksen, I.B., 2008. A Fuzzy agent-based model for reduction of bullwhip effect in supply chain systems. Expert Syst. Appl. 34, 1680–1691. https://doi.org/10.1016/j.eswa.2007.01.031.
Zheng, K., Jia, S., 2017. Promoting the Opportunity Identification of Industrial Symbiosis: Agent-Based Modeling Inspired by Innovation Diffusion Theory. Sustainability 9, 765. https://doi.org/10.3390/su9050765.
Zhu, J., Ruth, M., 2014. The development of regional collaboration for resource efficiency: A network perspective on industrial symbiosis. Comput. Environ. Urban Syst. 44, 37–46. https://doi.org/10.1016/j.compenvurbsys.2013.11.001.
Zhu, J., Ruth, M., 2013. Exploring the resilience of industrial ecosystems. J. Environ. Manage. 122, 65–75. https://doi.org/10.1016/j.jenvman.2013.02.052.
Zimon, D., Tyan, J., Sroufe, R., 2019. Implementing sustainable supply chain management: Reactive, cooperative, and dynamic models. Sustain 11, 7227. https://doi.org/10.3390/SU11247227.